

# DESIGN OF NOVEL ALKALI ACTIVATED MATERIALS EXHIBITING ADSORPTION PERFORMANCE AND PHOTOCATALYTIC ACTIVITY

by

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*to my family,*

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## ABSTRACT

### **DESIGN OF NOVEL ALKALI ACTIVATED MATERIALS EXHIBITING ADSORPTION PERFORMANCE AND PHOTOCATALYTIC ACTIVITY**

Alkali activated materials (AAMs) are environmentally friendly alternatives to traditional cement binders with their comparable mechanical properties. Geopolymers are a subcategory of AAMs and synthesized from aluminosilicate sources. The main motivation of this thesis is to understand the methylene blue (MB) adsorption and photocatalytic activity of AAMs and geopolymers by utilizing diffraction and microscopy techniques to establish an structure-performance relationship. Firstly, an industrial waste red mud together with metakaolin were used as raw materials and anatase amount in the geopolymer paste was varied to obtain a photocatalytically active geopolymer (RMGP) to remove MB dye from wastewaters. Findings implied that surface Ti species were responsible for the photocatalytic MB removal and 3.7 wt% addition of anatase was found to result in a tripled rate constant compared to that of pure anatase, due to synergistic effect of adsorption and photocatalysis processes. Secondly, novel and new Sep-based AAMs (Sep-AAM) as adsorbents for MB removal was introduced. Results showed that Sep-AAM has an enhanced MB adsorption capacity of 99.9 mg g<sup>-1</sup>, adsorption occurs via chemical adsorption, and is slightly endothermic. MB adsorption performance of monolith-formed Sep-AAMs and metakaolin-based counterparts (MKGP) with varying porosities were studied in the third part of this thesis. Outcomes of this part showed that it is possible to tune the MB adsorption performance and compressive strength by adjusting the porosity levels, and both of these monoliths can be regenerated up to four cycles. In the last part, MB adsorption performance of RMGP from part one was significantly enhanced by incorporating urea-based graphitic carbon nitride. The findings of this thesis demonstrate that AAMs and geopolymers with their economical and environmentally-friendly synthesis procedures offer high mechanical strength, enhanced adsorption and photocatalytic performance towards MB, and sustainable alternatives for wastewater treatment applications.

## ÖZET

### ADSORPSİYON PERFORMANSI VE FOTOKATALİTİK AKTİVİTE GÖSTEREN ALKALİ AKTİF MALZEMELERİN TASARIMI

Alkali aktif malzemeler (AAM) geleneksel çimento bağlayıcılarına çevre-dostu alternatifler olarak bilinen yüksek mekanik performanslı malzemelerdir. AAM'lerin bir alt kategorisi olan jeopolimerler ise aluminosilikat içeriği yüksek malzemelerden sentezlenirler. Bu tezin amacı, AAM ve jeopolimerlerin, metilen mavisi (MB) boyası adsorpsiyonu ve fotokatalitik özelliklerinin anlaşılması; çeşitli karakterizasyon teknikleri kullanılarak yapı-performans ilişkilerinin belirlenmesidir. İlk olarak, endüstriyel bir atık olan kırmızı çamur ve metakaolin kullanılarak sentezlenen jeopolimerlerin kompozisyonlarındaki anataz miktarı değiştirilerek, MB eliminasyonuna yönelik jeopolimerler (RMGP) üretilmiştir. Deneysel sonuçlar, fotokatalitik aktivenin nedeninin yüzey titanyum türleri olduğunu ve ağırlıkça %3.7 anataz içeren RMGP'nin, adsorpsiyon ve fotokataliz mekanizmalarının eş zamanlı etkisinden dolayı saf anataza kıyasla üç kat daha yüksek hız sabitine sahip olduğunu göstermiştir. İkinci olarak, adsorpsiyon literatüründe yeni bir malzeme grubu olarak sepiyolit bazlı bir AAM (Sep-AAM) sentezlenerek bu malzemenin  $99.9 \text{ mg g}^{-1}$  gibi yüksek bir MB giderim performansı gösterdiği, adsorpsiyonun endotermik olduğu ve adsorpsiyon esnasındaki temel mekanizmanın kimyasal olduğu ortaya koyulmuştur. Üçüncü bölümde, sepiyolit ve metakaolin kullanılarak farklı porozitelere sahip monolit formda AAM ve jeopolimerler sentezlenmiş, MB adsorpsiyonu ve mekanik dayanım özelliklerinin monolitlerin porozitesi ile modifiye edilebileceği ve üretilen malzemelerin rejenere edilebileceği gösterilmiştir. Tezin son kısmında ise, RMGP örneği, üre-bazlı grafitik karbon nitrür ile bir kompozit sentezinde ilk defa kullanılarak grafitik karbon nitrür katkısının MB adsorpsiyon kapasitesini salt grafitik karbon nitrüre göre yaklaşık 3.5 kat artırdığı gösterilmiş, kimyasal mekanizmaların adsorpsiyonda etkin olduğu belirlenmiştir. Bu tezin bulguları, etkin adsorpsiyon ve fotokatalitik aktivite performansları ile AAM ve jeopolimerlerin yenilikçi malzemeler olarak atık su arıtımı gibi uygulamalarda çevre-dostu ve sürdürülebilir alternatifler olabileceğini ortaya koymaktadır.

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## LIST OF SYMBOLS

|                 |                                                         |
|-----------------|---------------------------------------------------------|
| $A$             | Arrhenius pre-exponential factor                        |
| at              | Atomic                                                  |
| $C$             | Concentration                                           |
| $E_a$           | Activation energy                                       |
| h               | Hour                                                    |
| $K_F$           | Freundlich constant                                     |
| $K_L$           | Langmuir constant                                       |
| $k_{1,ads,app}$ | Apparent rate constant of pseudo-first-order kinetics   |
| $k_{2,ads,app}$ | Apparent rate constant of pseudo-second-order kinetics  |
| $k_{ads}$       | Actual adsorption rate constant                         |
| $k_p$           | Rate constant of intraparticle diffusion model          |
| $m$             | Order of the reaction with respect to adsorbent amount  |
| min             | Minute                                                  |
| $n$             | Order of the reaction with respect to dye concentration |
| $q$             | Uptake                                                  |
| $R_L$           | Langmuir separation factor                              |
| $T$             | Temperature                                             |
| $t$             | Time                                                    |
| $V$             | Volume                                                  |
| wt              | Weight                                                  |

## LIST OF ACRONYMS/ABBREVIATIONS

|                                                |                                                                       |
|------------------------------------------------|-----------------------------------------------------------------------|
| AAM                                            | Alkali activated material                                             |
| Al                                             | Aluminum                                                              |
| Al <sub>2</sub> O <sub>3</sub>                 | Aluminum oxide                                                        |
| ATR                                            | Attenuated total reflectance                                          |
| BET                                            | Brunauer–Emmett–Teller                                                |
| BJH                                            | Barrett–Joyner–Halenda                                                |
| CO <sub>2</sub>                                | Carbondioxide                                                         |
| FA                                             | Fly ash                                                               |
| FTIR                                           | Fourier transform infrared spectroscopy                               |
| GC/MS                                          | Gas chromatography–mass spectrometry                                  |
| GP                                             | Geopolymer                                                            |
| g-C <sub>3</sub> N <sub>4</sub>                | Graphitic carbon nitride                                              |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP          | Graphitic carbon nitride incorporated red mud and metakaolin-based GP |
| H <sub>2</sub> O <sub>2</sub>                  | Hydrogen peroxide                                                     |
| ICP-MS                                         | Inductively coupled plasma mass spectroscopy                          |
| LC/MS                                          | Liquid chromatography–mass spectrometry                               |
| MB                                             | Methylene blue                                                        |
| MK                                             | Metakaolin                                                            |
| MKGP                                           | Metakaolin-based geopolymer                                           |
| MIP                                            | Mercury intrusion porosimetry                                         |
| NaOH                                           | Sodium hydroxide                                                      |
| Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | Sodium silicate                                                       |
| EDS                                            | Energy dispersive X-Ray spectroscopy                                  |
| FE-SEM                                         | Field emission scanning electron microscopy                           |
| OPC                                            | Ordinary Portland cement                                              |
| RM                                             | Red Mud                                                               |
| RMGP                                           | Red Mud and metakaolin-based geopolymer                               |
| Sep                                            | Sep                                                                   |
| Sep-AAM                                        | Sep-based alkali activated material                                   |

|                  |                                             |
|------------------|---------------------------------------------|
| Si               | Silicon                                     |
| SiO <sub>2</sub> | Silicon dioxide                             |
| TGA              | Thermogravimetric analysis                  |
| TOC              | Total organic compound                      |
| TiO <sub>2</sub> | Titanium dioxide                            |
| UV-DRS           | UV/visible diffuse reflectance spectroscopy |
| UV               | Ultraviolet                                 |
| UV-Vis           | Ultraviolet-Visible spectroscopy            |
| XRD              | X-ray powder diffraction                    |
| XRF              | X-ray fluorescence                          |
| XPS              | X-ray photoelectron spectroscopy            |

## 1. INTRODUCTION

Concrete, being the mostly used construction material in the world, consists of sand, coarse aggregates, and a binding phase which helps holding these ingredients together. In general water and ordinary Portland cement (OPC) in powder form is utilized to bind all of these phases. Even though OPC technology is still one of the biggest industries in the world with a yearly cement production of 4,600 million tons, environmental options of this technology is a developing research area. Greenhouse gas emissions resulting from Portland cement production can be decreased by using environmental alternatives of these materials [1].

Alkali activated materials (AAMs) are sustainable versions of current cement binders. Even though there have been many controversial statements about their definition, these materials, which are also known as ‘geopolymers’ or ‘inorganic polymers’, can be produced as a result of a reaction between aluminosilicate sources and an alkaline solution. In fact AAM is the most general classification that covers all of the binding systems that are obtained as a result of a reaction between an alkaline salt and solid silicate powder [2]. The solid silicate powder can both be a calcium silicate source or a aluminosilicate source. Alkaline salts used for the synthesis can be solid or dissolved, and most commonly preferred alkaline salts can be listed as alkali hydroxides, carbonates, silicates or oxides. These salts should increase the pH of the reaction medium and dissolve the solid raw material. Inorganic polymers, on the other hand are a subcategory of AAMs and primary binding phase in inorganic polymers is a disordered silicate network. From this respect, comparably higher amounts of total  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are needed than it is needed for ordinary portland cements. Geopolymers are a subcategory of inorganic polymers and the binding phase for geopolymers composes almost entirely of aluminosilicates. Calcium content in the raw material should therefore be low for the formation of a pseudo-zeolitic structure rather than unique chains of calcium silicate hydrates [2]. Raw materials preferred for the synthesis, which are also known as ‘aluminosilicate precursors’ may be chosen by taking different aspects into consideration such as availability, cost, and reactivity [3].

## 1.1. Geopolymerization

Geopolymerization reaction consists of several steps. Firstly, solid aluminosilicate sources are dissolved in an alkaline medium to produce aluminate and silicate species. Secondly, an equilibrium between different species of silicate, aluminate, and aluminosilicates is established. Then, as a result of the presence of a basic medium, a saturated aluminosilicate solution occurs and this supersaturated aluminosilicate solution causes a gel formation due to the condensation of oligomers in the medium. Lastly, as a result of a continuous rearrangements and reorganizations and with the formation of a gel network, a three dimensional aluminosilicate network, so called ‘geopolymers’ occur [4]. In summary, dissolution of aluminosilicates, polycondensation, and structural reorganization can be considered as main steps of geopolymerization and the schematic diagram is provided in Figure 1.1 [5, 6].

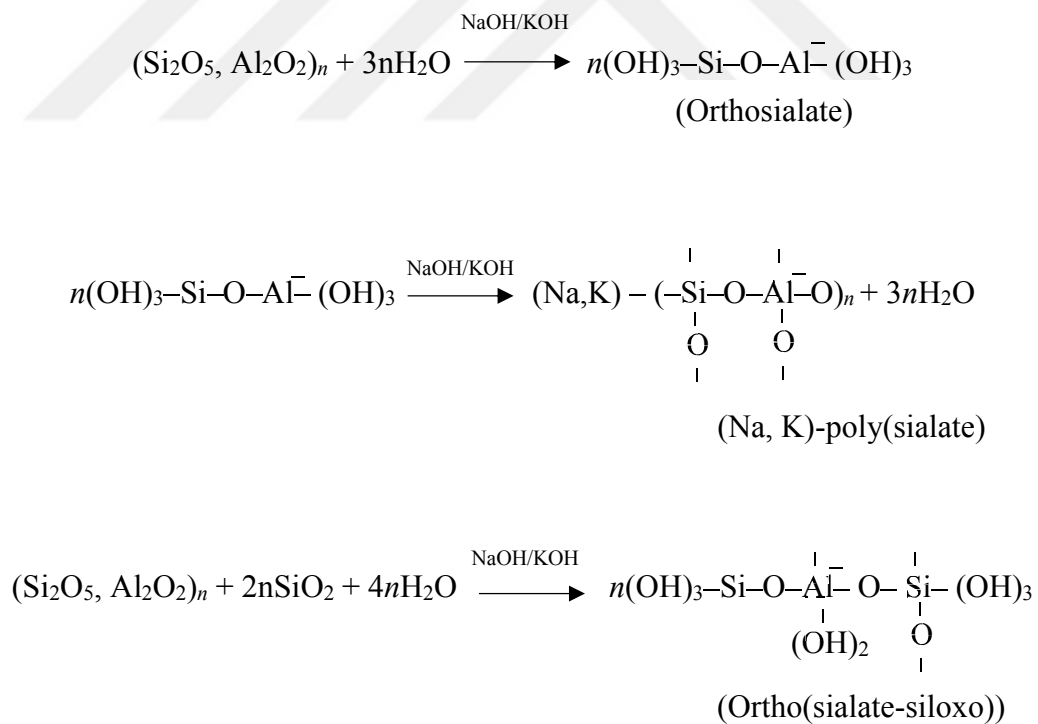


Figure 1.1. Schematic diagram of geopolymerization reactions [5, 6].

## 1.2. Raw Materials Used in Geopolymerization

### 1.2.1. Metakaolin

Kaolin is a white colored, soft clay and includes mainly kaolinite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ) mineral as a crystalline structure. Kaolinite is a 2D mineral and has a 1:1 type of layered structure consisting of an octahedral  $\text{AlO}_6$  layer and tetrahedral  $\text{SiO}_2$  layer [7]. It is abundant in nature and used as a raw material in industry, especially in paper, ceramics, plastics, pharmaceutical and catalyst industries [8, 9]. Its low cost, abundance, high adsorption performance, and high ion exchange capacity makes it a good candidate specifically for adsorption research field [9]. Chemical and physical properties of this mineral can be modified by different surface modification techniques including mechanochemical activation, thermal treatment, or acid activation [9].

Acid activation is known to be an effective procedure and studies in the literature showed that methylene blue (MB) dye adsorption capability of kaolinite can be increased by acid treatment [8, 10, 11]. For instance, acid activation via concentrated sulphuric acid of kaolinite together with thermal treatment was found to be an effective method to increase the surface area of kaolinite. This method led to an enhancement in the MB uptake capacity of kaolinite due to an increase in the porosity and surface area values. Approximately 20-fold increase in surface area and 6-fold increase in pore volume was detected, which as a result caused 1.3-fold increase in the uptake capacity of this material towards MB adsorption [8].

Calcined-hydrothermal approach was used to modify kaolinite mineral and obtain kaolin nanospheres [12]. Resulting material in this study displayed superior surface area to that of raw kaolin ( $157 \text{ mg g}^{-1}$  to  $29.3 \text{ mg g}^{-1}$ ) and uptake capacity had increased from 49.8 to  $184.9 \text{ mg g}^{-1}$  [12].

Aside from acid activation and thermal treatment procedures, one of the techniques widely used for increasing the adsorption capacity of kaolinite is to modificate the surface of this mineral with metal oxide nanoparticles [13, 14]. A research study of Meigoli et al. had shown that a nanocomposite of kaolin/ $\text{CuFe}_2\text{O}_4$  exhibits remarkable adsorption capacity

for MB and methyl violet dyes, which was mainly related with the high surface area of the kaolin/CuFe<sub>2</sub>O<sub>4</sub> nanocomposite produced by a chemical co-precipitation method [14]. Graphene oxide was also utilized for improving the adsorption performance of kaolin [15]. Study of He et al. had investigated the effect of graphene oxide content on the adsorption performance of graphene oxide modified kaolin composites. Outcomes of this study had demonstrated that composites including 10 wt% graphene oxide shows superior adsorption capacity towards MB dye due to its higher surface area [15].

One of the application areas of kaolin mineral is in geopolymerization. Thermal treatment of raw materials before geopolymerization process is a common and effective process which helps increasing the solubility of these materials in an alkaline medium. A series of phase transformations take place when kaolinite group clay is thermally treated under an atmospheric pressure. Dehydration of kaolinite group starts to occur at about 550-600 °C and this endothermic dehydroxylation gives rise to the formation of disordered metakaolin (MK) (Al<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>) [16]. MK-based geopolymer spheres by using three different techniques were produced by Medri et al, and these sphere's mechanical performance and MB adsorption capacity was investigated. Injection and solidification in polyethylene glycol, liquid nitrogen, and ionotropic gelation were applied to synthesize these materials and results pointed out that different methods resulted geopolymer spheres with different porosity levels; liquid nitrogen technique displaying the sample with the highest porosity (64%). Compressive strength measurements showed that mechanical performance and porosity of MK-based geopolymer spheres produced by different techniques were inversely proportional and porosity level had a positive effect on the adsorption capacity of a geopolymer [17]. The sample with the highest porosity level of 64% displayed a 2.1 MPa compressive strength and 5.4 mg g<sup>-1</sup> of MB uptake capacity [17]. Studies in the literature demonstrate that when MK-based geopolymers are used for MB dye adsorption [17, 18], experimental data better suit to pseudo-second-order adsorption kinetics, showing that the adsorption involves anion exchange process [17].

To be able to benefit from adsorptive properties of geopolymers, it would be better to use these materials in solid form rather than in powder form. Even though geopolymers can be casted into different shaped moulds and show promising mechanical performance, their adsorption properties when they are in solid form is limited. To increase their porosity and

therefore to cause an enhancement in their adsorption performance, several pore forming agents were considered in the existing literature. Most commonly used pore forming agents can be summarized as hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) [19, 20], expanded glass aggregates [21], sodium dodecyl sulphate [22], and aluminum oxide [23]. Rozek et al. had shown that 1 wt% expanded glass addition to MK-based geopolymer samples increases the MB uptake capacity of the sample from 3.5 to 4.9  $\text{mg g}^{-1}$  with a concomitant decrease in mechanical performance from 20.4 MPa to 1.6 MPa [21].

### 1.2.2. Red Mud

Red mud (RM) is a waste product of alumina production. The type of bauxite ore that is used to extract alumina has an effect on the RM properties. This material has a red colour owing to its high iron oxide content. It has been reported that about 1-1.8 tons of RM are discharged for every ton of alumina produced [24]. RM production data of some countries reported by Wang et al. show that China, Australia, Brazil, and India are the leading countries in RM production. It was shown that 105,169 million tons of RM is produced only in China in 2018 [24].

Even though chemical components present in different RM sources are the same, their content may vary. The constituents of RM are iron oxide, aluminum oxide, silicon oxide, calcium oxide and sodium oxide [25]. Some most common mineral phases existing in RM are hematite, calcite, and sodium aluminate. The morphological analysis of this material had shown that it has a porous structure and pore characteristics may differ [24].

Because of its highly alkaline nature, its storage is of great concern and two storage methods; wet storage and dry storage, are widely used for storing RM. Wet storage method consists of discharging RM into a pool and the water in RM is removed during the course of this method. One possible concern regarding this method is related with RM being highly basic and the effluents from RM may penetrate to the groundwater and may pose a serious risk to the environment. Dry storage method is currently the widely used method for storing RM. Water present in RM waste is removed by mechanical pressure filtration method and the rest of the RM is dried under air. One problem accompanied by using this method is the mixing of fine RM particles into the air as a result of wind blowing. Both of these storage

methods have negative effects on the environment and also require huge land areas for the storage [26]. Even though it is estimated that more than 130 million tonnes of alumina were produced annually by 2018 [27], total utilization rate of RM is only about 4-5 wt% [24], [28]. This huge gap between production and evaluation rate implies the importance and necessity of utilizing RM in different fields.

One of the mostly studied application areas of RM is in adsorption research field. Several distinct studies had shown that RM and RM-based materials can be evaluated in wastewater remediation applications. Wang et al. showed that heat treatment and  $\text{HNO}_3$  treatment applied on RM decreases the adsorption capacity of RM upon MB dye and the adsorption process between RM and MB dye is an endothermic process [29]. Another study conducted by Zhang et al. revealed that HCl-treated sintering process RM displays superior adsorption properties than sintering process RM itself, that was correlated with the increased surface area of acid activated sample [30]. A similar finding was reported by Çoruh et al. where HCl-activated RM was found to display higher adsorption capacity upon MB dye than as received RM and heat treated RM. Enhanced adsorption properties of acid activated RM in this study was associated with the dissolution of sodalite phase present in RM, as a result of acid activation. As sodalite dissolves, there occurs an increase in the number of pores and specific surface area of the material increases [31]. Two different studies had shown that RM activated by a hydrochloric acid digestion that is followed by an ammonium hydroxide precipitation method increases surface area results an increase in MB uptake performance [32, 33]. Calcination of RM was shown to cause a decrease in adsorption capacity of MB dye due to the decrease in total surface area of RM because of reduction in particle size and decomposition of goethite and gibbsite phases [34]. These different studies using RM and modified RM samples as adsorbents for MB dye adsorption had proven that the adsorption of MB onto RM samples are due to chemisorption and experimental data follow pseudo-second-order adsorption kinetics and Langmuir model better described the data [30, 32, 34].

Another application area of RM is in photocatalysis. Melamine-based graphitic carbon nitride integrated RM composite that was synthesized by one-step thermal polymerization method was found to show an ability to remove organic pollutants and antibiotics from wastewater through synergistic effect of adsorption and photocatalysis under visible-light conditions [35]. Cobalt-doped neutralized RM samples were prepared via impregnation

method and their visible light photocatalytic activity upon MB dye was investigated under natural solar light. Results showed that cobalt doping enhances the photocatalytic activity of RM due to accelerated photo induced electron-hole transfer and separation, and decreased recombination rate [36].

Aside from adsorption and photocatalysis, another option for evaluating this waste material is in construction industry. RM together with fly ash were used in geopolymerization for the development of paving blocks. It was revealed that RM addition causes an enhancement in the the degree of geopolymerization reaction and structural reorganization. Material composed of 10-20 wt% RM were found to be environmentally reliable with the leaching amount of toxic metals being within the permissible limit [37]. RM and MK-based geopolymers's structural characteristics and mechanical performance was examined by systematically increasing the RM content in the solid raw materials basis. Results pointed out that RM addition limits the dissolution of raw materials and decrease the mechanical performance of the geopolymers [38]. As mentioned previously, surface characteristics of RM can be tuned by applying different modification techniques. From this point forth, RM was structurally modified by applying an acid digestion procedure that is followed by calcination, and the effect of acid molarity and digestion temperature on geopolymerization degree and thermal stability was investigated [39]. Results of this study proved that acid modification significantly changes the surface characteristics of RM and improves the thermal stability of geopolymers synthesized form acid activated RMs, and calcination plays an important role in geopolymerization rate [39].

### **1.2.3. Fly Ash**

Fly ash (FA) is an industrial waste that is released from the flue gas of coal fire power plants [40] and is mainly a by-product of thermal power plants. Unavoidable increase in the production of this waste material makes its evaluation crucial. It was reported that the total accumulation of FA in China had reached to  $6.86 \times 10^{11}$  kg [40], and for Brazil total annual production amount of FA is estimated to be about 4 million tonnes; with only 30% of this waste being recycled for construction-related applications [41]. Studies from Turkey had shown that approximately 150 million tonnes of FA were produced in Turkey between 1970 and 2013 [42], and only 1% of this produced FA was evaluated in cement and brick industry

[43]. It is generally stored in landfills, however its disposal still is of great concern due to economical and environmental aspects [44, 45]. The recycling of this waste material should be put in the process carefully as it involves high amount of trace elements and radionuclides that may cause serious effects on human health and also to the environment [44].

This waste product, FA, is used as a supplementary material of cement in concrete production, road construction and asphalt [44, 46]. One of the application areas of this waste material is also in adsorption [47]. FA-based materials can be utilized for adsorbing different organic and non-organic chemicals [48]. Current literature on MB adsorption capacity of FA is very rich and FA and its modified forms were found to display a MB uptake capacity of 0.3 and 96 mg g<sup>-1</sup>. Adsorption performance of these materials depend on different factors such as modification, initial adsorbate concentration, pH of the solution, and adsorbent amount [29, 40, 41, 45, 47, 49-53, 54-61]. Tuning adsorption capacity by changing some parameters or applying modifications on FA material are good advantages and provides flexibility, however FA also has some drawbacks such as limited adsorption capacity towards some dyes and using high amounts of FA for dye adsorption may also result a sludge disposal problem [48]. From this point forth utilizing this waste material in geopolymerization is a good alternative that may increase the adsorption capacity and regeneration ability of this material.

Studies in the literature showed that FA together with different clay minerals such as granulated blast furnace slag, bottom ash [62] and MK [22] can also be used as a raw material for geopolymer synthesis [6, 63-65]. In these studies, produced geopolymers were evaluated as MB adsorbents. In a study of Padmapriya et al. for instance, coal FA, bottom ash and granulated blast furnace slag were used as geopolymer raw materials. Results of this study had shown that adsorption capacity of the geopolymer synthesized here shows an adsorption capacity of 59.52 mg g<sup>-1</sup> at an optimum dosage of 0.08 g L<sup>-1</sup>. It was asserted in this study that, proposed geopolymer formulation causes an enhancement in the pore properties and surface area of the final geopolymer compared to the existing geopolymer literature, and superior adsorption properties were mainly correlated with this enhancement [62].

#### 1.2.4. Sepiolite

Sepiolite (Sep) is a fibrous clay mineral that is composed of magnesium hydrosilicates and has a formula of  $\text{Si}_{12}\text{Mg}_8\text{O}_{30}(\text{OH})_4(\text{H}_2\text{O})_4 \cdot 8\text{H}_2\text{O}$  [16]. It has negatively charged 2:1 layers consisting of blocks and channels, and each block involves tetrahedral silica sheets and magnesium octahedral sheets [66]. High surface area and unique fibrous structure of Sep with interior channels provide a suitable environment for the penetration of inorganic and organic ions into its structure [67]. The adsorption capacity of Sep and its modified forms was studied by many researchers [68-70].

Largo et al. for instance demonstrated that Sep clay can effectively adsorb MB dye molecules and the adsorption performance increases at basic conditions showing that electrostatic interactions takes place during the adsorption process. Experiments showed that nearly 99% of the MB dye is removed from the solution when pH of the solution medium is 12, whereas only 60% of MB dye is removed when pH of the solution is 4, under identical experimental conditions. It was also shown that several factors including pH of the medium, temperature, adsorbent amount, and initial dye amount have an influence on the adsorption performance of Sep [68].

To improve the adsorption performance of Sep, many strategies were offered including sonication [67], thermal treatment [71], incorporation of an organic material [72-75], acid treatment [66, 71, 76], and alkaline treatment [76]. These modifications generate alterations at the surface of the Sep; generally cause an increase in the surface area [67, 75], and therefore increase the adsorption capacity of these materials.

Treating these materials with alkaline solutions can be taken one step further by using Sep as the main raw material for AAM synthesis. It has been reported previously that magnesium analogues of geopolymers can be synthesized by using Sep as a raw material [77]. In this respect, alkali activating of Sep offers a good potential to increase adsorption capacity of as-received Sep and newly synthesized material can also be evaluated as a construction material with a good mechanical strength. This potential of Sep mineral is discussed in detail in Chapter 3 of this thesis.

### 1.3. Application Areas of Geopolymers

Geopolymers (GP) have different application areas in construction industry [78] such as in paving blocks [37] and concrete products [79], or in waste management applications for immobilizing hazardous or radioactive wastes [42, 79]. One of the emerging application areas of geopolymers are also in adsorption and photocatalysis.

Adsorption studies in the literature have shown that geopolymers from different raw materials can successfully be utilized for the adsorption of dyes [6, 21, 80]. Geopolymers produced from different raw materials are highly alkaline in nature and increase the pH of the solution when they are immersed into aqueous solutions. As a result of mechanism of geopolymer formation (Figure 1.1.), these materials include negatively charged surface hydroxyl groups and this situation makes them good candidates as adsorbents especially for cationic dyes [6].

In a study of Novais et al. for instance, FA and MK-based GP spheres were synthesized and their adsorption performance upon MB dye were investigated. Several parameters including adsorption time, MB initial concentration, and the amount of the adsorbent effects on adsorption performance were studied in detail. Findings had shown that initial dye concentration have a huge effect on the adsorption capacity of geopolymers and uptake value was increased from 1.1 to 30.1 mg g<sup>-1</sup> when initial MB concentration was increased from 10 to 250 ppm [22].

Another parameter that has an important effect on the adsorption capacity of geopolymers is the pH of the solution medium. As stated previously, negatively charged surface of geopolymers provides a suitable medium for the adsorption of cationic molecules. In this respect, the adsorption performance of geopolymers can be enhanced by adjusting the pH of the solution medium. The effect of solution pH on the MB dye adsorption performance was investigated for volcanic ash-based geopolymers by Tome et al [81]. Experiments in this study showed that adsorption of MB is improved at higher pH values and low pH of the solution negatively effects the adsorption performance due to competition between the cationic MB molecules and hydrogen ions for the same binding sites [81]. The MB uptake

capacity of volcanic ash-based geopolymer in this study increased from 6 to 22.5 mg g<sup>-1</sup> when the pH value of the solution was increased from 2 to 12 [81].

In addition to applications related to construction industry and adsorption, another emerging application area of geopolymers is utilizing them for photocatalytic applications. Self-cleaning ability of a geopolymer may become important when it is used for construction purposes and geopolymers can be designed to display photocatalytic properties. This ability is introduced by including a photocatalyst within the geopolymer structure. The photocatalytic effect of geopolymers can be used to remove these organic pollutants from the geopolymer surface. FA-based geopolymers were used as a photocatalyst in the literature for the removal of MB dye from a wastewater under UV light [82]. Steel slag based Ni,Ca-geopolymer had also been used for photodegradation of MB from wastewater [83].

Titanium dioxide (TiO<sub>2</sub>) is one of the semiconductors which has been studied due to its superior properties such as high physical and chemical stability, low cost, easy availability, low toxicity, great photoactivity [84] and superhydrophilicity [85]. One of the ways to incorporate TiO<sub>2</sub> into the geopolymer is an ion exchange procedure in which geopolymers are immersed into an aqueous solution to form a geopolymer with a reactive surface that has TiO<sub>2</sub> in its structure. This procedure was carried out by Gasca-Tirado et al. and a degradation of a volatile organic compound 2-Butanone was recorded by using a gas chromatography [86]. In a different study, Mn<sup>+2</sup> doped, CuO loaded graphene bottom ash based geopolymeric composite was produced by a four step method involving an ion exchange procedure. Zhang et al. cured graphene bottom ash-based geopolymeric composite by aqueous solution of ammonium acetate to substitute NH<sub>4</sub><sup>+</sup> ions for Na<sup>+</sup> ions and then impregnated the GP sample in an aqueous solution of Cu(NO<sub>3</sub>)<sub>2</sub>.H<sub>2</sub>O and manganese nitrate. Coupling graphene with semiconductor is known to be an effective method that enhances the separation efficiency of photogenerated electron-hole pairs that causes an increase in photocatalytic activity [87]. In the study of Zhang et al., Mn<sup>2+</sup> doping amount was kept nearly constant for all of the samples, however CuO loading was increased up to a value of 20 wt%. Photocatalytic reduction to produce hydrogen under visible light by solar water splitting increased with the increasing amounts of Mn<sup>+2</sup> doping and CuO loading. The degradation efficiency of composites with different contents was measured under UV light by following the direct sky blue 5B dye absorption values with UV-Vis spectrophotometer at 365 nm. It was observed that sample with 15 wt% CuO loading displayed the highest

degradation efficiency of 100% and the degradation reaction fitted the first order kinetics [88].

Geopolymers can also be coated with thin films of photocatalytic materials. Coating  $\text{TiO}_2$  films onto different supports by sol-gel method is known to be an efficient process to enhance photocatalytic activity and wear resistance of the  $\text{TiO}_2$  film [89, 90]. In a study of Chen et al., geopolymer supported photocatalytic  $\text{TiO}_2$  films were produced via sol-gel dip coating process. MK and FA-based geopolymers were produced and sliced geopolymer samples were dip-coated with a solution of butyl titanate, diethanolamine and ethyl alcohol. Dip-coated slices were then annealed at different temperatures to induce the crystallization of  $\text{TiO}_2$ .  $\text{TiO}_2$  film which was thermally treated at 600 °C was found to consist mainly of anatase phase and revealed the highest degradation efficiency (~80%) of MB under UV light [89].

Within the scope of this thesis, geopolymers were synthesized from different raw materials including MK, RM, and Sep; the adsorption and photocatalytic performance of these materials in terms of MB removal were explored in detail. By extracting knowledge from various characterization tools, a relationship between structure and adsorption and/or photocatalytic performance was established.

#### **1.4. Methodology**

For measuring the MB removal performance of synthesized materials, firstly a MB solution with a known concentration was prepared. Then, a measured amount of adsorbent was immersed into this solution. Agitation speed was kept constant during the experiments and reported. These experiments were conducted under atmospheric pressure, whereas pH and temperature of the solution medium were also reported if they were varied within experiments. Samples were syringed from solutions at regular time intervals and their concentration was measured by using a UV-Vis spectrometer.

To extract information about synthesized material's adsorption and photocatalytic performance, data collected during experiments were studied by considering adsorption and reaction kinetics.

#### 1.4.1. Evaluation of Adsorption Performance

The removal efficiency (%) can be calculated as

$$\text{Removal efficiency (\%)} = \left( \frac{C_o - C_t}{C_o} \right) \times 100 = \left( \frac{A_o - A_t}{A_o} \right) \times 100 \quad (1.1)$$

where  $C_o$  and  $C_t$  are the concentration of MB solution at initial time  $t = 0$  and at time  $t$ , respectively.  $A_o$  and  $A_t$  denotes to absorbance values at initial time  $t = 0$  and at time  $t$ , respectively [91].

The amount of MB adsorbed on adsorbents can be determined as,

$$q_e = \left( \frac{C_o - C_e}{m} \right) \times V \quad (1.2)$$

where  $q_e$  is the amount of MB dye uptake by the adsorbent (mg MB dye/g adsorbent),  $m$  is the mass of the adsorbent (g) and  $V$  is the volume of the MB solution (L).

Pseudo-first-order and pseudo-second-order adsorption kinetic models can be used to reveal the MB adsorption mechanism of materials as

$$\ln(q_e - q_t) = \ln q_e - k_{1,ads,app} \times t, \quad (1.3)$$

$$\frac{t}{q_t} = \frac{1}{k_{2,ads,app} \times q_e^2} + \frac{t}{q_e} \quad (1.4)$$

where  $q_e$  (mg g<sup>-1</sup>) and  $q_t$  (mg g<sup>-1</sup>) represent the amounts of dye adsorbed on adsorbents at equilibrium and time  $t$ , respectively;  $k_{1,ads,app}$  (min<sup>-1</sup>) and  $k_{2,ads,app}$  (g mg<sup>-1</sup> min<sup>-1</sup>) are the apparent rate constants of pseudo-first- and pseudo-second-order adsorption kinetics, respectively.

The dependence of adsorption rate on both the adsorbent amount and adsorbed amount of MB dye can be determined as

$$\frac{dq_t}{dt} = k_{ads} \times (\text{adsorbent amount})^m \times (q_e - q_t)^n \quad (1.5)$$

where  $m$  is the order of the reaction with respect to adsorbent amount,  $n$  is the order of the reaction with respect to dye concentration,  $k_{ads}$  is the actual adsorption rate constant. If adsorbent amount is assumed to be constant, the adsorption rate can be expressed in terms of apparent adsorption rate constant,  $k_{ads,app}$  as

$$\frac{dq_t}{dt} = k_{ads,app} \times (q_e - q_t)^n, \quad (1.6)$$

$$k_{ads,app} = k_{ads} \times (\text{adsorbent amount})^m. \quad (1.7)$$

Equation (1.7) can also be utilized to determine the order of the adsorption rate with respect to adsorbent amount by taking the natural logarithm of both sides as

$$\ln k_{ads,app} = \ln k_{ads} + m \times \ln(\text{adsorbent amount}). \quad (1.8)$$

The Arrhenius equation was used to determine the activation energy of adsorption which shows the minimum required energy for adsorption to take place. It is shown as

$$\ln k_{ads} = \ln A - \frac{E_a}{R} \times \frac{1}{T} \quad (1.9)$$

where,  $k_{ads}$  is the actual adsorption rate constant,  $E_a$  is the activation energy (J/mol),  $R$  is the gas constant and is equal to 8.314 J/(mol.K) and  $A$  is the Arrhenius pre-exponential factor.

Intraparticle diffusion model can also be applied to experimental data in order to identify the diffusion mechanism as

$$q_t = k_p \times t^{\frac{1}{2}} + C \quad (1.10)$$

where  $q_t$  ( $\text{mg g}^{-1}$ ) represents the amount of dye adsorbed on adsorbents at time  $t$ ,  $k_p$  ( $\text{mg g}^{-1} \text{min}^{-0.5}$ ) is the rate constant of intraparticle diffusion model and  $C$  ( $\text{mg g}^{-1}$ ) is the intercept that gives information about the boundary layer thickness.

#### 1.4.1.1. Adsorption Isotherms

Two most common isotherm models, Langmuir and Freundlich models, were used to fit the equilibrium data of the samples. The Langmuir model assumes that the interaction between sorbed molecules are negligible and that the surface has homogeneous binding sites and equal sorption energies [19] and suitable for describing the chemisorption process [92]. The linearized form of Langmuir model is given as

$$\frac{C_e}{q_e} = \frac{1}{K_L \times q_{max}} + \frac{C_e}{q_{max}} \quad (1.11)$$

where  $K_L$  ( $\text{L mg}^{-1}$ ) indicates the Langmuir constant that shows the affinity of the sorbate for binding sites,  $q_{max}$  ( $\text{mg g}^{-1}$ ) is the maximum adsorption capacity [19] and  $q_e$  ( $\text{mg g}^{-1}$ ) is the equilibrium monolayer adsorption capacity.  $K_L$  can be used to calculate a separation factor  $R_L$  and Langmuir isotherm can then be expressed by this factor as

$$R_L = \frac{1}{1 + K_L \times C_0} \quad (1.12)$$

If  $0 \leq R_L \leq 1$  there is favorable adsorption [19, 93]. The Freundlich model assumes a multilayer adsorption on a heterogeneous surface that has sites which show different affinity. The binding strength exponentially decays and stronger binding sites are occupied first [19, 92]. The linearized form of Freundlich model, on the other hand, can be described as

$$\ln q_e = \ln K_F + \frac{1}{n} \times \ln C_e \quad (1.13)$$

where  $K_F$  ( $\text{mg g}^{-1}$ ) is the Freundlich constant and is associated with adsorption capacity,  $n$  ( $\text{g L}^{-1}$ ) being a parameter describing adsorption intensity and shows the absence of linearity of the adsorbed quantity in function  $C_e$ . When  $1 \leq n \leq 10$ , there is a favorable adsorption. When the value of  $n$  is greater than 10, there is a stronger interaction between surface of the adsorbent and adsorbate. When  $n$  equals to 1, a linear adsorption takes place [19, 80] which shows the identical adsorption energies for all sites [94].

#### 1.4.2. Evaluation of Photocatalytic Activity

To understand the kinetics of MB dye degradation reaction under UV light, Equations (1.14)-(1.19) were used [95]. MB degradation rate as a function of catalyst and dye concentration can be used to detect the kinetic rate as

$$-r_{dye} = k \times C_{cat}^a \times C_{dye}^b \quad (1.14)$$

where,  $k$  is the degradation rate constant,  $C_{cat}$  is the catalyst concentration,  $a$  is the order of the reaction with respect to catalyst concentration,  $C_{dye}$  is the MB dye concentration and  $b$  is the order of the reaction with respect to MB dye concentration. If catalyst concentration is assumed to be constant, the rate of degradation reaction can be expressed in terms of apparent rate constant,  $k_{app}$  as

$$-r_{dye} = \frac{dC_{dye}}{dt} = k_{app} \times C_{dye}^b, \quad (1.15)$$

$$k_{app} = k \times C_{cat}^a. \quad (1.16)$$

Pseudo-first-order and pseudo-second-order kinetic models had previously been used to represent the degradation kinetics of organic dyes [88, 96]. Therefore, in the case where the degradation reaction is assumed to be first order with respect to MB dye concentration ( $b = 1$ ), Equation (1.15) can be expressed as

$$\frac{\ln C_{dye0}}{C_{dye}} = k_{app} \times t. \quad (1.17)$$

Similarly, for the case where degradation reaction is considered as second-order with respect to MB dye concentration ( $b = 2$ ), Equation (1.15) becomes

$$\frac{1}{C_{dye}} = k_{app} \times t. \quad (1.18)$$

Furthermore, Equation (1.16) can also be used to find the order of the reaction with respect to catalyst amount by taking the natural logarithm of both sides to obtain

$$\ln k_{app} = \ln k + a \times \ln C_{cat}. \quad (1.19)$$

### 1.4.3. Structural Characterization of Materials

The structure of materials used in this thesis including raw materials, geopolymeric adsorbents and photocatalysts were characterized in detail by a variety of methods including X-ray fluorescence (XRF) spectroscopy, X-ray diffraction (XRD) spectroscopy, Fourier transform infrared (FTIR) spectroscopy, X-ray photoelectron spectroscopy (XPS), Scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS), Brunauer–Emmett–Teller (BET surface) area analysis, UV/visible diffuse reflectance spectroscopy (UV-DRS), and thermogravimetric analysis (TGA). XRF analysis was performed to determine the chemical composition of the raw materials. XRD was employed to determine the crystal constituents and amorphous character in the samples. FTIR spectroscopy was utilized to detect the vibrational spectra of the samples. XPS analysis was performed to understand the surface chemistry, composition, and binding state of the atoms. SEM-EDS measurements were conducted to have an understanding on the surface structure and morphology of the samples. BET analysis was employed to determine the surface area of the samples. UV-DRS was performed to investigate the band-gap values and maximum absorption wavelengths. TGA was conducted to determine the thermal stability of the materials. Zeta potential of the materials was also measured to determine the surface charge stability. Additionally, to determine the mechanical performance, compressive strength of the materials were evaluated by using servo-hydraulic test. The parameters and conditions regarding these characterization techniques slightly vary for each dataset in this thesis; therefore these are thoroughly presented in the relevant parts.

### 1.5. Scope and Aim of This Work

Geopolymers have a huge potential to be used in different research areas including construction, catalysis, photocatalysis, and adsorption. Wide range of raw material options and easy tunability of the processing conditions make them convenient materials for their evaluation in different fields of research. Intrinsic nature of these materials provides environmentally friendly options and increase their contribution as sustainable materials.

The objective of this thesis is to determine the MB adsorption and photocatalytic performance of geopolymeric materials synthesized by using different raw materials and techniques, and to establish an understanding of the structure and performance relationship. Within this framework, the results of this thesis point out that, these materials which were produced in a sustainable and environmentally friendly way, are promising and can successfully be used for environmentally friendly wastewater treatment applications

In Chapter 2 of this thesis, RM and MK-based geopolymers with varying anatase content were produced and their ability adsorption and photocatalytic degradation of MB. The effect of anatase content in the geopolymeric structure was studied in detail by considering both reaction and adsorption kinetics. Chapter 2 has been published in *Journal of Cleaner Production* in 2021 (K Kaya-Özkipir, A Uzun, S Soyer-Uzun, *Journal of Cleaner Production* (2021) 288, 125120) [25].

Findings of Chapter 2 demonstrated that geopolymers have a potential to be used in adsorption research area. Therefore, in Chapter 3, Sep mineral, which is a commonly mined clay mineral in Turkey, was evaluated as a new raw material for the synthesis of magnesium analogues of aluminosilicate geopolymers. The adsorption performance of these materials towards MB dye was studied in detail, kinetic and thermodynamic analysis were established. The findings presented in Chapter 3 has been published in *Journal of Hazardous Materials* in 2022 (K Kaya-Özkipir, A Uzun, S Soyer-Uzun, *Journal of Hazardous Materials* (2022) 424, 127256) [97].

In Chapter 4, monolith forms of the magnesium analogues of geopolymers introduced in Chapter 3 were enhanced to display varying porosities. These solid-formed monoliths

produced from Sep were used as an adsorbent for MB removal and the influence of porosity on the adsorption performance was studied in detail. MK-based counterparts of Sep-based monoliths were also studied and differences in adsorption performance was discussed by characterizing each sample with distinct characterization tools. The manuscript derived from Chapter 4 is being prepared for publication.

A new composite consisting of RM and MK-based geopolymer and graphitic carbon nitride was introduced in Chapter 5 to develop a composite with improved adsorption performance towards MB dye. The MB adsorption performance of this newly introduced composite was compared to that of pure graphitic carbon nitride. Main adsorption performance determining parameters were explored and discussed. The manuscript form of Chapter 5 is being prepared for publication.

## **2. RED MUD- AND METAKAOLIN-BASED GEOPOLYMERS FOR ADSORPTION AND PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE: TOWARDS SELF-CLEANING CONSTRUCTION MATERIALS**

### **2.1. Introduction**

A continuous increase in the demand for aluminum leads to the accumulation of tremendous amounts of red mud (RM) and the elimination of this hazardous industrial waste gains significant importance. Concerns about the storage problem of RM motivate researchers to evaluate its utilization in different fields; i.e., as concrete [98], geopolymers [38, 39], and catalysts [99, 100]. Utilization of RM in the cement-related applications is one of the paths in its remediation [101]. However, Pontikes et al. reported that only less than 5 wt% of RM has been evaluated in the cement related-applications [102]. In this direction, several studies demonstrated that RM used together with ordinary Portland cement (OPC) shows good mechanical strength; and thus, it can be used in applications regarding cement-based construction materials [26, 98, 103]. However, the generation of OPC is known to be responsible for 7-17% of the total anthropogenic CO<sub>2</sub> release in the world [104, 105]. Even though the study by Xi et al. demonstrated that a cumulative amount of 4.5 GtC has been sequestered in carbonating cement materials from 1930 to 2013, offsetting 43% of the CO<sub>2</sub> emissions from production of cement over the same period [106], the production of OPC can still be considered as one of the major sources of CO<sub>2</sub> emissions.

Possible evaluation of industrial wastes or ashes produced in huge amounts in geopolymerization is one of the several advantages of geopolymer production. One of the emerging application area regarding geopolymers is utilizing them as “self-cleaning” construction materials. Studies in the literature showed that geopolymers synthesized from different raw materials can be evaluated as adsorbents and/or photocatalysts [80, 83, 107].

Most of these studies focus mainly on the photodegradation of representative dyes under UV-light. However, geopolymers are also known to offer high adsorption capabilities

thanks to their porous characteristics. Even though there are some studies evaluating them as adsorbents for the removal of organic dyes [22] and heavy metals [108], there are a very limited number of studies demonstrating both adsorption and photo-degradation performance of these materials on the removal of a representative dye from wastewater [82], [109]. Besides, it is envisioned that utilization of RM, an environmental hazardous material, in the synthesis of geopolymers with self-cleaning ability not only offers opportunities for “cleaner production” but also presents a broad potential for sustainability.

In this part of this thesis, it is focused on investigating these opportunities and RM and MK were used as raw materials for the synthesis of geopolymers (RMGPs). RM is utilized for photocatalytic purposes because of its very high amount of  $\text{Fe}_2\text{O}_3$  (~37 wt%) and  $\text{TiO}_2$  (~6 wt%) content, which are known as photocatalytically active. The effect of both adsorption and photodegradation of MB were investigated by conducting experiments both under dark conditions that is subsequently followed by a UV-light exposure, and solely directly under UV-light exposure. Additionally, incorporation of photocatalytically active anatase, into the RMGP system demonstrated that the self-cleaning performance of RMGPs can be improved to an exceptionally high level. This chapter was published as a paper [25] and the original manuscript has been rearranged to conform to the format requirements of the dissertation.

## 2.2. Experimental Methods

### 2.2.1. Materials

Raw materials used as the aluminosilicate sources were MK ( $2.50 \text{ g/cm}^3$ ) and RM ( $2.70 \text{ g/cm}^3$ ). MK was obtained by the calcination of kaolinite mineral at  $700^\circ\text{C}$  for 1 h [110]. RM was kindly supplied by Eti Seydişehir Aluminum Factory, Konya-Turkey. Before utilizing RM in geopolymer synthesis, RM was first kept at  $100^\circ\text{C}$  in air to remove water molecules and then calcined at  $800^\circ\text{C}$  for three hours in air. Chemical compositions of raw materials are provided in Table A.1. Sodium silicate ( $\text{Na}_2\text{Si}_3\text{O}_7$ ) solution (9 wt% of  $\text{Na}_2\text{O}$ , 28 wt% of  $\text{SiO}_2$ , 63 wt% of  $\text{H}_2\text{O}$ , Merck,  $1.35 \text{ g/cm}^3$ ) was used together with sodium hydroxide pellets ( $\text{NaOH}$ , Merck,  $2.13 \text{ g/cm}^3$ ) as an alkali activator to synthesize RMGPs. Anatase (powder, 325 mesh,  $3.90 \text{ g/cm}^3$ ) was purchased from Sigma Aldrich.

### 2.2.2. Synthesis of Geopolymers

The amounts of raw materials used in the synthesis of RMGPs, synthesis conditions used in this study together with the corresponding molar Si/Al and Na/Al ratios are shown in Table A.2. Mix proportions (in terms of mass per unitary volume) calculated based on densities of the raw materials and assuming that the volumes of the components are additive are provided in Table 2.1. It should be noted that, right after mixing, total volumes for all samples are measured to be approximately 17% less than the hypothetical total volumes calculated from raw material densities which is associated with the presence of nonidealities in the system and geopolymerization reactions. RM and MK are the aluminosilicate sources, while anatase was the main photocatalytic component in the system. Earlier results demonstrated that a mixture with 20 wt% RM and 80 wt% MK in raw material basis leads to good mechanical properties in the final geopolymer [38]. Therefore, in the present study this ratio was employed for all samples. Anatase amounts added into the solid raw material mixtures were arranged to be 0, 1, 3, 5, and 10 wt% of the RM and MK mixture prior to the addition of alkali activating solution. Based on the values given in Table 2.1 and Table A.2, anatase content in the geopolymer pastes studied here are 0, 0.4, 1.2, 1.9, and 3.74 wt%. Therefore, the samples were named as  $x\%$ A-RMGP, where  $x$  corresponds to anatase loading in the geopolymer pastes. It should be noted here that these initial concentration values actually change with time as geopolymerization is a time-dependent process where water gradually leaves the system and concentrations change with solidification. Mixtures of NaOH and  $\text{Na}_2\text{Si}_3\text{O}_7$  solution were used as alkali activators. Physical properties of geopolymers predominantly depend on molar Si/Al and Al/Na ratios as previously reported [4, 111]. Therefore, in the experimental design of this part, molar Si/Al and Na/Al ratios were set to be constant as 2 and 0.83, respectively (Table A.2). During the synthesis of geopolymers, powdered and sieved (#70 mesh sieve, 200  $\mu\text{m}$ ) raw materials; RM, MK, and anatase were mixed thoroughly with alkali activators. These samples were kept at room temperature for a few hours and then thermally treated at 60 °C for one day followed by further aging at 25 °C for a week before being used as catalysts for MB degradation.

Table 2.1. Mix quantities per unit volume ( $\text{kg m}^{-3}$ ) calculated based on densities of the raw materials and assuming that the volumes of the components are additive. Corresponding wt. % are given in parenthesis for the RMGP pastes.

| Sample     | Anatase       | RM             | MK              | $\text{Na}_2\text{Si}_3\text{O}_7$<br>solution | NaOH           | Total           |
|------------|---------------|----------------|-----------------|------------------------------------------------|----------------|-----------------|
| 0%A-RMGP   | 0<br>(0)      | 132.3<br>(7.8) | 529.4<br>(31.1) | 927.1<br>(54.5)                                | 111.8<br>(6.6) | 1700.6<br>(100) |
| 0.4%A-RMGP | 6.6<br>(0.4)  | 132.1<br>(7.7) | 528.5<br>(31.0) | 925.5<br>(54.3)                                | 111.6<br>(6.5) | 1704.3<br>(100) |
| 1.2%A-RMGP | 19.7<br>(1.2) | 131.7<br>(7.7) | 526.7<br>(30.8) | 922.4<br>(53.9)                                | 111.3<br>(6.5) | 1711.8<br>(100) |
| 1.9%A-RMGP | 32.8<br>(1.9) | 131.2<br>(7.6) | 524.9<br>(30.5) | 919.3<br>(53.5)                                | 110.9<br>(6.5) | 1719.1<br>(100) |
| 3.7%A-RMGP | 65.1<br>(3.7) | 130.1<br>(7.5) | 520.5<br>(30.0) | 911.6<br>(52.5)                                | 109.9<br>(6.3) | 1737.2<br>(100) |

### 2.2.3. Materials Characterization

Elemental analysis of raw materials was carried out by a Bruker S8 Tiger XRF spectrometer that was used in standartless mode under He atmosphere with an 18 mm mask. XRD patterns were collected from 10 to 90° 2 $\theta$  with a 0.01263° step size by using a Bruker D8 Discover Diffraction system with a Cu  $K\alpha_1$  radiation source employing a wavelength of 1.5418 Å. The power rating of X-ray generator was set to 40 kV, and 40 mA and a Vantec-1 detector with a slit of 1 mm was used. Phase identification was achieved by using ICDD PDF-4 2016 database. FTIR spectroscopy was carried out on a Bruker Vertex 80v spectrometer using an attenuated total reflectance (ATR) cell at a resolution of 2  $\text{cm}^{-1}$  in a spectral range of 400-2000  $\text{cm}^{-1}$ .

To understand the morphology and microstructure of raw materials and geopolymers, Zeiss Ultra Plus Field Emission SEM coupled with an EDS was used. For EDS measurements Bruker XFlash 5010 EDS detector with 123 eV resolution was used. To measure the density of synthesized geopolymers powder samples were pelleted in a lab press

under 225 psi. Then, the Archimedes method was applied by using an OHAUS PA224C Pioneer analytical balance equipped with an OHAUS density kit. As the liquid, absolute ethanol was used with a density of  $0.785 \text{ g/cm}^3$ . At first, each sample's weight was determined. Then the samples were placed into the measurement place inside of ethanol solution and waited for a reasonable time. The samples were weighed inside of the ethanol solution again. The measurements were repeated three-times on each sample to determine the corresponding error ranges.

Surface areas of the samples were determined by the BET analysis conducted on a Micromeritics ASAP 2020-Physisorption Analyzer. Approximately 400 mg sample was used for each measurement and each sample were degassed at  $120^\circ\text{C}$  under vacuum for 8 hours before the measurement. Free space measurement was conducted in He gas and the volumetric  $\text{N}_2$  adsorption/desorption isotherm was measured between  $P/P_0 = 0.01\text{--}0.96$  at cryogenic temperature. BET surface area was calculated between  $P/P_0 = 0.05\text{--}0.3$  using liquid nitrogen (10 data points). Pore size distribution was obtained by the Barrett-Joyner-Halenda (BJH) model by using an adsorption isotherm. For XPS analysis a Thermo Scientific K-Alpha X-ray Photoelectron Spectrometer was utilized and Avantage 5.9 software was used to establish XPS data fitting. UV-DRS has been performed to investigate the band-gap values and maximum absorption wavelengths of each geopolymer on a Shimadzu UV-3600 UV-VIS-NIR Spectrophotometer.

A MTS model servo-hydraulic test machine with the capacity of 100 kN with a loading rate of 0.01 mm per second is used to obtain the compressive strength values of geopolymers. To prepare specimens for mechanical performance tests, geopolymers were transferred into  $10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$  silicon molds after mixing. The specimens were thermally treated at  $60^\circ\text{C}$  for 24 h followed by a resting period of 30 days at ambient temperature before the mechanical strength measurements. The compressive strength tests were conducted in triplicates and average values were reported.

#### **2.2.4. Evaluation of Photocatalytic Activities**

Powdered and sieved solid RMGP samples (0.03 g) were mixed with an aqueous MB dye ( $5 \times 10^{-5} \text{ M}$ ). Then, MB solution was irradiated by a UV-C lamp (OSRAM Puritec HNS

S, dominant wavelength: 253 nm, 4×9 W) under magnetic stirring at room temperature. Syringed MB solutions were centrifugated and analyzed by using a Flame-S-UV-Vis-ES spectrometer, Ocean Optics, USA. Each sample was studied under two different conditions: i) a treatment under dark conditions for 12 hours subsequently followed by a treatment under UV-light exposure for 12 hours; and ii) a treatment under direct UV-light only. The absorbance values were collected by the spectrometer at the characteristic maximum absorption wavelength of 664 nm. Degraded amount (%) was calculated according to Equation (1.1). Data collected under dark conditions were fitted to pseudo-first and second-order adsorption kinetics equations given in Equation (1.3) and Equation (1.4). To understand the kinetics of MB dye degradation reaction under UV light, Equations (1.14) – (1.19) were used.

## 2.3. Results and Discussion

### 2.3.1. Bulk Microstructure, Morphological, and Mechanical Properties

BET surface areas, average pore sizes, pore volumes, and the corresponding density values of geopolymers are given in Table A.3. Density values obtained by Archimedes method showed that the density of all geopolymers are very similar and values fluctuate between 2.10 and 2.13 g/cm<sup>3</sup>. The surface area of the calcined RM and MK were 11.3 and 14.4 m<sup>2</sup>/g, respectively. Their XRD and FTIR characterization results are provided in Figures A.1 and A.2 and A.3, respectively.

BET analysis results shown in Table A.3 imply that the pore size distribution was mainly in the mesoporous range and no significant change occurred in both surface area and pore size values upon the addition of anatase into the structure.

The XRD patterns of the synthesized geopolymers are given in Figure 2.1. The results indicate that geopolymers display an amorphous structure evident from a broad halo positioned at approximately 28°. The special feature observed at approximately 28° is an indication of the amorphous geopolymer formation [38]. It should be noted that one of the main raw materials, RM, is an industrial waste with amorphous, heterogenous and complex structure. Therefore, it is challenging to follow the changes in the crystalline components.

Based on Figure 2.1, quartz ( $\text{SiO}_2$ ) together with hematite phase ( $\text{Fe}_2\text{O}_3$ ) seemed to be the dominant crystalline components within the disordered framework. Sodalite phase detected for 0%A-RMGP was not observed in the rest of the geopolymers. For the 0.4%A-RMGP sample sodium iron oxide ( $\text{Na}_3\text{Fe}_5\text{O}_9$ ) phase was also identified together with quartz and hematite phases. Even though the characteristic peak of anatase observed at  $25^\circ$  has not been detected for 0%A-RMGP and 0.4%A-RMGP, upon a further increase in anatase loading, it becomes visible (Figure 2.1). Albite phase ( $\text{Na}(\text{Si}_3\text{Al})\text{O}_8$ ) seems to be present in 3.7%A-RMGP sample.

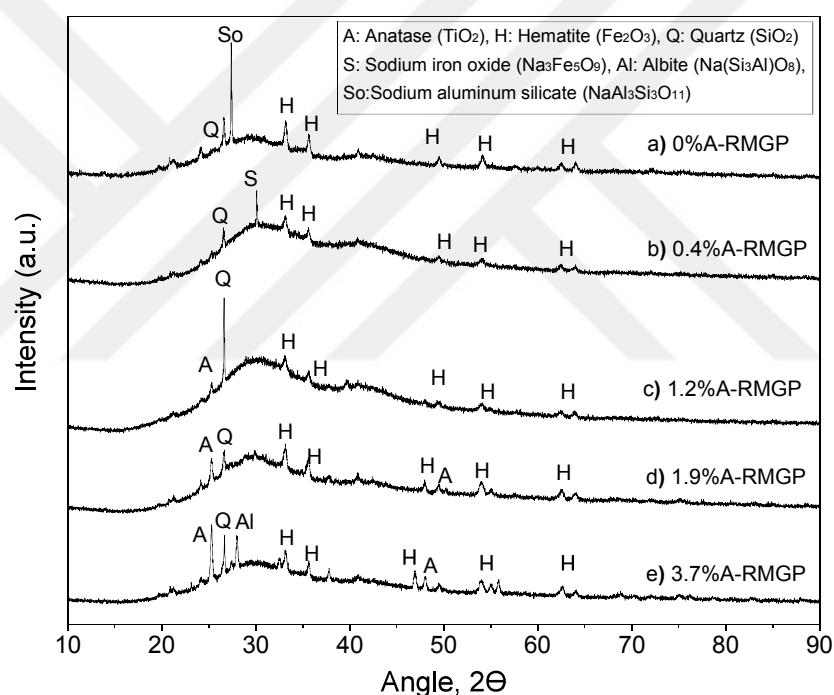


Figure 2.1. XRD patterns of geopolymers a) 0%A-RMGP, b) 0.4%A-RMGP, c) 1.2%A-RMGP, d) 1.9%A-RMGP, e) 3.7%A-RMGP.

FTIR spectra of all geopolymers, shown in Figure 2.2, display broad features in 900-1200  $\text{cm}^{-1}$  region confirming the presence of geopolymerization [4, 38, 39]. The band at approximately 870  $\text{cm}^{-1}$  indicates the presence of Si–OH bending vibrations [112]. The most dominant band observed at 970  $\text{cm}^{-1}$  indicates the asymmetric stretching vibrations of Si–O–T (T: Al or Si) bonds [113], which indicate the formation of the geopolymeric framework upon alkali activation. This broad feature called the ‘main band’ observed in the region of

900-1200  $\text{cm}^{-1}$  is a common indication of the geopolymer formation [38, 110]. The band at 1065  $\text{cm}^{-1}$  is assigned to the asymmetric stretching band of Si–O–Si bonds [114] in MK. Peaks at 670  $\text{cm}^{-1}$  verifies the presence of Ti–O–Ti bonds resulting from the presence of anatase phase in the geopolymeric matrix [115]. The bands in the region of 900-1200  $\text{cm}^{-1}$  were deconvoluted into corresponding contributions, Si–OH, Si–O–T, and Si–O–Si bonds, respectively. The ratio of the intensity of the Si–O–T feature, indicating a newly formed geopolymer framework to that of the intensity of the peak associated with the Si–O–Si feature, related to unreacted MK, ( $I_{\text{Si-O-T}}/I_{\text{Si-O-Si}}$ ) is evaluated to have an understanding on the change in the extent of geopolymerization with the addition of anatase. Figure A.4 displays the evolution of the  $I_{\text{Si-O-T}}/I_{\text{Si-O-Si}}$  ratio and the compressive strength of the specimens as a function of anatase content in the geopolymer pastes. Microstructural characteristics seem to be correlated with the changes in compressive strength. The compressive strength values of the specimens vary between 37.7 and 43.2 MPa, indicating that these materials are promising for construction applications. Addition of 1.2 wt% anatase into the RMGP paste (1.2%A-RMGP), seemed to increase the compressive strength by approximately 15% from 37.7 to 43.2 MPa. This increased trend observed in the compressive strength seems to be mainly associated with the evolution of  $I_{\text{Si-O-T}}/I_{\text{Si-O-Si}}$  ratio with the increasing anatase content (Figure A.4); this result indicates the presence of anatase, up to a certain limit, could have a positive effect in the geopolymerization process. This enhancement could also be correlated with the fact that the anatase acts as a filler in the geopolymer system resulting in a denser structure consistent with the previous reports [116], [117]. SEM images and corresponding EDS spectrum of geopolymers together with intensity maps of elements Si, Al, Na, Ti, and Fe are provided in Figures A5-A9. Atomic % of these elements in geopolymers which are calculated by additional EDS spectra recorded from 3 spots are given in Table A.4. As it is seen in Figure A.3, MK displays a layered structure composing mainly of Si, Al, and O elements. Calcined RM exhibits granulated surface and consists of various irregularly shaped aggregates due to including different metal oxides and several elements as detected by XRF and EDS analyses. SEM images of geopolymers and the intensity mapping of different elements (Figures A.5-A.9) show that geopolymer surface microstructures are rather homogenous and consist mainly of Si, Al, Na, and O atoms which form the geopolymeric framework together with minor amounts of iron and titanium atoms. The intensity of titanium atoms increased with the addition of anatase. Iron content was

found to be very similar for all of the geopolymers (Table A.4) which is found to be consistent with XPS results.

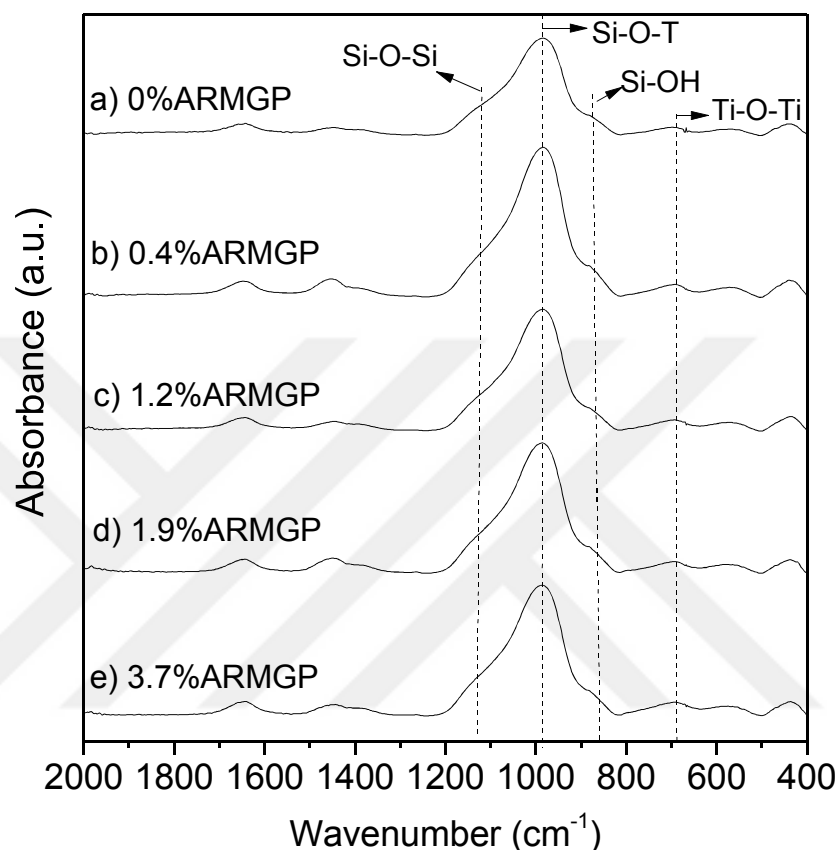


Figure 2.2. FTIR spectra of geopolymers a) 0%A-RMGP, b) 0.4%A-RMGP, c) 1.2%A-RMGP, d) 1.9%A-RMGP, e) 3.7%A-RMGP.

### 2.3.2. Surface Characteristics

XP survey spectrum of the sample with the highest anatase content of 3.7 wt% (3.7%A-RMGP) together with its O 1s spectrum are given in Figure 2.3. O 1s spectrum is deconvoluted into two main peaks that are centered at 531.6 and 532.5 eV. These features correspond to the surface hydroxyl groups [118] and the presence of metal-oxygen bonds associated with the presence of  $\text{TiO}_2$  [36], respectively. Deconvoluted Ti 2p, Fe 2p, and O 1s XP spectra of all RMGPs and their corresponding peak positions are given in Figure A.10 and Table A.5, respectively. The XPS of anatase is characterized with bands at approximately 458.6 (Ti 2p<sub>3/2</sub>) and 464.3 eV (Ti 2p<sub>1/2</sub>) [119], consistent with Ti 2p XPS of

geopolymers investigated in this study as shown in Figure A.10 and Table A.5. However, our data presented in Figure A.10 also indicated the presence of new Ti-related features at 454 and 460 eV as well. These new features might be indicating that anatase could be partly present within the geopolymeric framework.

Besides, two main contributions detected at approximately 711 (Fe 2p<sub>3/2</sub>) and 723 eV (Fe 2p<sub>1/2</sub>) are characteristic features of hematite phase [120] originated from RM (Figure A.10a,d,g,j,m). Even though the surface atomic % obtained from the XPS results regarding the Fe element was relatively low for all of the samples (Table A.6), its presence was also verified by the XRD measurements (Figure 2.1).

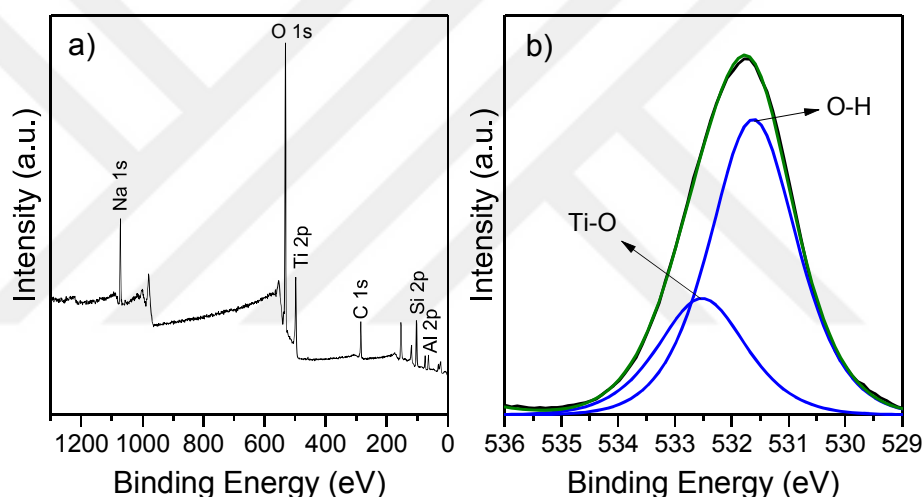


Figure 2.3. XPS patterns of a) survey spectrum, b) O 1s spectrum of 3.7%A-RMGP.

The availability of surface Ti atoms on the surface increases with anatase addition (Table A.6). However, the corresponding amounts for Fe atoms seem not to be affected by anatase addition.

Maximum absorption wavelength and band gap values of the raw materials as well as the geopolymer samples are provided in Table A.7, while Figure A.11 is listing the band gap values of the geopolymers. Maximum absorption wavelengths ( $\lambda_{\text{max}}$ ) of MK and RM were 381 nm and 588 nm, respectively. With geopolymerization, the spectral response was extended to a longer wavelength, which might be an indication of photocatalytic activity under visible light for the synthesized geopolymers. Furthermore, the absorption threshold of anatase-

added samples, especially for 1.9%A-RMGP and 3.7%A-RMGP, had shifted to a slightly higher wavelength (Figure A.12 and Table A.7). It is seen from Table A.7 that upon anatase addition, the band gap values of geopolymers approach to that of anatase; 3.2 eV. Concomitantly, a shoulder was detected at approximately 380 nm for the anatase-added samples (Figure A.12), referring the absorption at wavelengths shorter than 400 nm. This situation, observed only for the anatase-added samples, is an indication of the absorption across the band gap of  $\text{TiO}_2$  for the excitation of valence band electrons [121], [122].

### 2.3.3. Degradation of MB Dye

To evaluate the photocatalytic activity and distinguish it from the adsorption, the measurements were conducted at two different conditions: First, the measurements were conducted under dark conditions for 12 hours followed by exposure to UV irradiation for an additional 12 hours. The dark portion of this treatment provides information on the adsorption capability of the samples. Second, the experiments were performed directly under UV irradiation for 12 hours to explore the photodegradation of MB.

#### 2.3.3.1. Experiments Under Dark Followed by UV Irradiation

It was reported that negatively charged  $[\text{AlO}_4]^{5-}$  tetrahedrons in the geopolymeric porous structure could provide a suitable medium for the adsorption of MB cations [82] and they can adsorb cationic dyes because of the surface hydroxyl groups present on their surfaces [6, 109]. In this regard, the initial experiments were carried out under dark conditions for 12 h and then data were collected under UV light for 12 h to understand photodegradation capability of geopolymers. Residual MB concentrations, denoted as  $C/C_0$ , are shown in Figure 2.4. Even though the adsorption takes place for all of the samples, anatase content was found to be the main factor determining the removed amount of MB dye at the end of 24 h.

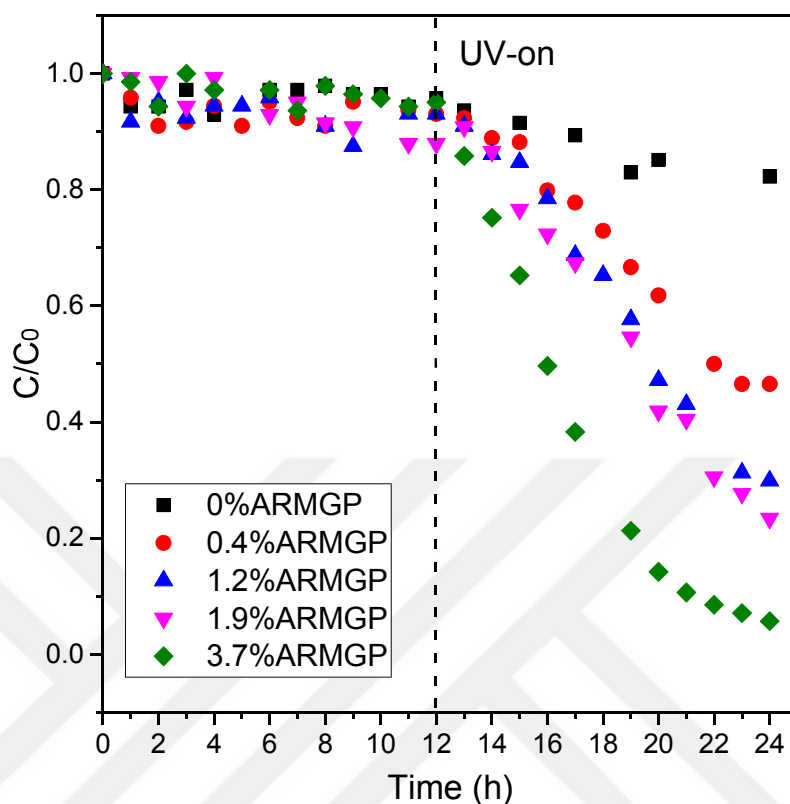


Figure 2.4. Variation of the residual MB dye concentration ( $C/C_0$ ) with time; values were collected under dark for 12 h followed by UV irradiation for 12 h.

The results collected during the dark-run were fitted to pseudo-first- and second-order adsorption kinetics. Extracted kinetics data are shown in Table 2.2 together with the corresponding degraded amounts (%) of MB dye under dark (initial 12 h under dark), and the total degraded amounts (%) of MB dye under dark followed by UV irradiation (12 h under dark + 12 h under UV irradiation).

Data imply that the adsorption behaviour of geopolymers under dark conditions are well-described by pseudo-second-order adsorption kinetics and both experimental and calculated values of  $q_e$  ( $q_{e,exp}$  and  $q_{e2,calc}$ , respectively) are close to each other. This result is consistent with the literature, where second-order adsorption was used for defining the adsorption behaviour of geopolymers under dark conditions [82, 109], for which the process is most possibly controlled by the chemisorption process [123] implying an electron

exchange and share between MB dye (adsorbate) and functional groups of geopolymer samples (adsorbent) on the surface [18, 124].

Table 2.2. Kinetic parameters for adsorption of MB on anatase added geopolymer samples under dark conditions.

| Sample     | $k_{1,ads}$<br>( $\text{min}^{-1}$ ) | $R^2$ | $k_{2,ads}$<br>( $\text{g mg}^{-1} \text{min}^{-1}$ ) | $R^2$ | $q_{e,exp}$<br>( $\text{mg g}^{-1}$ ) | Degraded amount<br>(%) (12 h dark) | Degraded amount (%)<br>(12 h dark + 12 h UV) | $\Delta(\text{UV-Dark})^*$ |
|------------|--------------------------------------|-------|-------------------------------------------------------|-------|---------------------------------------|------------------------------------|----------------------------------------------|----------------------------|
| 0%A-RMGP   | 0.0028                               | 0.77  | 0.025                                                 | 0.94  | 2.27                                  | 4.2                                | 17.7                                         | 13.4                       |
| 0.4%A-RMGP | 0.1476                               | 0.15  | 0.050                                                 | 0.86  | 3.33                                  | 6.2                                | 53.4                                         | 47.2                       |
| 1.2%A-RMGP | 0.0008                               | 0.14  | 0.007                                                 | 0.90  | 3.70                                  | 6.9                                | 70.1                                         | 63.2                       |
| 1.9%A-RMGP | 0.0009                               | 0.99  | 0.003                                                 | 0.90  | 6.43                                  | 12.0                               | 76.6                                         | 64.5                       |
| 3.7%A-RMGP | 0.0008                               | 0.62  | 0.005                                                 | 0.90  | 2.65                                  | 4.9                                | 94.3                                         | 89.3                       |

\*  $\Delta(\text{UV-Dark})$  identifies the difference between degraded amounts (%) obtained at the end of the 12 h dark+12 h UV period and 12 h dark period.

Since there is a lack of any significant difference between the surface characteristics, such as surface area and pore size values (Table A.3), Figure 2.4 shows that the behavior under dark conditions for all of the samples are not equal but similar.

It is known from the literature that pore volume and density of the geopolymers are related [125] and high density value of an adsorbent used for wastewater treatment may cause high uptake capability [126]. Density measurements presented in Table A.3 also show that anatase addition does not cause a significant difference in density values. However, when UV-light is switched on after a waiting period under dark conditions, further removal of MB dye takes place (Figure 2.4). Corresponding kinetic parameters which are obtained by fitting the experimental data collected under UV-light to pseudo-first- and pseudo-second-order reaction kinetics are displayed in Table 2.3.

Values given in Table 2.3 show that even though adsorption mechanism under dark conditions is defined better by pseudo-second-order kinetics (Table 2.2), with the introduction of UV-light to this system, the reaction mechanism suits better to pseudo-first-order reaction kinetics. It was previously mentioned that for the samples kept under dark

conditions for 12 hours, adsorption was most possibly controlled by the chemisorption process. However, in the presence of UV-light, the switch of mechanism from pseudo-second-order adsorption kinetics to pseudo-first-order reaction kinetics shows that photocatalytic rate limiting step in the presence of UV-light is physisorption [127]. Consequently, to achieve photocatalytic removal of MB dye, firstly MB molecules should be adsorbed on surface of the adsorbent [128].

Table 2.3. Pseudo-first- and second-order reaction kinetic parameters obtained for 0.03 g of sample in  $5 \times 10^{-5}$  M 100 ml MB solution under 12 hours of UV-light after 12 hours of dark conditions (data collected under UV light is used for the calculation of the parameters given in this table).

| Sample     | Pseudo-first-order |       | Pseudo-second-order |       |
|------------|--------------------|-------|---------------------|-------|
|            | $k_{app,1}$ (1/h)  | $R^2$ | $k_{app,2}$ (L/g.h) | $R^2$ |
| 0%A-RMGP   | 0.01               | 0.97  | 0.96                | 0.97  |
| 0.4%A-RMGP | 0.05               | 0.94  | 5.57                | 0.88  |
| 1.2%A-RMGP | 0.10               | 0.95  | 2.79                | 0.89  |
| 1.9%A-RMGP | 0.11               | 0.96  | 17.22               | 0.90  |
| 3.7%A-RMGP | 0.25               | 0.99  | 91.08               | 0.90  |

In the proposed mechanism describing the removal of MB dye with subsequent adsorption and photodegradation, first step is the ionization of MB dye into cationic form in aqueous solution. Cationized MB can either be adsorbed on the surface hydroxyl groups of the geopolymer surface. When the energy of the excitation source exceeds the band-gap energy value of the semiconductors, which are  $\text{TiO}_2$  and  $\text{Fe}_2\text{O}_3$  for this system, that are present in the geopolymeric framework, the separation of an electron ( $e^-$ ) from the valence band to the conduction band of the semiconductor creates a positive electron hole ( $h^+$ ) in the valence band. These electron and hole pairs on the surface react with oxygen and may reduce oxygen to superoxide radicals ( $\text{O}_2^-$ ), or oxidize the water adsorbed on the surface, respectively [84]. These reactive oxygen species released can oxidize the adsorbed MB cation to the degradation products [82]. It was previously shown that MB can be degraded

by TiO<sub>2</sub>-based photocatalysts [129-131] and degradation products and the degradation mechanism were also investigated in detail [129].

Houas et al, used total organic carbon (TOC) analysis together with GC/MS and LC/MS to understand the mineralization of organic carbon, and to determine the intermediate compounds, respectively [129]. Results of this study showed that, as a consequence of photodegradation of MB, gaseous CO<sub>2</sub>, and nitrogen and sulfur containing inorganic ions occur. Even though the degradation mechanism of MB under UV conditions involves several steps, this detailed process can be summarized in three main steps. Firstly, sulfate ions are produced as a result of an interaction between negatively charged TiOH and TiO<sup>-</sup> forms of TiO<sub>2</sub>; that occurs especially at high pH values, and C-S<sup>+</sup>=C functional group of MB. It is proposed that OH<sup>o</sup> radical, which had occurred as a result of oxidation of water, attacks C-S<sup>+</sup>=C group that is in coulombic interaction with the photocatalyst's surface. Secondly, nitrogen containing groups in MB molecules mineralize to form ammonia (NH<sub>3</sub>) and ammonium (NH<sub>4</sub><sup>+</sup>). Lastly, organic carbon is oxidized to form CO<sub>2</sub>, which is due to oxidative mineralization as a result of the opening of aromatic rings with the carboxylic acid formation [129].

Table 2.2 also demonstrates the variation of  $\Delta(\text{UV-Dark})$ , defined as the difference between the degraded amounts (%) obtained at the end of the treatments for 12 hours in dark followed by 12 hours under UV-light and at the end of the 12 hours under dark treatment, with changes in the amount of TiO<sub>2</sub> added. Results imply that anatase addition is the main factor controlling the  $\Delta(\text{UV-Dark})$ , it gradually increased from 13.4 to 89.3%, when the amount of TiO<sub>2</sub> added into the system increased from 0 to 3.7 wt%. Even though there is a lack of any significant variation between pore characteristics between the samples, the adsorption parameters given in Table 2.2 indicate that there are still small variations in samples' adsorption properties.

These small differences may also have an effect on the corresponding photodegradation behavior of samples. For instance, as the adsorption capabilities of each sample is different, the initial MB concentrations at the beginning of the photodegradation process (at  $t = 12$  hours) would be different (even though the starting amounts are identical); and this difference influences the photodegradation rate as it also depends on the MB

concentration. However, apparently, this possible difference was compensated with the addition of anatase, as the results indicated a positive correlation between anatase content (wt%) and degraded amount (%) at the end of 24 hours.

### 2.3.3.2. Experiments Under Direct UV Irradiation

During the experiments starting directly with the UV light conditions (skipping the treatment under dark period) it is challenging to distinguish the individual strengths of simultaneously occurring adsorption and photodegradation mechanisms. However, Figure 2.5 demonstrates that at the beginning of the experiments (0-3 hours) the main mechanism responsible for a slight decrease in MB concentration was nearly the same for all geopolymer samples and therefore it was mostly independent of the corresponding anatase content of the samples. Because there is a lack of any significant difference between the surface areas of the geopolymer samples (Table A.3), such similar behaviour at the beginning of the UV treatment can be mostly attributed to the adsorption mechanism. However, during a long exposure of up to 12 hours, the effect of anatase content becomes dominant and the samples present various extents of MB degradation performance, demonstrating an increased degradation performance well-correlated with their corresponding anatase amounts (Figure 2.5).

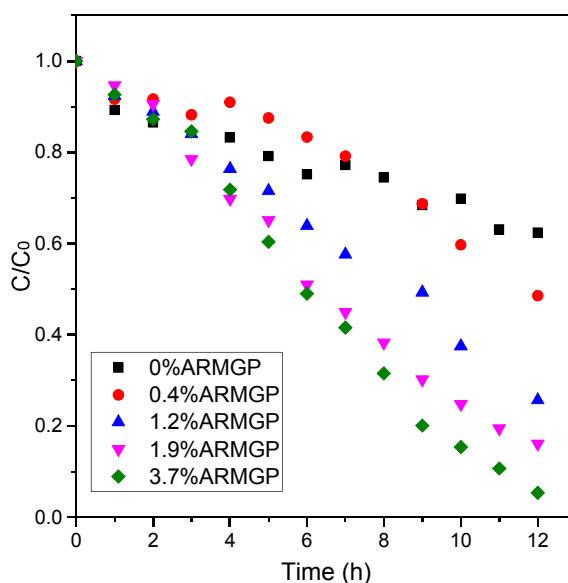


Figure 2.5. Residual MB dye concentration ( $C/C_0$ ) vs. time values collected under UV light conditions.

Reaction data of MB photodegradation by using anatase-added geopolymers were fitted to pseudo-first-order and pseudo-second-order reaction kinetics. Table 2.4 summarizes the corresponding degraded MB amounts (%) along with the corresponding pseudo-first- and pseudo-second-order reaction kinetics parameters after 12 hours of UV light irradiation together with their corresponding  $R^2$  values. For each sample, degraded MB amounts (%) of the samples, which were irradiated directly by UV-light for 12 hours (Table 2.4) were found to be higher than those of the samples that were kept under dark conditions followed by a UV-light (12 hours dark + 12 hours UV) given in Table 2.2. It is speculated that keeping the samples under dark conditions at the beginning possibly led to a blockage of the photocatalytically active sites because of the adsorption of MB particles during the dark run.

Table 2.4. Pseudo-first and second-order- reaction kinetics parameters and degraded amount (%) values obtained for 0.03 g of sample in  $5 \times 10^{-5}$  M 100 ml MB solution under UV light after 12 hours.

| Sample     | Pseudo-first-order |       | Pseudo-second-order |       | Degraded MB amount (%) in 12 h under UV |
|------------|--------------------|-------|---------------------|-------|-----------------------------------------|
|            | $k_{app,1}$ (1/h)  | $R^2$ | $k_{app,2}$ (L/g.h) | $R^2$ |                                         |
| 0%A-RMGP   | 0.03               | 0.99  | 2.97                | 0.98  | 37.6                                    |
| 0.4%A-RMGP | 0.08               | 0.96  | 7.27                | 0.93  | 51.4                                    |
| 1.2%A-RMGP | 0.13               | 0.98  | 18.08               | 0.92  | 74.3                                    |
| 1.9%A-RMGP | 0.17               | 0.99  | 30.11               | 0.89  | 83.9                                    |
| 3.7%A-RMGP | 0.28               | 0.99  | 95.36               | 0.83  | 94.6                                    |
| Anatase    | 0.09               | 0.96  | 9.24                | 0.97  | 87.7                                    |

Table 2.4 shows that the degraded MB % under UV irradiation for 12 h increases with an increase in the anatase content of the corresponding geopolymer. UV spectrum of samples 0%A-RMGP and 3.7%A-RMGP are provided in Figure A.13, which was found to be in accordance with the data obtained in Table 2.4. Absorption intensity gradually decreases for 3.7%A-RMGP, whereas the decrease in intensity is comparatively very lower for 0%A-RMGP. Figure 2.6 indicates that this variation presents a correlation between these degraded

amounts with the corresponding atomic surface concentrations of Ti, determined by XPS measurements, on each geopolymer. The degraded MB amount with 3.7%A-RMGP was 94.6%. Compared to the corresponding degraded MB amount with pure anatase (87.7%), the performance of the 3.7%A-RMGP was superior. This result indicates that the anatase-added geopolymers successfully remove MB, besides they have good mechanical properties and offers an environmentally friendly and efficient way of utilizing a hazardous industrial waste, RM.

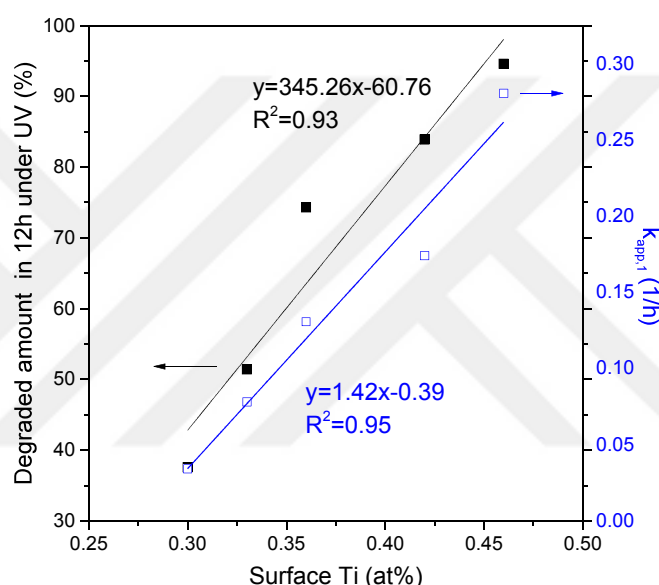


Figure 2.6. The change of degraded MB amount under UV in 12h (black symbols) and change of  $k_{app,1}$  with surface Ti amount (at%) (blue symbols).

Comparison of the  $R^2$  values obtained by fitting the data presented in Figure 2.5 to reaction rate expressions indicated that the pseudo-first-order reaction rate kinetics provide a better model for the experimental data as shown in Table 2.4, consistent with the previous inference where the data collected under UV-light after dark conditions displayed a better fit to pseudo-first-order reaction kinetics (Table 2.3). These values compare well with the corresponding values for pure anatase, where the degraded MB amount and  $k_{app,1}$  value was 87.7% and 0.09 (1/h), respectively, at a corresponding theoretical surface Ti amount of 33 atomic % for pure anatase. Values of  $k_{app,1}$  clearly show a systematic positive trend upon anatase addition. The  $k_{app,1}$  value starts to exceed that of pure anatase, when the anatase loading in the geopolymer was 1.2 wt% or higher.

This phenomenon might be originated from the aggregation behavior of pure anatase particles [132], such that the light emitted from the UV source cannot diffuse into the aggregated forms of  $\text{TiO}_2$  as good as the geopolymers having a more efficient  $\text{TiO}_2$  dispersion. The second cause of this situation is possibly originated from the reaction mechanism of the photocatalytic degradation reaction; as it is mentioned above, the reaction follows a pseudo-first-order kinetics in the presence of UV-light and the photocatalytic rate limiting step is physisorption. To accomplish the photocatalytic degradation, the first step is the adsorption of dye molecules on the adsorbent. Owing to the surface characteristics of the geopolymer structure, compared to pure anatase, geopolymer surface, possessing negatively charged surface species, offering a more suitable adsorption site for the adsorption of a cationic dye compared to the surface of pure anatase.

To determine the dependency of the photocatalytic degradation rate on the surface Ti atomic percent (at%), the variation of  $k_{app}$  with the surface Ti amount determined by XPS measurements is investigated, as shown in Figure 2.7. The data present a strong correlation with an  $R^2$  of 0.95.

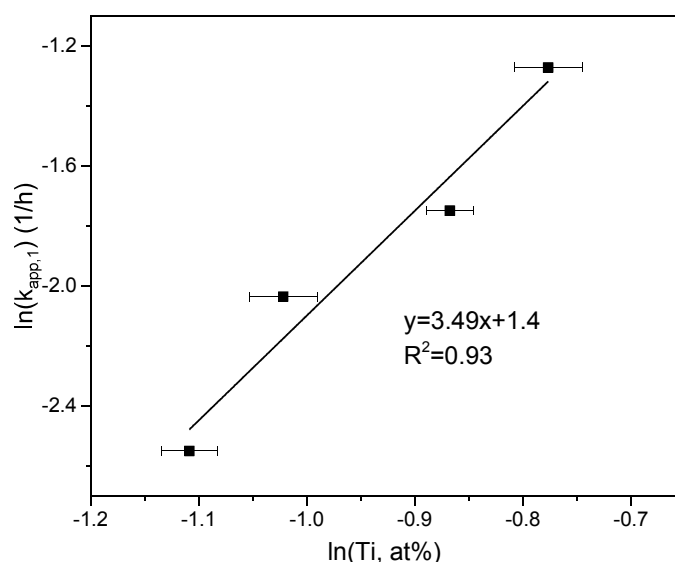


Figure 2.7. Experimental data fit to pseudo-first-order reaction kinetics for anatase-added RMGP samples. Error bars represent the standard error of surface Ti amount (at%).

Besides surface Ti species, it is also well known that hematite originated from RM have photocatalytic activity and Fe sites might also be playing a role in MB degradation. However, the Fe atomic % is rather low at the geopolymer surface as revealed by XPS (Table A.6). To investigate any effects of surface iron species on the photocatalytic activity, variation of  $k_{app}$  with the surface Fe amount was investigated. However, the corresponding plot employing surface Fe atomic% did not present any correlation ( $R^2 = 0.3$ ), ruling out any strong photocatalytic contribution of surface Fe species in RMGP system investigated here. Thus, we infer that the surface Ti species are the dominant species responsible for the photocatalytic activity in RMGP system.

Strini et al. demonstrated that segregated  $\text{TiO}_2$  molecules that are present in the layers of anatase-added geopolymer samples show photocatalytic activity depending on the amount of surface  $\text{TiO}_2$  molecules [133]. Accordingly, the first-order degradation rate constant ( $k$ ) was evaluated (this rate constant is different than the apparent rate constant, please see Section 1.4.2 for detailed discussion) and the reaction rate order with respect to surface Ti amount ( $a$ ) using Equation (1.19) on the anatase-added samples (0.4%A-RMGP, 1.2%A-RMGP, 1.9%A-RMGP, and 3.7%A-RMGP). For this analysis, it is assumed that all surface Ti atoms behave nearly the same for MB photodegradation in each A-RMGP samples on the basis of an  $R^2$  value of 0.93 in Figure 2.6 and the identification of surface Ti atoms as the dominant active species responsible for photocatalytic activity. The line presented in Figure 2.7 had a slope of 3.49, setting the reaction order with respect to the surface atomic% Ti for the A-RMGP samples based on Equation (1.19). Based on this slope and the intercept values of the line presented in Figure 2.7, the MB degradation rate constant,  $k$ , is determined as  $4.04 (\text{surface atomic\% Ti})^{-3.49} \times \text{h}^{-1}$ .

## 2.4. Concluding Remarks

The effects of systematic anatase addition into RM- and MK-based geopolymer systems on the corresponding mechanical strength and MB removal performance were investigated in this part. Adsorption behavior of geopolymers under dark conditions is described by pseudo-second-order adsorption kinetics, possibly controlled by the chemisorption processes. When UV-light was turned on following a treatment under dark conditions, the photocatalytic degradation of MB took place at significantly enhanced rates

as a function of anatase content in the system. Data indicated that the dominant responsible sites for the photocatalytic activity in the geopolymers were identified as the surface Ti species. MB degradation under direct UV light conditions was described by pseudo-first-order kinetics. Data revealed that addition of anatase up to 3.7 wt% in the geopolymeric paste (3.7%A-RMGP) resulted in a tripled  $k_{app,1}$  value compared to that of pure anatase. These results demonstrate that a hazardous industrial waste, RM, has a huge potential as a cost-free raw material for obtaining self-cleaning geopolymers. The resulting geopolymers offer a sustainable-route towards self-cleaning construction materials with competitive mechanical properties.



### **3. A NOVEL ALKALI ACTIVATED MAGNESIUM SILICATE AS AN EFFECTIVE AND MECHANICALLY STRONG ADSORBENT FOR METHYLENE BLUE REMOVAL**

#### **3.1. Introduction**

Dyes are synthetic organic compounds that have extensive applications in textile, printing, leather, cosmetics, and other industries [134, 135]. Each year more than 100,000 types of different dyes are produced with an annual production rate of  $7 \times 10^5$  tonnes [136], and after use, they are mostly discharged to the hydrosphere with effluent waters and cause a huge environmental problem. Considering the inevitable possibility of half of the population living in water-stressed areas in 2025 [137], it becomes crucial to find solutions for the removal of dyes in wastewaters. If purification of wastewaters that are contaminated with harmful organic dyes cannot be managed adequately, not only the water ecosystem but also humans will be affected drastically from this situation. Several distinct methods were suggested for this purpose, including ozonation [138], photocatalytic degradation [91], membrane separation [135], and adsorption [136]. Among these techniques, adsorption is regarded as a widely accepted and preferred method for the removal of dyes owing to the presence of various distinct adsorbent materials, cost effectiveness; which can be arranged by the appropriate selection of the adsorbent material, fast reaction rate, and ease of operation [134, 139, 140].

Various different adsorbent materials were developed by many researchers for the removal of dyes from aqueous solutions involving activated carbons [134, 141, 142], biochars [140, 143], clays [67, 144], metallic organic frameworks [93, 145], membranes [135, 146], and geopolymers, which are also known as AAMs [22, 147, 148]. Even though adsorbent design may differ with the type of the dye, there are some accepted properties which are common for a desired adsorbent. These features include low cost and availability, ease of synthesis, high adsorption capacity, fast kinetics, good chemical stability, and regeneration and reusability capability [139]. Moreover, it is also desired to have high mechanical strengths so that these materials can be practically utilized in various

applications, such as water storage and water purification [147]. However, this latter criterion has been overlooked for many of the studies in the literature. Besides, it is very challenging to synthesize an adsorbent which can offer properties satisfying all of these desired properties. The synthesis of most of the adsorbents stated above requires tedious energy intensive procedures with very limited yields and/or complex processing of raw materials that also causes inevitable side products. Most of the time, these specially made materials offer good adsorption capabilities but they generally lack in mechanical performance and also economical sustainability. In this regard, AAMs come forward, as these materials have a great potential to be tuned to ensure all of the above listed preferred properties of a desired adsorbent with high yield and less environmental footprint during the synthesis procedure.

When the AAMs are synthesized, use of cheap and abundant minerals as raw materials can offer significant cost benefits. In this regard, sepiolite (Sep) offers a broad potential because of several reasons. For instance, it is a naturally existing phyllosilicate clay with a general formula of  $\text{Mg}_8\text{Si}_{12}\text{O}_{30}(\text{OH})_4(\text{OH}_2)_4 \cdot n\text{H}_2\text{O}$ ;  $n \leq 8$ , offering a significantly high silica content [149]. The unique structure of Sep is composed of blocks and channels. Each structural block of Sep mineral consists of continuous tetrahedral silica sheets with discontinuous magnesium octahedral sheets [67, 77, 150]. Mining of Sep mainly takes place in Spain, USA, France, China, and Turkey [149, 151] totalling approximately 850,000 tons globally [152]. Besides, it has distinct properties, such as a high specific surface area that may reach up to  $320 \text{ m}^2 \text{ g}^{-1}$  [153], fibrous morphology, and characteristic microporosity, offering broad opportunities in various applications, such as in catalysis, where it is used as a support to disperse metal nanoparticles [154], in construction, where it is used as an additive to improve the mechanical properties of construction materials [155, 156], and in separation, where it is used as an adsorbent [157, 158]. In this regard, previous studies showed that Sep can effectively adsorb water or organic molecules due to its specific structure involving zeolite-like channels with an approximate width of  $5.6 \text{ \AA} \times 11.0 \text{ \AA}$  [159]. The adsorption properties of both as-received Sep and its modified form obtained by different treatments were investigated by many researchers [67, 68]. Some of these studies illustrated an enhanced adsorption capability of Sep towards cationic dyes, MB and methyl violet removal [69]. In addition to these cationic dyes, this mineral was also tested for the removal of anionic dyes, reactive blue 221 and acid blue 62 [68, 157], as well.

Even though these studies demonstrated a broad potential of Sep in wastewater treatment, the literature broadly lacks its use as a raw material in the synthesis of AAMs with high performance for dye removal from water. Treatment of Sep with alkaline NaOH solution was established in an attempt to investigate the CO<sub>2</sub> sorption capacity by Walczyk et. al, and it was shown that Sep may transform into loughlinite mineral upon suggested NaOH treatment procedure [160]. Sodalite synthesis from Sep mineral was also conducted by an energy intensive alkali fusion and hydrothermal treatment procedure to investigate heavy metal removal from aqueous solutions [161]. Even though these studies offer alternatives for evaluating Sep mineral for different purposes, utilizing Sep for the synthesis of AAMs with high mechanical performance values, which are also green construction materials with low energy requirement, has not been studied in the existing literature for MB dye removal. Besides, the adsorbent materials used in reactors or columns should meet the necessary mechanical properties to prevent possible problems that may cause malfunctioning of industrial units [162].

Sep itself or its modified forms do not offer any mechanical performance, which prevents their broad utilization for different purposes that may need a certain level of integrity and mechanical endurance. In this regard, having high mechanical strength in these materials is crucial for practical applications, however, most of the time, this property is overlooked. Here, we are geared up to fill this gap in the literature and introduce a Sep-based AAM (Sep-AAM) as an effective adsorbent for the removal of dyes from water. The adsorbent was synthesized by the alkali activation of Sep, characterized in deep detail revealing its structural and mechanical characteristics, and tested for MB removal from water. Kinetic and thermodynamical parameters of adsorption of MB onto calcined Sep and Sep-AAM were determined. Mechanical performance together with surface characteristics-performance relationship for Sep-AAM have also been established and discussed in detail. This chapter was published as a paper [97] and the original manuscript has been rearranged to conform to the format requirements of the dissertation.

## 3.2. Experimental Conditions

### 3.2.1. Materials

Sep mineral was kindly supplied by Dolsan Mining, Eskişehir-Turkey. Calcined Sep was obtained by the calcination of Sep mineral at 750 °C for 1 h (2.8 g/cm<sup>3</sup>) [77]. MB hydrate (Sigma-Aldrich, purity >97%, molecular weight 319.85 g/mol) was used as a model adsorbate. Sodium silicate (Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub>) solution (9 wt% of Na<sub>2</sub>O, 28 wt% of SiO<sub>2</sub>, 63 wt% of H<sub>2</sub>O, Merck, 1.35 g/cm<sup>3</sup>) was used as an alkali activator for the synthesis of Sep-AAM. Chemical compositions of the as-received Sep and its calcined form are provided in Table B.1 (in the Appendix B).

### 3.2.2. Preparation of the AAM

Preliminary experimental results revealed that highest mechanical performance (compressive strength) is obtained when Si/Mg and Na/Mg ratios are 3 and 1, respectively. Therefore, initial gel chemical composition of Sep-AAMs in this study was set to have the molar Si/Mg and Na/Mg ratios of 3 and 1, respectively, as given in Table B.2. To ensure these ratios in the synthesized material, the XRF results presented in Table B.1 were used and the added necessary amount of Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution is arranged simply by calculating the amount needed to obtain desired Si/Mg and Na/Mg ratios. Mix proportions in terms of mass per unitary volume are presented in Table B.3. Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution was used as an alkali activator. Powdered and sieved (#70 mesh sieve, 200 µm) calcined Sep was mixed thoroughly with Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution and then thermally treated at 40 °C for 24 hours that is followed further by aging at room conditions for a week before being utilized as an adsorbent for MB adsorption.

### 3.2.3. Materials Characterization

Bruker S8 Tiger XRF spectrometer was utilized to determine the elemental composition of raw materials. XRD measurement of the samples were performed on a Bruker D8 Discover Diffraction system with a Cu Kα<sub>1</sub> radiation source employing a wavelength of 1.5418 Å. For FTIR spectroscopy, a Bruker Alpha II with an ATR cell, in

absorption mode was used. A Zeiss Ultra Plus FE-SEM coupled with an EDS was used to designate the microstructure and morphology of raw materials and the synthesized geopolymer. BET surface area, pore size, and pore volume values of samples were performed on a Micromeritics ASAP 2020 –Physisorption Analyzer. To find pore size distribution of the BJH model is utilized by using desorption adsorption isotherm. XPS analysis was conducted on a Thermo Scientific K-Alpha X-ray Photoelectron Spectrometer and Avantage 5.9 software was utilized for XPS data fitting. TGA was conducted on a TA Instruments TGA Q500 instrument. The temperature of each sample (25 mg) placed in a platinum pan was increased to 800 °C at a ramp rate of 3 °C/min in flowing N<sub>2</sub> (60 mL/min N<sub>2</sub>). Compressive strength measurements were conducted on a MTS model servo-hydraulic test machine with capacity of 500 kN with a loading rate of 0.01 mm per second. Prior to mechanical performance tests, alkali activated materials which were mixed thoroughly were moved into 10 mm × 10 mm × 10 mm silicon molds and kept at 40 °C for 24 h followed by a resting period of 28 days at ambient temperature. The compressive strength tests were conducted in quadruplicates and average value was reported together with standard deviation value. pH of the solutions was measured by using a lab pH meter (VTW, model 7110). A Malvern Zetasizer Nano ZS was utilized to determine the zeta potential of the samples. Zeta potential measurements were conducted at ambient temperature (25 °C) and 0.1 M HCl and NaOH solutions were used to adjust the pH. The chemical composition of the MB solution after adsorption were determined by using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x, Agilent Technologies Inc., Tokyo, Japan) and measurements were replicated five times.

### 3.2.4. MB Adsorption Tests

Adsorption behaviors of materials was studied by immersing 10 mg of powdered and sieved (#70 mesh sieve, 200 μm) forms of the adsorbents into 50 ml of MB solution with various predetermined MB concentrations (5-40 mg L<sup>-1</sup>). The mixtures were magnetically stirred at 700 rpm until equilibrium was reached. Aliquots collected from MB solutions at regular time intervals were centrifugated and then analyzed by using a Flame-S-UV-Vis-ES spectrometer (Ocean Optics, USA) by measuring the absorbance value at  $\lambda = 664$  nm. Removal efficiency (%) was measured as given in Equation (1.1). The amount of MB adsorbed on adsorbents were determined by Equation (1.2). Pseudo-first- and pseudo-

second-order adsorption kinetic models were used to reveal the MB adsorption mechanism of materials. The dependence of adsorption rate on both the adsorbent amount and adsorbed amount of MB dye was evaluated by using Equation (1.8). The Arrhenius equation given in Equation (1.9) was used to determine the activation energy of adsorption. Intraparticle diffusion model given in Equation (1.10) was also applied to experimental data in order to identify the diffusion mechanism. Langmuir and Freundlich models shown in Equation (1.11) and Equation (1.13) were used to fit the equilibrium data of the samples.

#### 3.2.4.1. Thermodynamical Properties

The thermodynamic parameters of adsorption, such as Gibbs Free Energy ( $\Delta G^\circ$ ), enthalpy ( $\Delta H^\circ$ ) and entropy ( $\Delta S^\circ$ ) changes were calculated [163] as

$$\Delta G^\circ = \Delta H^\circ - T \times \Delta S^\circ. \quad (3.1)$$

To obtain the value of  $\Delta H^\circ$  and  $\Delta S^\circ$ , Van't Hoff equation is used in the following form

$$\ln K_{ads} = -\frac{\Delta H^\circ}{R \times T} + \frac{\Delta S^\circ}{R} \quad (3.2)$$

where  $R$  is the universal gas constant (8.314 J/(mol.K)),  $T$  is the temperature (K),  $K_{ads}$  is the adsorption equilibrium constant. When there is a non-ionic solute or ionic solute in a dilute solution (which is the case in this study) equilibrium constant term ( $K_{ads}$ ) in Equation (3.2) can be written as [163]

$$K_{ads} = K_L \times M_A \quad (3.3)$$

where  $M_A$  is the molecular weight of the adsorbate (mg/mol). Equation (3.3) becomes

$$\ln(K_L \times M_A) = -\frac{\Delta H^\circ}{R \times T} + \frac{\Delta S^\circ}{R}. \quad (3.4)$$

### 3.2.4.2. Adsorbent Regeneration Test

Calcined Sep in powder form and powdered form (#70 mesh sieve, 200  $\mu\text{m}$ ) of the Sep-AAM was used for four consecutive adsorption experiments of 3.5 h. Thermal treatment procedure is known to be an effective method for removing surface adsorbed MB molecules [19], [80]. After each use, calcined Sep and Sep-AAM was regenerated by calcination at 400  $^{\circ}\text{C}$  in static air for 2 hours. The initial MB concentration was 40  $\text{mg L}^{-1}$  (500 ml) and the amount of adsorbent used for the first adsorption experiment was 100 mg. MB concentration was adjusted between each regeneration experiment to compensate the mass loss of the adsorbent by keeping the MB amount per adsorbent amount constant.

Regeneration performance of the Sep-AAM was also investigated in the monolith form to be able to estimate the regeneration performance by minimizing the mass loss. Desorption tests were conducted prior to regeneration experiments for calcined Sep and Sep-AAM with the highest MB initial concentration in this study. For this purpose, adsorbents that were magnetically stirred in 50 ml of 40  $\text{mg L}^{-1}$  MB solution for 3.5 h at room temperature were separated by centrifugation which were later immersed into 50 ml of distilled water for 24 h at room temperature. The quantity of MB dye that was leached to distilled water at the end of this period were measured by using a UV-Vis spectrometer.

## **3.3. Results and Discussions**

### **3.3.1. Morphological, Bulk Microstructure, Thermogravimetric, and Mechanical Properties**

BET surface areas, pore volumes, and average pore sizes of Sep, calcined Sep, and Sep-AAM are summarized in Table 3.1. Data showed that there is a significant decrease in the surface area of Sep upon calcination at 750  $^{\circ}\text{C}$ . This decrease is associated with the loss of the water molecules with an increase in the temperature, consistent with the previous reports [157]. It is known from the literature that the amounts of soluble silica and alumina content increase upon the calcination of the raw mineral, and this increase is accompanied with an increase in the amorphous content of the clay minerals [164]. These changes in the amorphous contents favor the alkali activation. Our characterization results are consistent

with these earlier findings. Table B.1 shows that the available silica, alumina, and magnesium content, which are obtained from XRF spectroscopy, increases with calcination (as expected by the removal of the water molecules trapped in the structure). Further drop in the surface area upon alkali activation is sourced from the formation of a denser structure with alkali activation.

Table 3.1. BET surface area, average pore size, and pore volume of samples.

| Sample          | Surface area<br>(m <sup>2</sup> /g) | Pore volume<br>(cm <sup>3</sup> /g) | Pore size<br>(Å) |
|-----------------|-------------------------------------|-------------------------------------|------------------|
| As-received Sep | 251.8                               | 0.4                                 | 165.4            |
| Calcined Sep    | 101.8                               | 0.5                                 | 273.8            |
| Sep-AAM         | 8.6                                 | 0.007                               | 770.5            |

Morphological characteristics of the materials are shown in Figure 3.1. The as-received Sep consists mainly of crystal bundles together with particles that are aggregated by fibrous clusters as also stated previously in the literature [165, 166]. Calcination seems not to affect the morphology as the fibrous structure of Sep was not altered. With the effect of alkali activation, however, there is a substantial transformation. SEM image given in Figure 3.1c illustrates more homogeneous and continuous morphology upon alkali activation. The decrease in specific surface area detected by BET measurements (Table 3.1) are in line with this newly formed denser and less porous morphology. The EDX results indicate that the surface of Sep-AAM consists mainly of Si, Mg, Na, Ca, Al, and O atoms constituting the main framework (Figure B.1).

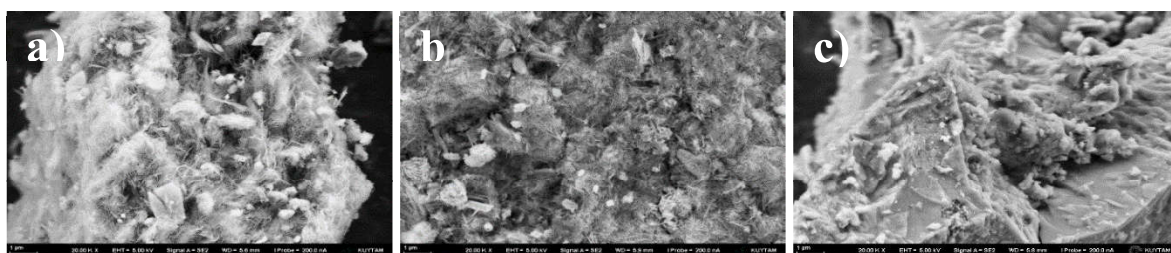


Figure 3.1. SEM images of materials at a magnification of 20 k $\times$ : a) As-received Sep, b) Calcined Sep, and c) Sep-AAM.

Compositional factors, including the molarity and type of the alkali activator used, water amount, and additives have a determining effect on the surface properties of the geopolymers [167, 168]. From this respect, each AAM has its unique surface properties that not only depends on the origin raw material composition, but also on the alkali activator preference and the molarity of the alkali activator. As it is reported in the literature previously for FA-based geopolymers, obtaining geopolymers with small pore volumes and low surface area corresponds to a dense geopolymer matrix with low permeability, high durability and is an indication of a compact and denser structure [169].

During the alkali activation of a precursor several reactions occur. However, as well documented by Glukhovsky et. al, this process can be summarized in three main stages involving, destruction-coagulation, coagulation-condensation, and condensation crystallization [4, 170]. The presence of higher degree of polycondensation during these series of reactions results a lower surface area of the final AAM [168]. With the hardening of the gel phase and as a result of a structural reorganization and densification during time, it is common for an AAM to form into a denser structure, as it is also the case for synthesized Sep-AAM in this chapter (Figure 3.1).

The decrease in surface area upon alkali activation observed in this part (Table 3.1) is in accordance with the previous findings of the study of Walczyk et. al [160], where Sep is treated with NaOH solution to form loughlinite and a major reduction in the surface area of Sep is detected upon alkali treatment. The decrease in the surface area observed in this part accompanied by a concomitant decrease in pore volume and a parallel increase in pore size values upon alkali activation have occurred. During the alkali activation, because of presence of high amounts of  $\text{OH}^-$  ions in the alkali activator, hydroxides might have precipitated to form the magnesium silicate framework with surface structural hydroxyl groups that are linked to Mg sites.

Figure 3.2 compares the XRD patterns of Sep, calcined Sep (750 °C, 1 h), and Sep-AAM over a  $2\theta$  range between 10 to 90°. Main crystalline phase detected for as-received Sep is found to be Sep and dolomite phases together with minor amount of quartz and main peaks of these crystalline phases were detected at 35, 31, and 27°, respectively. Calcination of the raw materials before alkali activation is a common procedure since thermal treatment

has a positive effect on the solubility of the aluminosilicate materials and [112] and magnesium silicate materials [77]. Data indicated that calcination of Sep caused some structural changes associated with the dehydroxylation and dehydration of the starting material. The peaks owing to dolomite and Sep, located at 31 and 35°, respectively, disappeared upon calcination and formed calcium aluminum silicate, calcium magnesium silicate, and pericase phases indicated by the formation of features at 28, 33, and 43°, respectively. The formation of pericase phase that is accompanied by the disappearance of dolomite phase is most possibly related with the release of CO<sub>2</sub> in the dolomite upon calcination [166].

As pointed out in the previous studies, AAMs display a featureless hump located in between 18° and 38° and centered at approximately 28°, which is an indication of the amorphous geopolymer formation [4, 38, 110]. During the alkali activation, complex multiphase series of reactions occur including dissolution, reorientation and solidification [171].

Obtaining less crystalline structure that is accompanied by the the formation of an amorphous phase upon alkali activation has previously been observed for high calcium FA-based, RM and MK-based geopolymers [25, 172]. As it is deduced from Figure 3.2, the XRD pattern of Sep-AAM has the characteristic feature of amorphous structure displayed by the hump located at 28° together with minor amounts of undissolved MgO phase. Upon alkali activation there is a profound decline in the amount of crystalline phases. Therefore, from a mechanistic perspective, a slight dissolution of calcium magnesium silicate existing in calcined Sep is an indication that this crystalline material partly takes place in alkali activation process. The decrease in the amount of crystal components (calcium magnesium silicate and pericase) in Sep-AAM sample demonstrates the dissolution of magnesium and silicate related phases within geopolymeric framework.

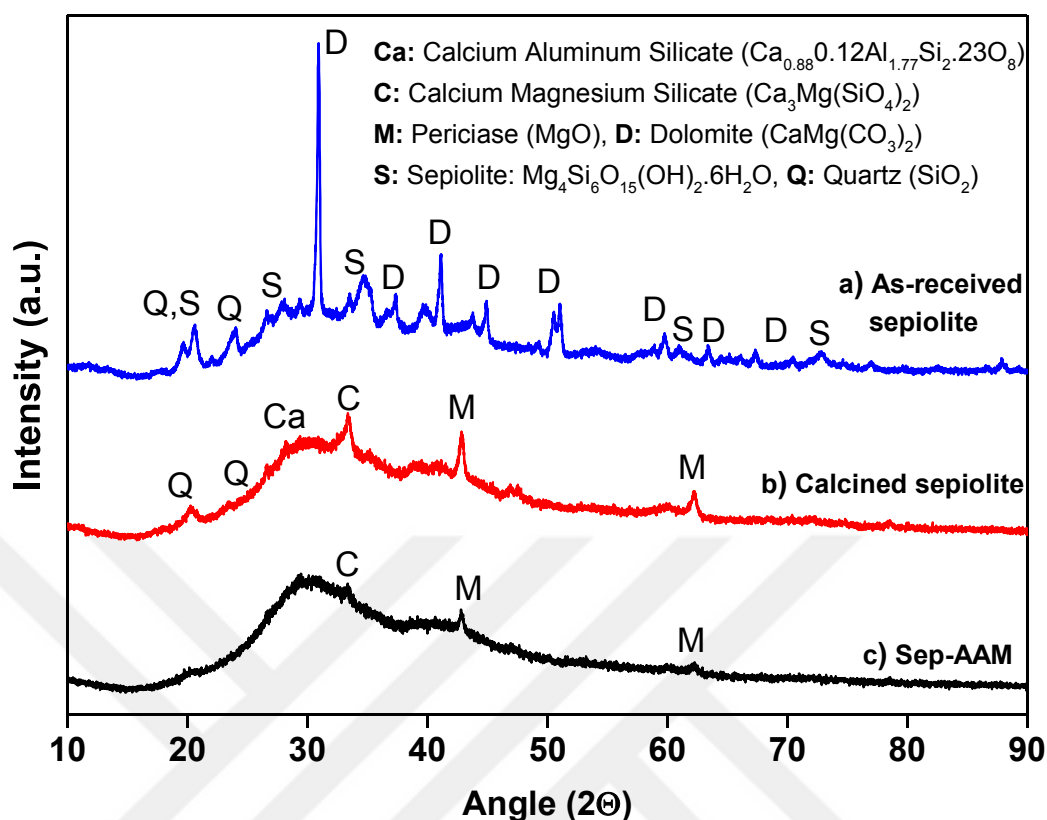


Figure 3.2. XRD patterns of a) as-received Sep, b) Sep calcined at 750 °C, and c) Sep-AAM.

Figure 3.3 demonstrates the FTIR spectra of Sep, calcined Sep, and Sep-AAM. FTIR spectrum of Sep displays features at 3632, 3557, 3380, and 3236  $\text{cm}^{-1}$ , indicating the presence of water molecules. The band at  $\sim 3632 \text{ cm}^{-1}$  is associated with the stretching vibrations of hydroxyl groups that are linked to octahedral Mg ions inside the Sep mineral. The feature observed at 3557  $\text{cm}^{-1}$  is related to magnesium coordinated water, and the peaks at 3380, 3236 and 1656  $\text{cm}^{-1}$  are attributed to vibrations of  $-\text{OH}$  stretching and bending of water molecules in the channels [173, 174]. Two minor contributions positioned at 786 and 661  $\text{cm}^{-1}$  are assigned to octahedrally coordinated  $\text{Mg}-\text{OH}$  bending vibrations [173]. The feature located at 1458  $\text{cm}^{-1}$  is associated with the stretching vibration of  $\text{C}-\text{O}$  indicating the presence of carbonate groups [37] that are related to dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) impurities. Furthermore, peak positioned at 879  $\text{cm}^{-1}$  is also related to the deformation mode of carbonate impurities [160, 175]. Two major contributions located at 1021 and 974  $\text{cm}^{-1}$  are assigned to out-of-plane stretching vibrations of  $\text{Si}-\text{O}$  [160, 176]. The peak observed at  $\sim 443$

$\text{cm}^{-1}$  is due to the presence of Si–O–Mg bonds that are between the tetrahedral and the octahedral sheets of Sep mineral [173, 177].

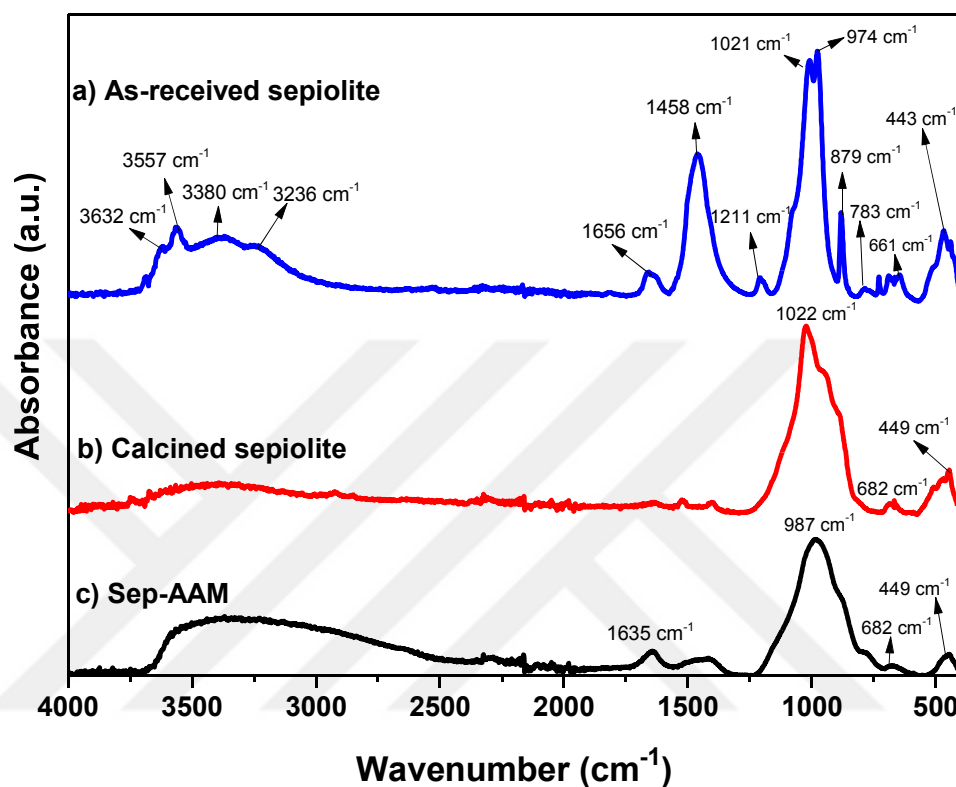


Figure 3.3. FTIR spectra of a) As-received Sep, b) Calcined Sep, and c) Sep-AAM.

Several changes were observed in these features upon calcination of Sep at 750 °C for 1 h. Data presented in Figure 3.3 indicated the disappearance of IR features associated with water molecules upon calcination. As stated previously, calcination temperature was chosen in this part as 750 °C, since it is known from the literature that coordinated and structural water loss from Sep mineral takes place at elevated temperatures [77, 150]. FTIR analysis results presented in Figure 3.3. are also in line with this information, as the disappearance of contributions regarding the magnesium coordinated water (3557  $\text{cm}^{-1}$ ), and –OH stretching and bending of water molecules in the channels (3380, 3236, and 1656  $\text{cm}^{-1}$ ) of Sep material, is observed upon calcination. The remaining major contributions located at 1022 and 449  $\text{cm}^{-1}$  are related to the presence of Si–O–Si vibrations and Si–O–Mg bonds, respectively [173]. The shoulders observed at 950 and 876  $\text{cm}^{-1}$  are contributed to asymmetric stretching vibrations of Si–O–Si and Si–OH bending vibrations, respectively [112]. Minor feature at

682  $\text{cm}^{-1}$  is assigned to asymmetric stretching vibrations of Si–O–Si bonds [112]. After calcination, the peak at 1460  $\text{cm}^{-1}$ , ascribed to carbonite impurities (dolomite), disappeared, consistent with XRD results (Figure 3.2) showing the dissolution of dolomite phase upon calcination.

The broad characteristic feature positioned between 900–1200  $\text{cm}^{-1}$  indicates the presence of geopolymerization [38, 178] and is also found to be the main feature observed for alkali activated Sep in Figure 3.3c. This main feature points out the structural transformation showing the dissolution of calcined Sep as a consequence of alkali activation. The position of the main contribution of calcined Sep (1022  $\text{cm}^{-1}$ ) shifted to a lower wavenumber (987  $\text{cm}^{-1}$ ) upon alkali activation and is attributed to the formation of a tridimensional geopolymeric framework with silicon and magnesium tetrahedra. This feature corresponds to asymmetric stretching vibrations of Si–O–Si bonds [178]. The shoulder detected at 876  $\text{cm}^{-1}$  contributed to Si–OH bending vibrations in calcined Sep is still present for Sep-AAM sample. The relatively weak band at 1635  $\text{cm}^{-1}$  is related with the stretching (–OH) and bending (H–O–H) vibrations of bound water molecules [114, 160]. The intensity of the feature at 443  $\text{cm}^{-1}$  observed in the spectra of both as-received Sep and its calcined counterpart decreases upon alkali activation. As stated earlier, this contribution is related to the Si–O–Mg bonds between the tetrahedral and the octahedral sheets and weakening in the intensity of this feature possibly indicates that more Mg ions become located in tetrahedral sites upon the alkali activation, as expected for a conventional geopolymer.

Formation of a denser structure upon alkali activation (Figure 3.1) resulted in satisfactory compressive strength values, showing the possible applicability of these materials also for construction purposes, where the adsorption capability brings in significant benefits. Four repetitive compressive strength measurements were conducted on the Sep-AAM specimens and the average value was determined as  $39.8 \pm 4.9$  MPa. Here we note that the literature lacks any study reporting the compressive strength of an analogous Sep-based AAMs. The literature mostly focuses on the strength development of AAMs, which were produced from conventional raw materials, such as MK, FA, and granulated blast furnace slag [4, 38, 110, 179] and these studies indicate a typical compressive strength of 20–70 MPa for these AAMs. For instance, on a volcanic ash-based geopolymer, compressive

strength was reported to be almost 20 MPa [180]. The strength enhancement in these materials was found to be strongly correlated with the amount of aluminosilicate gel formation, which is also controlled by the molar Si/Al ratios [181]. During the synthesis of AAMs, the presence of impurities, such as calcium, iron, and titanium, in the raw material affects the formation of final product and its mechanical properties by adding reaction pathways to gel formation [4]. The use of non-conventional raw materials for the synthesis of AAMs, such as RM, which has a very high  $\text{Fe}_2\text{O}_3$  content, and C-type FA, which has a very high CaO content, were found to result in compressive strength values of 1 MPa [80] and 23-32 MPa [182], respectively. Thus, it is inferred that a compressive strength in the order of 40 MPa of the Sep-AAM introduced here is very promising in terms of offering opportunities for practical usage of these materials as adsorbents.

Thermal stability is also crucial for determining the practical usability of these materials. Figure 3.4 compares the TG and DTG curves of Sep, calcined Sep, and Sep-AAM. Mass losses occurred during a temperature ramp from room temperature to 800 °C in flowing  $\text{N}_2$  (60 ml/min) were determined as 28.1, 8.5, and 17.8 wt% for Sep, calcined Sep, and Sep-AAM, respectively. The as-received Sep exhibits five stages of thermal decomposition corresponding to mass losses of 9.16 wt% (between room temperature to 84 °C), 2.1 wt% (84-283 °C), 4.6 wt% (283-623 °C), 11.5 wt% (623-721 °C) and 0.7 wt% (721-800 °C). These losses were attributed to release of adsorbed water, release of structural water related to dehydration, dehydration of hydroxyls along the octahedral edge, release of water by dehydroxylation, such as dehydroxylation of Mg–OH groups, calcination of dolomite [150, 151, 159], respectively. The highest amount of mass loss detected in the region between 623 and 721 °C is thought to be related with the loss of water due to dehydroxylation of Sep phase. Water loss observed from 721 to 800 °C is ascribed to calcination of dolomite phase [151]. On the other hand, Sarı Yılmaz et. al reported that for Sep mineral, mass loss observed in the temperatures between 564-822 °C denotes both calcination of dolomite, and dehydroxylation of Sep [183]. For this reason, mass losses observed in temperatures between 623-800 °C in this chapter are thought to be sourced both from dehydroxylation of Sep phase and calcination of the dolomite phase.

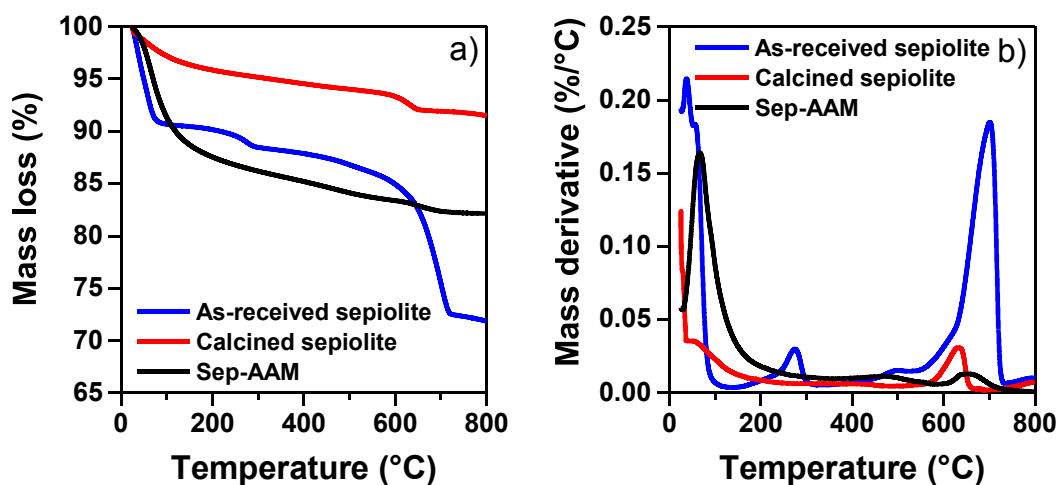


Figure 3.4. a) TG and b) DTG curves of as-received Sep, calcined Sep and Sep-AAM.

Dehydroxylation of Sep and calcination of dolomite phases conform with the findings from XRD analysis, where these two phases were found to be no longer exist in calcined Sep (Figure 3.2b). Calcined Sep was found to be more thermally stable as expected and only 8.5 wt% of mass loss was observed. Vast majority of the mass loss in calcined Sep (6.3 wt%) was observed from room temperature to 560 °C, attributed to loss of water due to dehydration of hydroxyls. Mass loss detected for Sep-AAM mostly occurs up to 150 °C, approximately 11.2 wt%, in this region occurs as a result of release of adsorbed water. Further mass loss detected in the region between 150 and 600 °C is associated with the release of chemically bounded water from Si–OH and/or Al–OH groups [184].

### 3.3.2. Surface Characteristics

Aiming at understanding the changes in the surface composition of elements in Sep, calcined Sep, and Sep-AAM, we performed XPS analysis. XP spectrum of Sep-AAM, given in Figure B.2, shows that the surface composes mainly of O, Si, Mg, Al, Ca, and Na elements. Results indicated the changes in surface composition upon the alkali activation of calcined Sep. Deconvoluted O 1s, Mg 2p, and Mg 1s together with Si 2p spectra of the samples and related peak positions are provided in Figure B3 and Tables B.4-B.6.

Deconvolution of O 1s spectra showed that intensity of the contribution detected at ~532 eV, which is related with the surface hydroxyl groups [160, 185], decreased upon

calcination (Figure B.3b&f) for Sep. This situation is associated with the release of surface hydroxyl groups in Sep with calcination [173]. Concomitantly, a slight decrease in intensity was also observed on the feature located at 534 eV upon the calcination of Sep. This decrease is related with the evaporation of water molecules [186]. Strong peak detected at approximately 531 eV for all of the samples is correlated with the O 1s in Si–O–Si environment [187]. Upon alkali activation the amount of contribution detected at 531–532 eV increased. This increase is associated with the expected formation of surface hydroxyl groups on the surface of the AAM which is due to the presence of structural hydroxyl groups that are linked to Mg sites [187] and OH<sup>−</sup> groups on the surface [185]. Band observed at approximately 530 eV in the calcined Sep and Sep-AAM is related with the presence of Si–O oxygens [160]. Peak at 536 eV detected for Sep-AAM sample indicates the presence of water in vapor phase [188]. Corresponding peak positions of O 1s spectra are provided in Table B.4.

Si 2p spectra of Sep and calcined Sep display two main characteristics located at approximately 102.1 and 102.8 eV for Sep, and 102.4 and 103 eV for calcined Sep (Table B.5, Figure B.3a&e) corresponding to Si bonding in Si–O–Mg and Si–O–Si environments [187]. Upon alkali activation there is a slight shift to lower binding energies. Two contributions located at 101.8 and 102.8 eV for Sep-AAM also correspond to tetrahedral Si bonding in Si–O–Al [160, 189] and amorphous SiO<sub>x</sub> derivatives, respectively [190], showing the possible existence of Si atoms in different environments.

Two main contributions positioned at 1303 and 1304 eV in the Mg 1s spectra for Sep and calcined Sep are related with the Mg–O and Mg–O–Si bonds of Sep clay, respectively [120]. Mg 2p spectra of samples given in Figure B.3c, Figure B.3g and Table B.6 display two main features that are located at 50 and 45 eV. Contribution at 50 eV corresponds to the presence of Mg–Al bonds [160].

As it can also be seen from Table B.6, there is a slight red shift in the order of almost 1 eV in binding energies of Mg 1s and Mg 2p spectra in Sep-AAM sample, this lowering in binding energy is most possibly related with the transition of octahedral Mg atoms into tetrahedral coordination upon alkali activation since low number of oxygen atoms are needed in tetrahedral Mg than it is for octahedrally coordinated Mg [191]. Furthermore, the

transformation of coordinated Mg atoms present in calcined Sep from octahedral to tetrahedral coordination occurs upon alkali activation and was previously verified by  $^{25}\text{Mg}$  MAS NMR spectroscopy [77]. Zhuang et al. reported that the contribution observed at 532.1 eV in O 1s spectrum is also related with the presence of  $[\text{SiO}_4]$  tetrahedra and  $[\text{Mg}(\text{Al})\text{O}_6]$  octahedra [186]. In this perspective, the reduction in contribution at 532 eV upon alkali activation (Figure B.3j) indicates that the amount of octahedrally coordinated Mg sourced from calcined Sep decreases with alkali activation. Atomic % of Si, O, Mg, Ca, Al, and Na elements obtained from XPS fitting are shown in Table B.7.

### 3.3.3. MB Adsorption Tests

The pH of the medium, and thus, the zeta potential of the adsorbents, plays an important role in adsorption kinetics. Thus, the pH of the MB solutions at initial and equilibrium conditions was recorded. The pH of the  $40 \text{ mg L}^{-1}$  MB solution at the beginning of the adsorption test was recorded as 6.2. After 210 minutes of MB adsorption, pH values detected for calcined Sep and Sep-AAM were found to be 10.6 and 10 for calcined Sep and Sep-AAM, respectively. The change of zeta potential with pH are presented in Figure B.4. Results illustrate that both for calcined Sep and Sep-AAM zeta potential is negative for a wide range of pH values. The zeta potential evolution of calcined Sep with pH is found to be more stable for calcined Sep with a profound lowest zeta potential of -30.6 detected at a pH of 12. The zeta potential evolution of Sep-AAM decreased with an increase in pH and reached its lowest value of -39.6 when pH is equal to 12. Still, for all of the pH values measured, the zeta potential of Sep-AAM was found to be lower than calcined Sep. These results point out that the surface of Sep-AAM is more negatively charged than calcined Sep for the studied equilibrium pH values (10-10.6), suggesting superior adsorptive properties of Sep-AAM towards the adsorption of cationic MB molecules. Higher electrostatic attraction between cationic MB dye and negatively charged surface of Sep-AAM enhances the adsorption capability. It is known from the literature that the surface of AAMs is normally negatively charged due to the dissociation of various oxygen containing hydroxyl groups makes it an effective adsorbent for removing organic pollutants from wastewater [6, 192, 193]. Furthermore, silanol groups existing on the surface of AAMs induce a negative charge at basic medium enhancing the adsorption of cationic species [194]. Therefore, superior adsorption properties for Sep-AAM can be expected and are most possibly

associated with the existence of surface hydroxyl groups on Sep-AAM surface which is confirmed by a lower zeta potential value of Sep-AAM sample in Figure B.4. The effect of initial pH on adsorption performance of both calcined Sep, and Sep-AAM is investigated in detail in Section 3.3.3.4.

### 3.3.3.1. Effect of Contact Time, $C_0 = 20 \text{ mg L}^{-1}$

The effect of contact time needed to reach the adsorption-desorption equilibrium was determined for calcined Sep and Sep-AAM by setting the initial MB concentration to  $20 \text{ mg L}^{-1}$  and adsorbent amount to  $10 \text{ mg}$ . Typical patterns of the changes in  $C_t/C_0$  ratio and uptake values with time are presented in Figure 3.5. For calcined Sep, after 60 minutes of adsorption experiment,  $C_t/C_0$  and uptake values stabilized at 0.57 and  $46 \text{ mg g}^{-1}$ , respectively, and remained nearly constant until the end of the adsorption experiment. Even though the equilibrium time needed for calcined Sep (60 min) is less than it is for Sep-AAM, experimental results revealed that optimum time needed for both calcined Sep and Sep-AAM can be taken as 3.5 h (210 min) since further contact time does not cause any significant change in the adsorbed amount of MB dye for Sep-AAM. For Sep-AAM,  $C_t/C_0$  and uptake values changed systematically with time and stabilized at 0.26 and  $74.64 \text{ mg g}^{-1}$ , respectively, after 210 minutes.

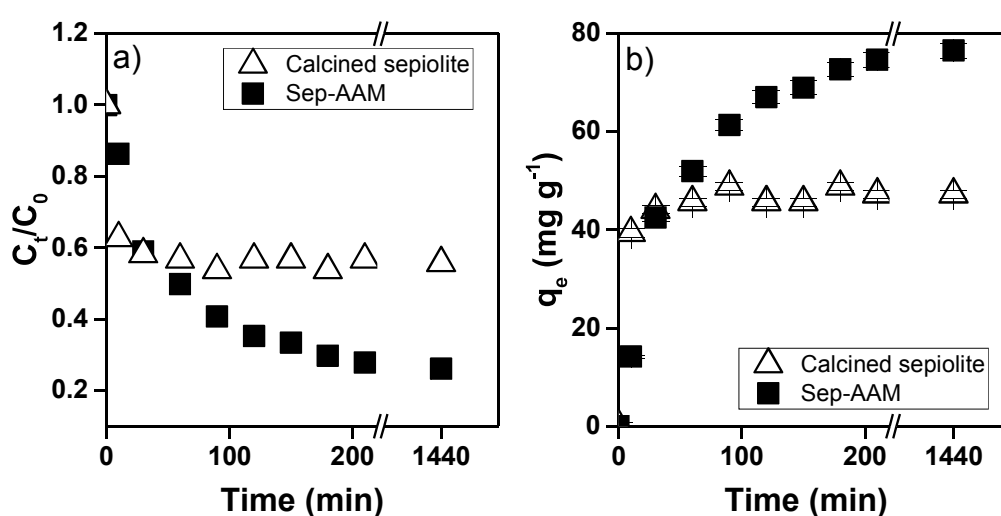


Figure 3.5. The effect of contact time on a)  $C_t/C_0$  and b) Uptake of calcined Sep and Sep-AAM.

### 3.3.3.2. Effect of Initial MB Concentration

Figure 3.6 shows the uptake and removal capability of calcined Sep and Sep-AAM for different initial MB concentrations using 10 mg sample for each run. As it is seen from this figure, both for calcined Sep and Sep-AAM, uptake capacity increases with the increase in MB concentration. Within the studied highest concentration of 40 mg L<sup>-1</sup> MB concentration, uptake values were 55.9 and 80.3 mg g<sup>-1</sup> for calcined Sep and Sep-AAM, respectively. The effect of the increase in MB initial concentration is more evident for Sep-AAM than it is for calcined Sep. For instance, 8-fold increase in initial MB concentration caused a 3.5-fold enhancement in the uptake value for Sep-AAM, whereas this enhancement was found to be 2.5 for calcined Sep. Concomitantly, a decreasing trend was observed in the MB removal efficiency (%) upon increasing MB concentration. Since there are a higher number of active sites that are available for dye adsorption at lower concentrations, the interaction between adsorbate and adsorbent is promoted at low concentrations. With the increase in MB concentration, the active sites become more occupied with MB dye molecules blocking the further adsorption of MB, consistent with the existing literature for FA-based geopolymers and MK-based geopolymers [19].

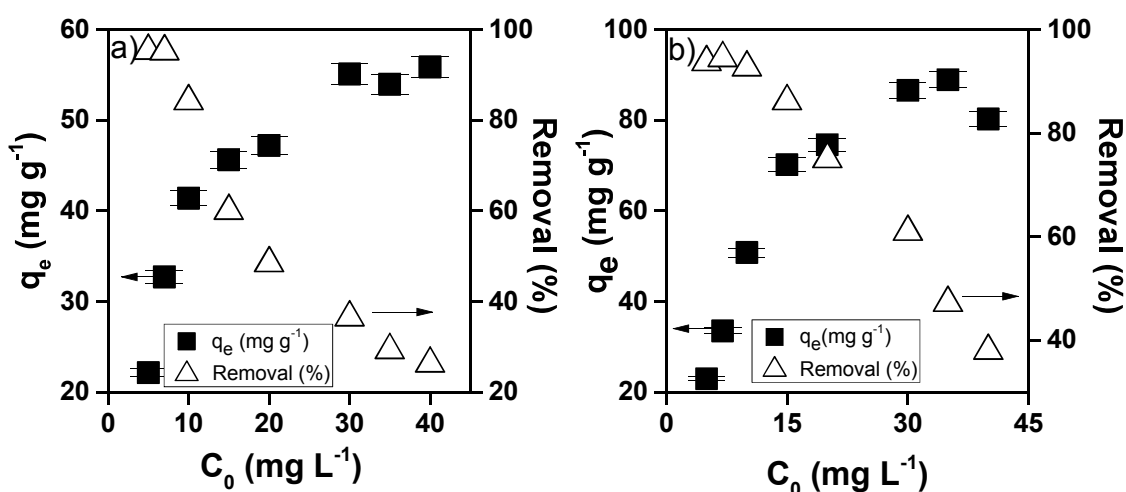


Figure 3.6. Effect of initial MB concentration on uptake ( $q_e$ ) and removal (%) of MB for a) Calcined Sep, and b) Sep-AAM.

### 3.3.3.3. Effect of Adsorbent Amount on Adsorption of MB Dye

The effect of adsorbent amount on the adsorption properties was further investigated and results are given in Figure 3.7 together with the results showing the effect of both the adsorbent amount and temperature on Table B.8.

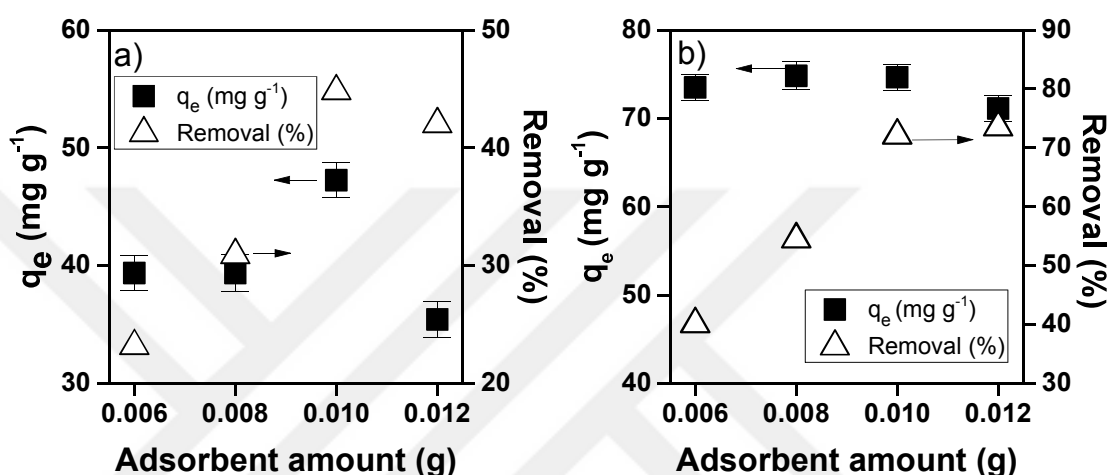


Figure 3.7. The effect of adsorbent amount on MB uptake and MB removal (%) by a) Calcined Sep, and b) Sep-AAM (*Contact time* = 3.5 h,  $C_0 = 20$  mg L<sup>-1</sup>).

As it is seen from Figure 3.7, both for calcined Sep and Sep-AAM, uptake values and removal efficiency are influenced differently from the increase in adsorbent amount. This increase is more profound for the removal efficiency, whereas there is a non-monotonous trend in the uptake capacity. Both the uptake capacity and removal amount obtained by using Sep-AAM as an adsorbent are more profound than that are for calcined Sep, which is in line with the observations from previous section where the effect of the increase in MB initial concentration was found to be superior for Sep-AAM than it is for calcined Sep.

With the increase in adsorbent amount, the number of available adsorption sites also increases explaining the increase in removal efficiency. However, the uptake capacity of Sep-AAM seems to be directed towards to slightly lower values with an increase in adsorbent dosage (Figure 3.7b) which is possibly associated with the presence of unsaturated adsorption sites [195]. The very minor decrease in the uptake capacity with an increase in adsorbent amount was also previously reported for FA-based geopolymers [22, 196]. For

calcined Sep (Figure 3.7a), similar to Sep-AAM, removal efficiency increases with the adsorbent amount. Trend observed in the uptake capacity with adsorbent amount increase is non-monotonous and adsorption performance of calcined Sep for all of the adsorbent amounts was found to be lower than that of Sep-AAM.

#### 3.3.3.4. Effect of pH on Adsorption of MB Dye

Another important parameter that has an effect on the adsorption efficiency is the pH of the effluent. To determine the influence of pH on the MB adsorption performance of both calcined Sep and Sep-AAM, adsorbents with definite amounts (10 mg) were mixed with 50 ml of MB dye solution ( $20 \text{ mg L}^{-1}$ ) at initial pH values of 2, 3, 4, 7, 8, and 9. The pH of the  $20 \text{ mg L}^{-1}$  MB solution at the beginning of the adsorption test was recorded as 7.0 without any interference, whereas to obtain different pH values, initial pH of the solutions was adjusted by using 0.1 M hydrochloric acid and sodium hydroxide solutions. pH values of these solutions were recorded by using a lab pH meter. Effect of initial pH on the adsorption performance was investigated at  $31^\circ\text{C}$  and presented in Figure 3.8.

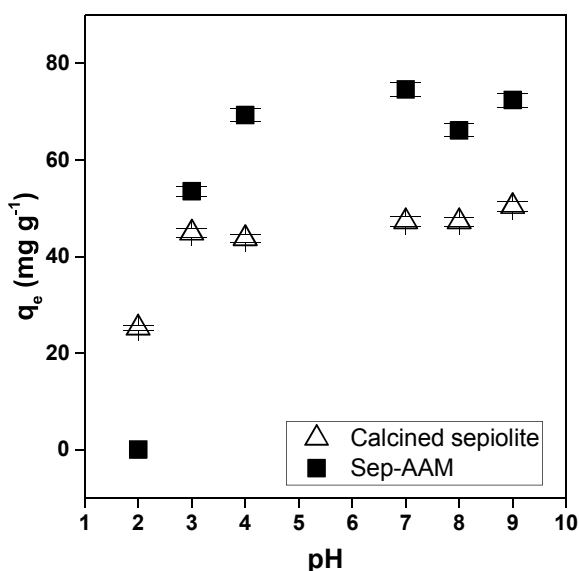


Figure 3.8. The effect of initial pH on MB uptake by calcined Sep and Sep-AAM (*Contact time* = 3.5 h,  $T = 31^\circ\text{C}$ ,  $C_0 = 20 \text{ mg L}^{-1}$ ).

The results presented in Figure 3.8. show that both for calcined Sep and Sep-AAM, increase in the initial pH values causes an increase in the MB adsorption capacity of the adsorbents. Even though calcined Sep and Sep-AAM display differences regarding adsorption capacities, they still show similar trends upon an increase of pH values. For both of these adsorbents, uptake values increase and becomes stable after an initial pH of 7. As investigated also in the previous sections, uptake capacity of Sep-AAM is superior to calcined Sep for a wide range of initial pH values (initial pH = 3-9), indicating that alkali activation enhances the MB adsorption performance, especially at alkaline conditions.

This enhancement in adsorption performance is related with the increased amount of negatively charged surface hydroxyls upon alkali activation, that can be arranged during the synthesis of an AAM by simply changing the alkali activator content. When pH of the solution medium is highly acidic (pH = 2), on the other hand, Sep-AAM does not show any adsorption performance and calcined Sep displays an adsorption capacity of 25.2 mg g<sup>-1</sup>, most possibly related with the comparably high surface area of calcined Sep with respect to Sep-AAM. However, as evident from this figure, the effect of presence of high amounts of surface hydroxyls on Sep-AAM becomes dominant at higher initial pHs, which is correlated with the zeta potential profile of these adsorbents (Figure B.4). The highest uptake capacity is obtained at normal pH for Sep-AAM (74.64 mg g<sup>-1</sup>). A higher adsorption at higher initial pH values is related with the presence of OH<sup>-</sup> ions and these ions attract positively charged MB molecules, increasing the adsorption performance. At acidic conditions, on the other hand, the existence of protons hinders the attraction between the adsorbate and the adsorbent and therefore caused a decrease in the adsorption performance. This profile is in accordance with the current literature, showing that adsorption performance of cationic MB dye is favoured at basic pH values, and acidic pH of the solution medium has a negative effect on the adsorption performance [23, 197].

#### 3.3.3.5. Effect of Temperature on Adsorption of MB Dye

To understand the effect of temperature on the adsorption behavior of MB dye onto calcined Sep, and Sep-AAM, experiments were conducted at 31, 40, and 50 °C for different initial MB concentrations. The data presented in Figure 3.9 verify that the adsorption capability of both of these adsorbents enhances with increasing temperature from 47.25 to

49.28 and to 62.99  $\text{mg g}^{-1}$  for calcined Sep and from 74.64 to 79.07, and to 99.92  $\text{mg g}^{-1}$  for Sep-AAM as the temperature increases from 31 to 40  $^{\circ}\text{C}$ , and to 50  $^{\circ}\text{C}$ , respectively, for an initial MB concentration of 20  $\text{mg L}^{-1}$ . Adsorption capacity of calcined Sep for all of the studied temperature values were found be less than those obtained on Sep-AAM. The enhancement in adsorption capacity with temperature points out the endothermic nature of the adsorption process at these experimental conditions, as investigated further below. Increase in the chemical potential of MB dye molecules with temperature to permeate to the adsorbent surface [67, 144] is one of the possible reasons of the improvement obtained for both calcined Sep, and Sep-AAM adsorption capacity. According to the observations presented in Figure 3.7, the optimum adsorbent amount for this experimental set up is 10 mg. Therefore, similar adsorption tests for as-received Sep were also conducted at three different temperatures for as-received Sep and uptake performance of as-received Sep was detected as 31.5, 26.8, and 26.8  $\text{mg g}^{-1}$  for temperatures 31, 40, and 50  $^{\circ}\text{C}$ , respectively and details of these experiments are provided in Table B.9.

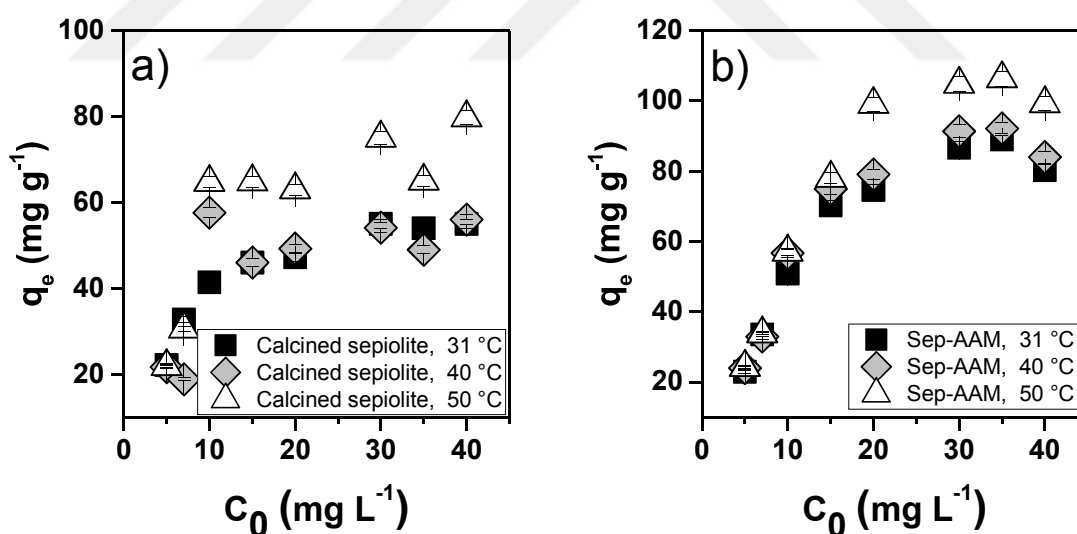


Figure 3.9. Effect of temperature on the equilibrium uptakes for MB on a) Calcined Sep, and b) Sep-AAM.

### 3.3.3.6. Adsorption Kinetics Modeling and Mechanism

Adsorption data were assessed by considering pseudo-first and pseudo-second-order kinetic models, as shown in Figure B.5, in Table 3.2 for Sep-AAM, and in Table B.10 for

comparison of the corresponding data of calcined Sep. As it is given in Figure B.5, Table 3.2, and Table B.10, the pseudo-second-order plot of the samples at different temperatures reflects linearity with high correlation coefficient values ( $R^2 > 0.98$ ). High consistency between calculated and experimental values of  $q_e$  given in these tables also infers that adsorption mechanism for these samples are better described by the pseudo-second-order kinetics than the pseudo-first-order kinetics. Thus, we infer that the adsorption of MB dye on calcined Sep and Sep-AAM at different temperatures are in accordance with pseudo-second-order adsorption model and that the adsorption process is possibly dominated by chemical adsorption process, suggesting the presence of electron exchange and/or sharing between the adsorbate and the adsorbent [198, 199], especially for Sep-AAM. Table 3.2 shows that both the value of apparent pseudo-second-order rate constant and removal efficiency (%) of MB increases with temperature for Sep-AAM.

Table 3.2. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto Sep-AAM at different temperatures (*Contact time* = 3.5 h,  $C_0 = 20 \text{ mg L}^{-1}$  and  $m = 10 \text{ mg}$ ).

| Adsorbent      | $q_{e,exp}$<br>( $\text{mg g}^{-1}$ ) | Pseudo-first-order adsorption<br>kinetics ( $C_0 = 20 \text{ mg L}^{-1}$ ) |                                       |       | Pseudo-second-order adsorption<br>kinetics ( $C_0 = 20 \text{ mg L}^{-1}$ ) |                                       |       | Removal<br>(%) |
|----------------|---------------------------------------|----------------------------------------------------------------------------|---------------------------------------|-------|-----------------------------------------------------------------------------|---------------------------------------|-------|----------------|
|                |                                       | $k_{1,ads,app}$<br>( $\text{min}^{-1}$ )                                   | $q_{e,cal}$<br>( $\text{mg g}^{-1}$ ) | $R^2$ | $k_{2,ads,app}$<br>( $\text{g mg}^{-1} \text{ min}^{-1}$ )                  | $q_{e,cal}$<br>( $\text{mg g}^{-1}$ ) | $R^2$ |                |
| Sep-AAM, 31 °C | 74.64                                 | $1.87 \times 10^{-2}$                                                      | 67.49                                 | 0.98  | $6.65 \times 10^{-4}$                                                       | 78.74                                 | 0.98  | 72.11          |
| Sep-AAM, 40 °C | 79.07                                 | $1.61 \times 10^{-2}$                                                      | 55.45                                 | 0.87  | $9.45 \times 10^{-4}$                                                       | 80.01                                 | 0.98  | 75.20          |
| Sep-AAM, 50 °C | 99.92                                 | $1.30 \times 10^{-2}$                                                      | 67.82                                 | 0.95  | $9.80 \times 10^{-4}$                                                       | 96.15                                 | 0.99  | 81.25          |

As it is stated earlier, to evaluate the actual pseudo-second-order adsorption constant ( $k_{2,ads}$ ), the dependence of the adsorption rate on the adsorbent amount should also be evaluated. Therefore, the adsorbent amount was varied and results are presented in Table B.8.

As it is also evident from Table B.8, for both Sep-AAM and calcined Sep, the increase in adsorbent amount causes a systematic increase in the apparent pseudo-second-order adsorption rate constant ( $k_{2,ads,app}$ ). For this reason, by using the values from Table B.8, for Sep-AAM, the variation of  $k_{2,ads,app}$  ( $\text{g mg}^{-1} \text{ min}^{-1}$ ) with the adsorbent amount (g) is

investigated, as given in Figure 3.10. The data demonstrate a strong correlation with  $R^2$  values greater than 0.95 for all three temperatures considered.

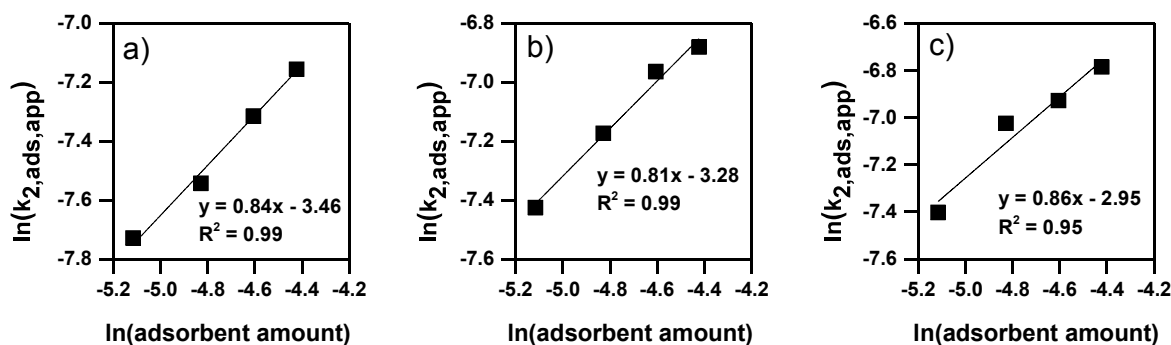


Figure 3.10. Experimental data fit to pseudo-second-order adsorption kinetics for Sep-AAM samples at a) 31 °C, b) 40 °C, and c) 50 °C.

Concordantly, the actual second-order adsorption rate constant ( $k_{2,ads}$ ) (Please see Equation (1.8) for more information on its difference from its apparent counterpart,  $k_{2,ads,app}$ ), and the adsorption rate order with respect to adsorbent amount for Sep-AAM was calculated. The slopes of the lines given in Figure 3.10 are the same at  $0.84 \pm 0.03$  for all temperatures considered. Therefore, based on the slope and intercept values presented in Figure 3.10, the actual second-order adsorption rate constants ( $k_{2,ads}$ ) for Sep-AAM were calculated and reported in Table 3.3 as follows:

Table 3.3. Actual second-order adsorption rate constants ( $k_{2,ads}$ ) of Sep-AAM at different temperatures.

| Temperature (°C) | $k_{2,ads} ((\text{g adsorbent})^{0.16} (\text{mg MB})^{-1} \text{ min}^{-1})$ |
|------------------|--------------------------------------------------------------------------------|
| 31               | 0.031                                                                          |
| 40               | 0.037                                                                          |
| 50               | 0.052                                                                          |

For comparison the corresponding data for calcined Sep are also provided in Figure B.6 and Table B.11. The slopes of the lines shown in Figure B.6 are  $4.2 \pm 0.75$  for all temperatures considered and based on these values presented in Figure B.6, the actual

second-order adsorption rate constants ( $k_{2,ads}$ ) for calcined Sep were evaluated and shown in Table B.11.

By using Arrhenius Equation (Equation (1.9)) and plotting  $\ln(k_{2,ads})$  values that were collected from Table 3.3 and Table B.11, vs  $1/T$  graph, the activation energy of the adsorption process of MB onto Sep-AAM and calcined Sep was calculated as 21.9 kJ/mol and 260.20 kJ/mol, respectively, and shown in Figure B.7.

As it was stated previously, to make a correct estimation about the rate limiting step and the time dependent diffusion mechanism, kinetic results extracted from the experimental data were further investigated by using intraparticle diffusion model. Intraparticle diffusion model for the adsorption of MB onto Sep-AAM at different temperatures together with parameters of intraparticle diffusion model are provided in Figure B.8 and Table B.12, respectively. Considering relatively lower correlation coefficients obtained for pseudo-first-order adsorption model and intraparticle diffusion model (Table 3.2 and Table B.12), the adsorption mechanism between Sep-AAM and MB dye was better defined by pseudo-second-order adsorption kinetics, where adsorption process is dominated by chemisorption [200]. The adsorption mechanism between calcined Sep and MB dye molecules was also better defined by pseudo-second-order adsorption kinetics (Table B.10). Chemisorption process involves a chemical reaction between the adsorbate and the adsorbent during the adsorption and involves the presence of interactions between the adsorbate and the adsorbent [201]. Our adsorbate, MB, is a cationic dye that is ionized in water to form a cationic portion and a chlorine portion [202]. Surface chemistry plays a major role for the determination of the specific adsorbent towards a pollutant removal [203]. Thus, it is claimed that the chemical attraction between the anionic surface hydroxyl groups present on Sep-AAM, which were also verified by XPS analysis and zeta potential measurements, and the cationic portion of MB molecule is mainly responsible for the high MB adsorption capacity. As stated earlier, XPS analysis indicated that Mg ions are located in tetrahedral sites upon the alkali activation. For the magnesium analogues of conventional AAMs, the negative charge on the tetrahedral magnesium is charge balanced by  $\text{Na}^+$  cations. The presence of negative charge in geopolymeric network also creates an electrostatic interaction between the negatively charged AAM network and positively charged MB molecules, therefore also accounts for the enhanced adsorption capacity.

Even though Sep-AAM shows low surface area and low porosity, the existence of a denser structure and the presence of surface hydroxyl groups (evident from XPS and zeta potential analyses) makes this material a very suitable adsorbent for MB dye and this material also displays high mechanical strength, making it a possible candidate for practical applications. XPS results showed that contribution observed at 531-532 eV in O1s spectra increases (Figure B.3) that is related with the formation of negatively charged surface hydroxyl groups that are linked to Mg sites [187] and OH<sup>-</sup> groups on the surface [185]. These negatively charged hydroxyl groups present on the surface are responsible to make an ion exchange when there are cations present in the medium [204]. Therefore, negatively charged surface of these materials offer a suitable medium for electron exchange or sharing between the cationic adsorbate MB.

#### **3.3.4. Adsorbent Regeneration**

Regeneration of the spent adsorbents is important both for the economics and the sustainability of the adsorption process. Before conducting regeneration experiments, dye fixation capability of both calcined Sep and Sep-AAM were determined by immersing them into distilled water. MB desorption from calcined Sep and Sep-AAM were found to be 4.02 % and 6.72 %, respectively, offering a rather strong fixation capability of these adsorbents upon cationic MB dye prohibiting the leaching in water. From this point of view, desorption can possibly be conducted more effectively by using several other solutions that have a higher capacity of solving MB dye, such as 2-propanol, ethanol, and acetone [202], or by using acidic solutions [192]. The possibility of leaching was also checked by analyzing the used solution by ICP-MS. The data presented in Table B.13 indicate that the leaching is almost negligible, with the amounts of leached elements associated with the adsorbent, remaining in trace amounts (<4 ppm). Among different regeneration techniques, thermal regeneration is a cost-effective method that is extensively used and in wastewater treatment plants [205] and widely preferred for the regeneration of AAMs in the literature [22], [80]. Thus, we performed the regeneration by calcination at 400 °C in static air for 2 h in between the consecutive adsorption runs. Consecutive thermal regeneration experiment results for calcined Sep are shown in Figure B.9. Results demonstrated that regeneration via thermal treatment increased the adsorption capacity of calcined Sep and regeneration can be conducted for four consecutive runs. The increase in uptake capacity after a calcination

process had previously been reported also for different clay minerals based adsorbents [206], [207], and the increase in adsorption performance after calcination was ascribed to the removal of non-clay matter and the formation of anionic sites for binding MB cations [207]. MB removal efficiency (%) and uptake values for powderized Sep-AAM sample detected during the regeneration experiments are presented in Figure B.10. As it is seen from Figure B.10, there is a decrease in the MB uptake and removal efficiency values up to four cycles. The drop in performance within regeneration experiments can be related with the loss of adsorbent which is known to be one of the drawbacks of using powder formed adsorbents. The decrease in the amount of the adsorbent during regeneration causes an alteration in the adsorption kinetics and possibly responsible for the reduction in adsorption performance. Furthermore, as it was deduced from TGA results (Figure 3.4), Sep-AAM sample loses about 15 % of its own mass when temperature rises to 400 °C that is associated with the release of adsorbed and structural water. Another possible reason for the decrease in adsorption performance within regeneration experiments is related with the pH of the medium. The pH value of the MB solution at the end of the first adsorption experiment was recorded as 10 after 3.5 h of adsorption. This value dropped to 6.5 at the end of the last regeneration run, which is related with the decrease of the amount of alkalis in the solution medium. This situation causes a reduction in the attraction between cationic MB dye and negatively charged surface of Sep-AAM sample.

Figure B.11 shows the FTIR patterns of MB, powderized Sep-AAM before and after MB adsorption and thermally regenerated form of Sep-AAM. The FTIR spectrum of MB consists of distinct peaks located at 3342, 1592, 1464, 1379, 1322, 1145, and 876  $\text{cm}^{-1}$  which correspond to bonded -OH groups, stretching vibrations of C=N and C=C groups, CH<sub>2</sub> deformation vibration, C-N bonds, C-S bonds, and wagging vibration of C-H in aromatic ring, respectively [208]. Peaks located at 1635 and 987  $\text{cm}^{-1}$  for Sep-AAM before adsorption shifted to 1600 and 1005  $\text{cm}^{-1}$ , respectively (Figure B.11), upon MB adsorption indicating that C=O and C-O groups and nitrogen containing groups participate in the adsorption process [143], [208]. Newly occurred peaks at 1400  $\text{cm}^{-1}$  for MB adsorbed Sep-AAM indicate that -CH<sub>3</sub> and nitro groups of MB causes an interaction between MB and surface of the adsorbent [143]. It is known that the pH of the medium has an effect on the dissociation of functional groups and the surface charge of the adsorbent and the adsorbate [209]. For the system in this chapter, high pH values sourcing from the alkaline nature of the AAMs

increases the electrostatic interactions between functional groups of MB dye and Sep-AAM. Therefore, dissociation of functional groups on the surface at studied high pH values ( $\text{pH} \approx 10$ ) designated the interactions between the surface of the adsorbent and the adsorbate [210] causing a dissociative chemisorption mechanism as also supported by pseudo-second-order adsorption kinetics (Table 3.2).

However, considering the inevitable loss of the adsorbent during the regeneration which possibly altered the adsorption mechanism, regeneration experiments were further conducted by utilizing monolith form of the same Sep-AAM specimen. To establish a similar environment enabling a fair comparison between the powdered and monolith form of Sep-AAM, same MB amount per amount of adsorbent is used as a starting point of the regeneration test for monolith versions of Sep-AAM. The variation in the uptake performance within regeneration experiments reported in terms of percentage are presented in Figure B.12 for monolith Sep-AAM samples. Data showed that the performance was the same within 5%, for four cycles of regeneration tests. Obtaining a higher uptake stability during regeneration with monolith samples is thought to be mainly associated with the conservation of the adsorbent mass. Another parameter contributing to stability is about the surface area. Monolith samples have a lower surface area that is in interaction with MB solution than it is for powderized samples, therefore the pH of the solution is less affected by AAMs presence. After four cycles of regeneration, the pH value of the MB solution was recorded as 7.05, which is a slightly higher pH value than that is obtained for powder counterpart of the same sample obtained (6.55) at the end of fourth regeneration.

### 3.3.5. Adsorption Isotherm Model Studies and Thermodynamical Properties

For the sample with the highest adsorption capability, Sep-AAM, and for calcined Sep, data obtained at three different temperatures were fitted using Freundlich and Langmuir models. Freundlich and Langmuir parameters for adsorption of MB dye onto Sep-AAM and calcined Sep are shown in Table 3.4 and Table B.14, respectively. The  $R^2$  values presented in these tables were found to be greater than 0.98 for all of the samples for Langmuir isotherm, whereas  $R^2$  values were between 0.68 and 0.89 for Freundlich isotherm model. Langmuir model demonstrating a better fit for these two adsorbents with higher correlation coefficients offers a monolayer adsorption and the homogeneity of the surface in terms of

functional groups. Comparatively very high  $q_{max}$  values detected for Sep-AAM indicates that alkali activation of calcined Sep is an effective method that enhances the adsorption performance and surface of this novel material is homogeneous in terms of functional groups. This situation points out that, in theory, Sep-AAM has a finite adsorption capability upon MB dye and when a MB molecule occupies a site on the surface of Sep-AAM, this site becomes unavailable for adsorption [67]. The results obtained here for the Sep-AAM are in line with the previous findings, where MK-based counterparts of Sep-AAMs were found to display a better fit to Langmuir isotherm and pseudo-second-order adsorption kinetics for MB adsorption [23]. Similar results were also obtained for FA-based geopolymers upon MB adsorption [6]. The value of the Langmuir separation factor (Table B.15)  $R_L$ , calculated by using Equation (1.12), is found to be between 0 and 1 implying favourable adsorption within the studied experimental conditions.

Table 3.4. Langmuir and Freundlich isotherm constants for MB adsorption on Sep-AAM at different temperatures.

| Adsorbents     | Langmuir Model                 |                                    |       | Freundlich Model               |                             |       |
|----------------|--------------------------------|------------------------------------|-------|--------------------------------|-----------------------------|-------|
|                | $K_L$<br>(L mg <sup>-1</sup> ) | $q_{max}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $K_F$<br>(mg g <sup>-1</sup> ) | $n$<br>(g L <sup>-1</sup> ) | $R^2$ |
| Sep-AAM, 31 °C | 1.90                           | 86.21                              | 0.99  | 43.59                          | 3.95                        | 0.83  |
| Sep-AAM, 40 °C | 2.33                           | 89.29                              | 0.99  | 47.99                          | 4.25                        | 0.72  |
| Sep-AAM, 50 °C | 3.07                           | 103.31                             | 0.99  | 55.56                          | 3.93                        | 0.72  |

Next, a thermodynamics study by replacing the adsorption equilibrium constant ( $K_{ads}$ ) in Equation (3.2) with the multiplication of Langmuir equilibrium constant ( $K_L$ ) and molecular weight of the adsorbate (Equation (3.3)) was conducted. Van't Hoff plot of  $\ln(K_{ads})$  vs  $1/T$  was found to be linear (Figure B.13) and the increase in  $K_{ads}$  value with temperature increase was observed (Table 3.5 for Sep-AAM and Table B.16 for calcined Sep) as expected from an endothermic process. The endothermic behaviour of the adsorption process can also be seen from Figure 3.9.  $\Delta H^\circ$  value was found to be 8.68 and 20.6 kJ/mol, for calcined Sep and Sep-AAM, respectively and other thermodynamic parameters calculated from Van't Hoff plot are presented in Table 3.5 and Table B.16.

Negative  $\Delta G^\circ$  values indicate that adsorption onto calcined Sep and Sep-AAM is spontaneous. The results obtained in this part, shown in Table 3.5 indicate that  $\Delta G^\circ$  increases slightly with temperature and become more negative than -20 kJ/mol (-33.6 kJ/mol for 31 °C, -35.2 for 40 °C and -37.0 for 50 °C for Sep-AAM), implying that the interaction between Sep-AAM surface and MB possibly involves weak chemical bonding, consistent with our interpretation presented above [67].

For Sep-AAM,  $\Delta S^\circ$  was calculated as 178.44 J/mol.K from the Van't Hoff plot (Figure B.13b and Table 3.5). The positive value of  $\Delta S^\circ$  indicates the affinity between MB dye molecules and Sep-AAM demonstrating the randomness at solid-liquid interface, stability and irreversibility during adsorption [67, 211].  $\Delta S^\circ$  being greater than zero shows that number of degrees of freedom of adsorbed species is higher than it is for before adsorption. This situation shows that chemical adsorption takes place for MB molecule and Sep-AAM system causing a positive entropy change and endothermicity throughout adsorption [212]. The electron share and/or loss between the cationic portion of MB and negatively charged surface hydroxyl groups on the surface of Sep-AAM during adsorption is found to be main reasons for chemisorption together with dissociative adsorption in this system, as confirmed by FTIR analysis (Figure B.11). Calculated  $\Delta H^\circ$  value for calcined Sep is lower than it is for Sep-AAM. Even though adsorption kinetic results for calcined Sep better suited to pseudo-second-order adsorption model (Table B.10), which possibly indicates chemisorption mechanism takes place, this comparatively small enthalpy value for calcined Sep implies that physisorption mechanism dominates with minor contribution of chemisorption mechanism.

Table 3.5. Thermodynamic parameters for adsorption of MB onto Sep-AAM for 31, 40, and 50 °C.

| Sample  | $T$ (°C) | Thermodynamic parameters |                                    |                              |                              |                               |
|---------|----------|--------------------------|------------------------------------|------------------------------|------------------------------|-------------------------------|
|         |          | $K_L$ (L/mg)             | $K_{ads}$<br>(L/mol) $\times 10^4$ | $\Delta G^\circ$<br>(kJ/mol) | $\Delta H^\circ$<br>(kJ/mol) | $\Delta S^\circ$<br>(J/mol.K) |
| Sep-AAM | 31       | 1.90                     | 60.80                              | -33.63                       | 20.61                        | 178.44                        |
|         | 40       | 2.33                     | 74.53                              | -35.24                       |                              |                               |
|         | 50       | 3.07                     | 98.19                              | -37.02                       |                              |                               |

The comparison of maximum adsorption capacity of various AAMs towards MB dye removal is given in Table 3.6.

Table 3.6. MB adsorption capacity of various AAMs.

| Adsorbent                                                           | Form of the adsorbent | T (°C) | $q_e$ (mg g <sup>-1</sup> ) | Compressive strength (MPa)     | Ref.               |
|---------------------------------------------------------------------|-----------------------|--------|-----------------------------|--------------------------------|--------------------|
| Biomass FA-geopolymer                                               | Cylindrical monolith  | RT     | 15.4                        | 8                              | [19]               |
| Modified bauxite residue-based porous inorganic polymer             | Cylindrical monolith  | 25     | 17                          | 1                              | [80]               |
| MK-based geopolymer                                                 | Powder                | 40     | 39.2                        | -                              | [18]               |
| Foamed coal FA geopolymer                                           | Cubic monolith        | 25     | 50.7                        | 0.55                           | [196]              |
| MK-based geopolymer with Cu <sub>2</sub> O/TiO <sub>2</sub> content | Powder                | RT     | 19.7                        | -                              | [109]              |
| Graphene oxide added kaolin based geopolymer                        | Powder                | RT     | 4.7                         | -                              | [213]              |
| Potassium activated FA based geopolymer                             | Cubic monolith        | RT     | 84                          | 1.7                            | [63]               |
| Phosphoric acid activated MK-based geopolymer                       | Powder                | 28     | 3.35                        | -                              | [23]               |
| MK-based geopolymer with expanded glass aggregates                  | Monolith              | RT     | 4.9                         | 1.6                            | [21]               |
| MK-based geopolymer spheres                                         | Sphere                | RT     | 0.9                         | 3.3                            | [17]               |
| MK -based ice-templated geopolymer beads                            | Bead                  | RT     | 5                           | 5.9                            | [214]              |
| Geopolymer prepared from Jordanian kaolin and zeolitic tuff filler  | Powder                | RT     | 22.4                        | 21                             | [147]              |
| Sep-AAM                                                             | Powder                | 31     | 74.64                       | 40 (measured in monolith form) | <i>This thesis</i> |
| Sep-AAM                                                             | Powder                | 40     | 79.07                       | -                              | <i>This thesis</i> |
| Sep-AAM                                                             | Powder                | 50     | 99.92                       | -                              | <i>This thesis</i> |

\*RT: Room temperature.

This comparison indicates that the equilibrium experimental uptake values reported in this part for three different temperatures are higher than that of most of the AAMs in the

literature used for the purpose of MB adsorption. Table 3.6 further shows that even though AAMs used for adsorptive purposes synthesized from different raw materials were widely studied with focus mainly on their performance upon dye removal, their mechanical performance still needs improvement. Sep-AAM synthesized in this part provides a satisfactory option in terms of both adsorptive and mechanical performance. Superior adsorption properties of Sep-AAM is sourced from the presence of high amount of surface hydroxyl groups on the surface of this novel material as confirmed by zeta potential measurements.

Mechanical strength measurements suggested that these materials also offer a high compressive strength values making these materials a perfect promising candidate for further practical water remediation applications. Newly introduced adsorbent Sep-AAM in this part sets a benchmark value in terms of both adsorptive and mechanical properties and assures the successful utilization of alkali activated materials for adsorption related applications.

### **3.4. Concluding Remarks**

In this part of this thesis, calcined Sep without any additives has been used as a raw material for the first time for the synthesis of Sep-AAM to be employed for MB adsorption. It is evaluated as an adsorbent for MB removal and its adsorption properties were compared with calcined Sep. The influence of alkali activation in terms of MB adsorption and also on the corresponding microstructural properties and mechanical performance were investigated. Adsorption results revealed that Sep-AAM exhibits significantly higher adsorption capacity upon MB dye than calcined Sep itself, which was mainly related with the more negatively charged surface of Sep-AAM as confirmed by zeta potential measurements. The adsorption process was found to follow pseudo-second-order adsorption kinetics and Langmuir isotherm model demonstrated a better fit altogether revealing the dominant effect of chemisorption during the adsorption process. Calculation of thermodynamical parameters showed that the adsorption of MB onto Sep-AAM is a slightly endothermic process and the interaction between Sep-AAM surface and MB is due to weak chemical bonding. Adsorptive properties of Sep-AAM was found to enhance with temperature increase. Pseudo-second-order adsorption rate constant with respect to adsorbent dosage and activation energy of the adsorption of MB onto Sep-AAM were also

calculated. Regeneration results revealed that Sep-AAM can be regenerated up to four cycles for both in powder and monolith forms with monolith forms showing higher regeneration capability. Data revealed that Sep-AAM are sustainable and innovative options as adsorbents for MB removal with an MB uptake value of  $74.64 \text{ mg g}^{-1}$  in 3.5 hours that is further enhanced to  $99.92 \text{ mg g}^{-1}$  with an increase in temperature to  $50^\circ\text{C}$  due to endothermic nature of the adsorption process. The remarkable compressive strength value of 40 MPa shows that these materials may have a wide application area in the construction industry.



## 4. SEPIOLITE- AND METAKAOLIN-BASED ALKALI ACTIVATED MONOLITHS FOR METHYLENE BLUE REMOVAL: A COMPARATIVE STUDY

### 4.1. Introduction

Existing literature on alkali activated materials (AAMs) for adsorptive purposes utilize powder formed AAMs. However, for many practical applications monolith formed adsorbents with sufficient mechanical strength can offer opportunities such as ease of regeneration, suitability for applications in water storage and water purification, and in packed bed reactors. Monolithic AAMs have been utilized for MB dye removal [19, 21], cesium removal from a nuclear waste [215], as a thermal insulator [216], and also in heat exchangers [217]. Some recent studies focused on monolith formed AAMs [63, 215] showed that adsorption performance of these materials can be enhanced by inducing porosity via several pore foaming agents including hydrogen peroxide ( $H_2O_2$ ) [19, 63, 215, 216, 218], aluminum powder [80], sodium dodecyl [22], and glass aggregates [21]. One of the best well-known and studied blowing agents is  $H_2O_2$ . Hydrogen peroxide is thermodynamically unstable in alkaline environment and can easily decompose into water and oxygen. As a result of this reaction and due to oxygen formation, there occurs an increase in the volume of the materials causing an increase in the macropores [218]. However, most of these foamy and monolith formed AAMs display lower levels of mechanical strength compared to their counterparts with no pore foaming agent content. Even though adding a foaming material increases the adsorption ability of these materials, they have lower mechanical performance, limiting their utilization in practical applications.

A recent study showed that, magnesium silicate rich sepiolite (Sep) mineral; an uncommon raw material for AAM synthesis, can successively be used as a powder formed adsorbent for MB dye adsorption with high adsorption performance and Sep-based AAMs (Sep-AAM) in monolith form display high mechanical performance [97]. The adsorption performance of Sep-AAM's in monolith form, on the other hand, has not been investigated yet. Furthermore, it has been shown that inclusion of foaming agents in classical geopolymer

systems could modify porosity and adsorption characteristics of solid adsorbents [19, 219]. From this point forth, this part of this thesis aims to investigate the adsorption performance of cubic monolith formed Sep-AAMs with different porosity levels obtained by varying  $\text{H}_2\text{O}_2$  content between 0 and 8 wt%. Metakaolin (MK) counterparts of Sep-AAMs, MK-based geopolymers (MKGP), were also produced to represent traditional aluminosilicate geopolymer systems for comparing adsorption characteristics. Mechanical performance of these materials are investigated and structure-performance relationships are presented. The effect of raw material selection and porosity of AAMs on MB adsorption performance are investigated. Hydrogen peroxide was used as a foaming agent. Adsorption kinetics of monolith formed adsorbents synthesized based on Sep and MK is also investigated to establish an understanding on the adsorption mechanism. The manuscript form of this chapter is being prepared to be submitted for publication.

## 4.2. Experimental Methods

### 4.2.1. Materials

Raw materials that are used for AAM synthesis in this study are Sep and MK. Sep is utilized as a magnesium silicate source, whereas MK is evaluated as an aluminosilicate source. Sep mineral was kindly supplied by Dolsan Mining, Eskişehir-Turkey. Calcination procedure was conducted before the alkali activation process since calcination is known to have a positive effect on solubility of aluminosilicate raw materials [112] and magnesium silicate raw materials [77]. Calcined Sep was obtained by calcining Sep mineral at 750 °C for one hour before utilizing in alkali activation (2.8 g/cm<sup>3</sup>). MK, on the other hand, was obtained by the calcination of kaolinite mineral at 700 °C for 1 h (2.5 g/cm<sup>3</sup>). Sodium silicate ( $\text{Na}_2\text{Si}_3\text{O}_7$ ) solution (28 wt% of  $\text{SiO}_2$ , 9 wt% of  $\text{Na}_2\text{O}$ , 63 wt% of  $\text{H}_2\text{O}$ , Merck, 1.35 g/cm<sup>3</sup>) and sodium hydroxide pellets ( $\text{NaOH}$ , Merck, 2.13 g/cm<sup>3</sup>) was used together as an alkali activator.  $\text{H}_2\text{O}_2$  solution (30%, Merck, 1.11 g/cm<sup>3</sup>) was used as a blowing agent. MB hydrate (Sigma-Aldrich, purity > 97%, molecular weight 319.85 g/mol) was used as a model adsorbate. Chemical compositions of calcined Sep and MK are provided in Table C.1 (in the Appendix C).

#### 4.2.2. Synthesis of AAMs

Tables C.2 and C.3 show the amounts of raw materials (in g) utilized during the synthesis of Sep-AAMs and MKGPs, respectively, together with molar Si/Mg, Na/Mg ratios of Sep-AAMs and molar Si/Al and Na/Al ratios of MKGPs with different H<sub>2</sub>O<sub>2</sub> contents. These molar ratios belong to initial gel compositions of the synthesized material. Na/Mg ratio of Sep-AAMs and Na/Al ratio of MKGPs were kept constant at 1.2. Molar Si/Mg ratio of Sep-AAMs and molar Si/Al ratios of MKGPs, on the other hand, were kept constant at values of 3 and 2, respectively, as previous mechanical performance results revealed that highest compressive strength values are obtained within these ratios [38, 97]. To arrange these molar ratios in initial gel compositions, chemical compositions of raw materials shown in Table C.1 was employed and required amount of NaOH and Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution was adjusted simply by calculating the amount needed to provide desired ratios. As stated previously, Sep was used as a magnesium silicate source and MK was used as an aluminosilicate source in this study. Na<sub>2</sub>Si<sub>3</sub>O<sub>7</sub> solution and sodium hydroxide pellets were used as alkali activators. For the synthesis of Sep-AAMs, powdered and sieved (#70 mesh sieve, 200 µm) calcined Sep was mixed thoroughly with alkali activators. Previously determined amounts of H<sub>2</sub>O<sub>2</sub> solution were added to the alkali activator solution prior to mixing to ensure different levels of porosity. After mixing solid raw materials with H<sub>2</sub>O<sub>2</sub> added alkali activator solutions, samples were transferred into 10 mm × 10 mm × 10 mm silicon molds and kept at 40 °C for 24 h followed by aging at room temperature for a week before being used as adsorbents for MB adsorption. Identical procedure was followed for the synthesis of MKGPs, however, unlike Sep-AAMs, thermal treatment was conducted at 60 °C, that is chosen based on our preliminary experimental results, for 24 h which is followed by aging at room temperature for a week. Details of the mixture composition of Sep-AAMs and MKGPs are displayed in Table C.2 and C.3, respectively. Based on the H<sub>2</sub>O<sub>2</sub> amounts and weight % given in these tables, H<sub>2</sub>O<sub>2</sub> content in synthesized samples are 0, 0.5, 1, 2, 3, 6, and 8 wt% for Sep-AAMs and 0, 0.5, and 1 wt% for MKGPs. These H<sub>2</sub>O<sub>2</sub> amounts in AAMs are adjusted to ensure the integrity of the synthesized material at the end of thermal treatment procedure. Displaying a certain level of integrity and therefore having a comparable mechanical performance are important parameters that directly affect the practical usability of these materials. Further addition of H<sub>2</sub>O<sub>2</sub> caused a loss of the integrity of the samples so that mechanical performance tests could not be applied.

#### 4.2.3. Materials Characterization

Elemental composition of raw materials and AAMs were carried out XRF spectrometer. XRD patterns of all the samples were conducted by a Bruker D8 Discover Diffraction system with a Cu  $K\alpha_1$  radiation source employing a wavelength of 1.5418 Å. FTIR spectroscopy was conducted by a Bruker Alpha II with ATR cell, in absorption mode and at a resolution of 2  $\text{cm}^{-1}$  in a spectral region of 400-2000  $\text{cm}^{-1}$ .

To determine BET surface area, pore size, and pore volume values of the samples a Micromeritics ASAP 2020–Physisorption Analyzer was utilized. Approximately Pore size distribution of the samples was determined by BJH model, by using adsorption isotherm. Total porosity and bulk density of the materials were measured by using mercury intrusion porosimetry, MIP (Micromeritics Autopore IV Mercury Porosimeter). Morphology and microstructure of the materials were analyzed by using a Zeiss Ultra Plus FE-SEM with a secondary electron detector. To perform compressive strength measurements, a MTS model servo-hydraulic test machine with 500 kN capacity and a 0.01 mm per second loading rate was used. Mechanical performance of the specimens (10 mm  $\times$  10 mm  $\times$  10 mm in size) were implemented after a resting period of 4 weeks at ambient temperature. Malvern Zetasizer Nano ZS was used for recording the zeta potential of the samples and pH of the solutions were measured by utilizing a lab pH meter (VTW, 7110).

#### 4.2.4. MB Adsorption Tests

To understand the adsorption performance of monoliths (cubic bodies with a size of 1  $\text{cm}^3$ ), each sample was immersed into 100 ml of MB solutions with different previously determined concentrations (30-110  $\text{mg L}^{-1}$ ). These solutions were magnetically stirred at 300 rpm to reach an equilibrium and aliquots from these solutions are syringed at definite time intervals. Syringed samples absorbance values at  $\lambda = 664 \text{ nm}$  were measured and analyzed by using a Flame-S-UV-Vis-ES spectrometer (Ocean Optics, USA).

Removal efficiency (%) was calculated according to Equation (1.1). The amount of MB adsorbed on synthesized adsorbents were calculated by using Equation (1.2). Data collected under dark conditions were fitted by using pseudo-first- (Equation (1.3)) and

pseudo-second-order (Equation (1.4)) adsorption kinetic models. Langmuir and Freundlich adsorption isotherm models were used to fit the equilibrium data of the specimens.

### 4.3. Results and Discussion

#### 4.3.1. Morphological, Bulk Microstructure, and Mechanical Properties

BET surface area, average pore size, and pore volume of raw materials and synthesized samples are shown in Table C.4 and Table 4.1, respectively. As it is evident from these tables, both for Sep and MK -based AAMs, alkali activation caused a significant decrease in surface area values followed by a parallel decrease in pore volume values. This reduction is related with the formation of a denser structure with alkali activation and is in accordance with the previous findings [39, 97].

Raw material selection, processing conditions, and compositional factors such as type of the alkali activator and concentration of the alkali activator have a huge effect on surface properties and mechanical performance of AAMs [4, 168]. In this respect, both the processing conditions (such as curing time and curing temperature selection) and initial molar Si/Mg, Na/Mg ratios for Sep-AAMs, and Si/Al and Na/Al ratios for MKGPs were arranged to obtain an AAM with optimum properties. Alkali activation is a time-dependent process and therefore involves structural reorganization and densification with time [97]. As a result of higher degree of polycondensation occurring during series of reactions, it is common for AAMs to display a lower surface area compared to their origin raw materials [168].

Similar results of obtaining a lower surface area and pore volume upon alkali activation, were also reported for FA and Sep-based AAMs [97, 169]. As stated previously, adding  $H_2O_2$  to an alkaline environment causes formation of oxygen and water, which also changes the porosity of the material. In this respect, as a result of this reaction by adding  $H_2O_2$  into the paste, the water content of the initial gel composition is also affected which is known to be an important parameter influencing the final properties of the AAMs [4]. Comparatively lower surface area determined for  $H_2O_2$  added samples (Table 4.1) therefore might be associated with the shrinkage that have occurred by the evaporation of increased

amount of water molecules introduced by H<sub>2</sub>O<sub>2</sub> addition during the curing procedure (40 °C for 24 h for Sep-AAMs, and 60 °C for 24 h for MKGPs).

Table 4.1. BET surface area, average pore size, and pore volume of samples.

| <b>Sample</b>                              | <b>Surface area<br/>(m<sup>2</sup>/g)</b> | <b>Pore volume<br/>(cm<sup>3</sup>/g)</b> | <b>Pore size<br/>(Å)</b> |
|--------------------------------------------|-------------------------------------------|-------------------------------------------|--------------------------|
| Sep-AAM                                    | 1.5                                       | 0.006                                     | 519.3                    |
| 0.5%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 2.4                                       | 0.002                                     | 636.4                    |
| 1%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.6                                       | 0.004                                     | 1176.8                   |
| 2%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 2.43                                      | 0.004                                     | 672.3                    |
| 3%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.6                                       | 0.003                                     | 619.9                    |
| 6%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.9                                       | 0.003                                     | 558.2                    |
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 4.6                                       | 0.005                                     | 156.2                    |
| MKGP                                       | 29.7                                      | 0.170                                     | 269.8                    |
| 0.5%H <sub>2</sub> O <sub>2</sub> -MKGP    | 2.6                                       | 0.028                                     | 563.2                    |
| 1%H <sub>2</sub> O <sub>2</sub> -MKGP      | 3.4                                       | 0.034                                     | 689.6                    |

However, mercury intrusion porosimetry results presented in Table 4.2 designate that increase in H<sub>2</sub>O<sub>2</sub> content cause a significant increase in total porosity (%) and total intrusion volume values with a concomitant decrease in bulk density of each sample. The increase in total porosity (%) with H<sub>2</sub>O<sub>2</sub> addition is more profound for MK-based samples, than they are for Sep-based samples, showing that binder nature has a significant effect on the behaviour of material's porosity upon H<sub>2</sub>O<sub>2</sub> addition.

Table 4.2. Bulk density, total volume, and total porosity of samples.

| <b>Sample</b>                              | <b>Bulk density<br/>(g/cm<sup>3</sup>)</b> | <b>Total volume<br/>(cm<sup>3</sup>/g)</b> | <b>Total porosity<br/>(%)</b> |
|--------------------------------------------|--------------------------------------------|--------------------------------------------|-------------------------------|
| Sep-AAM                                    | 1.92                                       | 0.068                                      | 13.12                         |
| 0.5%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 1.65                                       | 0.147                                      | 24.36                         |
| 1%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.59                                       | 0.174                                      | 27.67                         |
| 2%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.39                                       | 0.252                                      | 35.02                         |
| 3%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.37                                       | 0.266                                      | 36.35                         |
| 6%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.32                                       | 0.296                                      | 39.03                         |
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 1.26                                       | 0.320                                      | 40.48                         |
| MKGP                                       | 1.42                                       | 0.224                                      | 31.88                         |
| 0.5%H <sub>2</sub> O <sub>2</sub> -MKGP    | 0.82                                       | 0.606                                      | 49.58                         |
| 1%H <sub>2</sub> O <sub>2</sub> -MKGP      | 0.69                                       | 0.921                                      | 63.54                         |

Figure C.1 shows the XRD patterns of calcined Sep (750 °C, 1 h) and MK over a 2θ range between 10 to 90°, which are main raw materials that are alkali activated to obtain monolith samples with different porosity levels. As it is evident from Figure C.1a, for calcined Sep, main crystalline phases are calcium magnesium silicate and periclasite which were detected at 34°, 43° and 62°, respectively. For MK (Figure C.1b), feature positioned at 27° is assigned to quartz phase. XRD patterns of Sep-AAMs and MKGPs with different H<sub>2</sub>O<sub>2</sub> contents are shown in Figure 4.1. Data presented in Figure 4.1 and Figure C.1 imply that XRD patterns of calcined Sep and MK were transformed into an amorphous form displaying a special broad feature positioned at 28° with different crystalline components. This special broad feature observed for both Sep-AAMs and MKGPs indicates the formation of an AAM with an amorphous structure [25, 38]. Similar patterns were reported for geopolymers synthesized from different sources including volcanic ash, RM and MK [97, 180]. Decrease observed in the amount of crystalline phases upon alkali activation for both Sep-AAM and MKGP demonstrates the ability of dissolution of raw materials in an alkaline environment. According to Figure 4.1a, crystalline phases observed for Sep-AAMs are

muscovite (M,  $(\text{Na}_2\text{K}_2(\text{Al}_{12}\text{Si}_{12}\text{O}_{40}(\text{OH})_8)$ , quartz (Q,  $\text{SiO}_2$ ), anorthite (A,  $\text{CaAl}_2\text{Si}_2\text{O}_6$ ), merwinite (Mer,  $\text{Ca}_3\text{Mg}(\text{SiO}_4)$ , and periclasite (P,  $\text{MgO}$ ), and very similar patterns were detected for Sep-AAMs with different  $\text{H}_2\text{O}_2$  contents. Based on Figure 4.1b, on the other hand, for MKGPs main crystalline component is quartz, which is in accordance with the current literature [38, 220]. As deduced from this figure, the addition of  $\text{H}_2\text{O}_2$  into Sep-AAM and MKGP does not cause an alteration in the crystalline structure of the end product. Modification of geopolymers by addition of  $\text{H}_2\text{O}_2$  reported in the existing literature did not also induced a change in the mineralogical composition of FA and MK-based geopolymers [19, 219, 221].

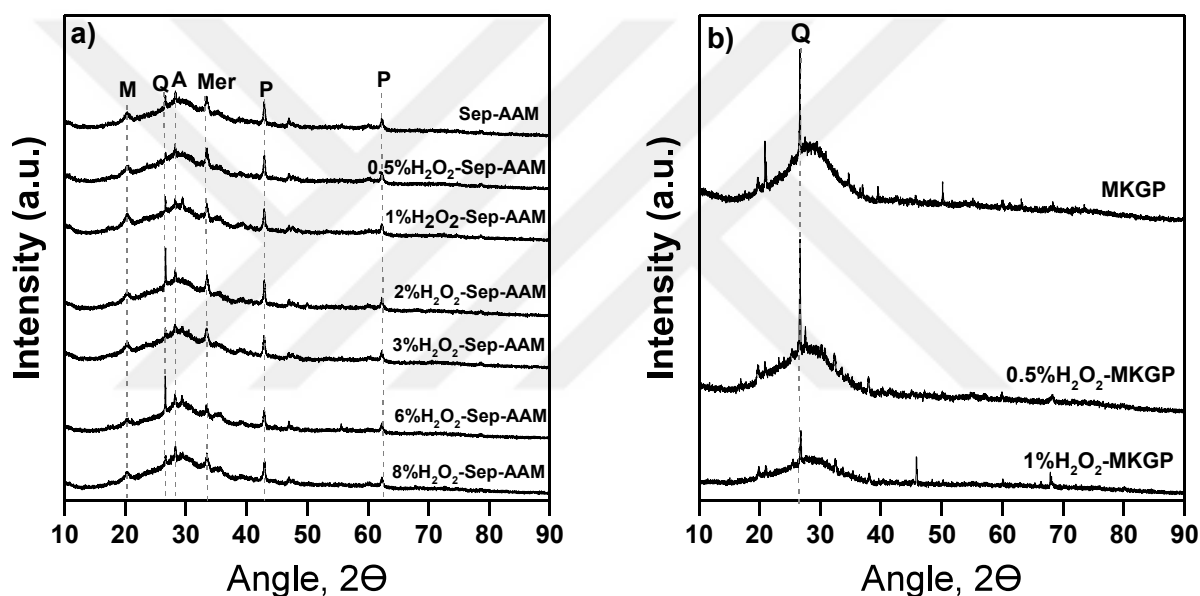


Figure 4.1. XRD patterns of a) Sep-AAMs with different  $\text{H}_2\text{O}_2$  content, and b) MKGPs with different  $\text{H}_2\text{O}_2$  content.

FTIR spectra of raw materials calcined Sep and MK are provided in Figure C.2. For calcined Sep, two major contributions located at  $1022$  and  $449\text{ cm}^{-1}$  are assigned to Si–O–Si vibrations and Si–O–Mg bonds, respectively [173, 177]. Two shoulders observed at  $950$  and  $876\text{ cm}^{-1}$  are due to stretching vibrations of Si–O bonds [177] and Si–OH bending vibrations [112], respectively. Very minor contribution detected at  $682\text{ cm}^{-1}$  is related with the presence of asymmetric stretching vibrations of Si–O–Si bonds [112]. For MK (Figure C.2b), the most intense feature located at  $1063\text{ cm}^{-1}$  is assigned to stretching vibrations of Si–O bonds of the amorphous MK structure, whereas the contribution detected at  $797\text{ cm}^{-1}$  is related with the vibrations of  $\text{AlO}_4$  tetrahedra in MK [38, 110]. Feature observed at the low frequency region

at  $442\text{ cm}^{-1}$  is most possibly sourced from bending vibration of Si–O/Al–O bonds [113]. Figure 4.2 shows the FTIR spectra of Sep-AAM and MK-based geopolymers (MKGP) having different  $\text{H}_2\text{O}_2$  content. For both Sep-AAMs and MKGPs, broad characteristic feature located between  $900\text{--}1200\text{ cm}^{-1}$  indicates the formation of a geopolymeric network [25]. This major contribution refers to the structural transformation as a result of dissolution of raw materials in an alkali activator. Main feature located at  $1022$  and  $1063\text{ cm}^{-1}$  for calcined Sep and MK, respectively, had shifted to  $986\text{ cm}^{-1}$  for Sep-AAMs and  $975\text{ cm}^{-1}$  for MKGPs as a result of alkali activation. This shift to lower wavenumbers as a consequence of alkali activation detected for Sep-AAM and MKGP, refer to the formation of a tridimensional geopolymeric framework with silicon and magnesium tetrahedra for Sep-AAMs, and formation of a framework with silicon and aluminum tetrahedra for MKGPs [97, 180]. Features positioned at  $1639$  and  $1648\text{ cm}^{-1}$  for Sep-AAMs and MKGPs, respectively, denote to bending vibrations (H–O–H) and stretching (–OH) vibrations of water molecules [114, 160]. Minor shoulder located at about  $873\text{--}876\text{ cm}^{-1}$  contributes to the Si–OH bending vibrations [112].

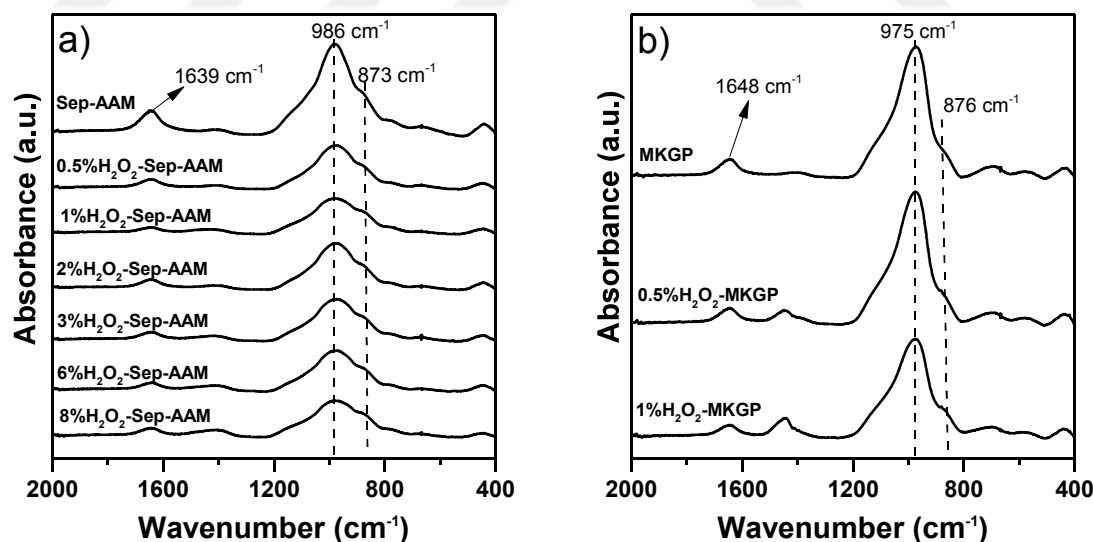


Figure 4.2. FTIR spectra of a) Sep-AAMs with different  $\text{H}_2\text{O}_2$  content, and b) MKGPs with different  $\text{H}_2\text{O}_2$  content.

Figure C.3 shows SEM images of calcined Sep, MK, and synthesized AAMs. Sep and MK-based AAMs with no  $\text{H}_2\text{O}_2$  content and their highest  $\text{H}_2\text{O}_2$  content counterparts

synthesized in this study together with 1 wt%  $\text{H}_2\text{O}_2$  content for comparison are provided in Figure 4.3.

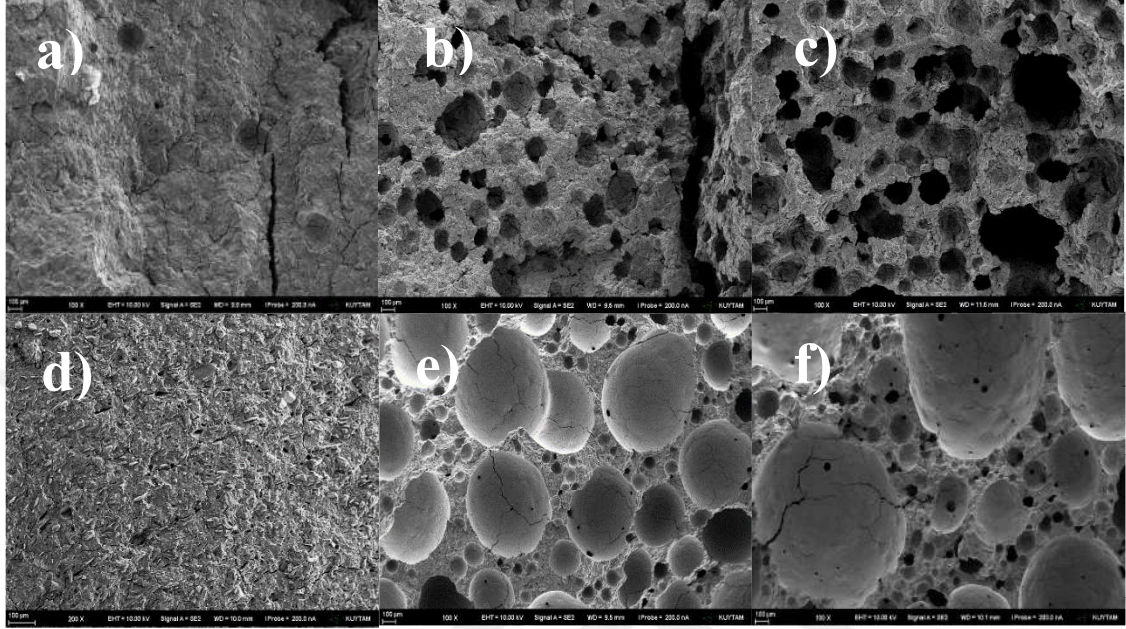


Figure 4.3. SEM images of materials at a magnification of 100 $\times$ : a) Sep-AAM, b) 1% $\text{H}_2\text{O}_2$ -Sep-AAM, c) 8% $\text{H}_2\text{O}_2$ -Sep-AAM, d) MKGP, e) 0.5% $\text{H}_2\text{O}_2$ -MKGP, and f) 1% $\text{H}_2\text{O}_2$ -MKGP.

As it is seen from both of these figures, there is a formation of a denser structure with alkali activation and this situation causes satisfactory mechanical performance results both for MK and Sep based AAMs as presented in Figure 4.4. This figure shows the results of three repetitive compressive strength measurements employed on synthesized materials in this study. As seen from Figure 4.4, both for Sep-AAMs and MKGPs with distinct  $\text{H}_2\text{O}_2$  content, compressive strength values show a decreasing trend upon  $\text{H}_2\text{O}_2$  addition and results are presented in Table C.5. Increase in porosity levels introduced by  $\text{H}_2\text{O}_2$  addition resulted a consistent decrease in mechanical performance values as expected. This decrease is more profound for MKGP samples, since even 1 wt%  $\text{H}_2\text{O}_2$  addition caused 13.3-fold decrease in compressive strength values from 28 to 2.1 MPa. For Sep-AAMs on the other hand, 8 wt%  $\text{H}_2\text{O}_2$  addition caused 5.7-fold decrease in compressive strength value, corresponding to a reduction from 37 to 6.5 MPa. These reduction levels in mechanical performance of these materials are correlated with the changes in the porosity levels that are observed for Sep-AAMs and MKGPs with distinct  $\text{H}_2\text{O}_2$  contents. As stated previously, MKGP is more

sensitive to  $\text{H}_2\text{O}_2$  addition and introduction of  $\text{H}_2\text{O}_2$  into MKGP system causes a comparatively higher porosity levels compared to Sep-AAMs that are accompanied with a decrease in bulk densities of these samples (Table 4.2).

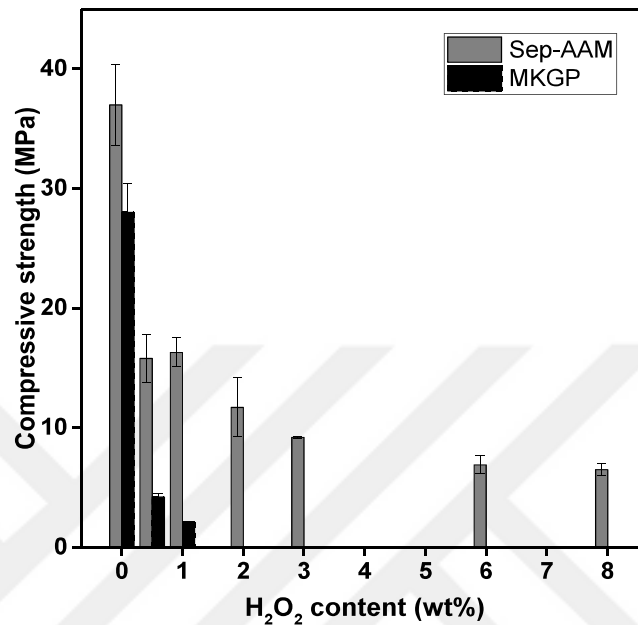


Figure 4.4. Compressive strength of the Sep-AAM and MKGP samples with different  $\text{H}_2\text{O}_2$  content (Cured for four weeks).

As mentioned earlier, several factors including raw material selection, gel formation, molar Si/Al ratios, and processing conditions have a huge effect on the mechanical performance of the final product [4, 222]. Existing literature on the mechanical performance of AAMs with different foaming agent content revealed that all different types of foaming agents, such as glass aggregates,  $\text{H}_2\text{O}_2$ , aluminum powder, cause a reduction in mechanical performance [19, 21, 80]. For instance, it was reported by Novais et al. that for FA-based geopolymers,  $\text{H}_2\text{O}_2$  content increase from 0.11 to 0.57 wt% resulted a decrease in compressive strength from 7.9 MPa to 180 kPa [19]. From this respect, compressive strength value in the order of 6.5 MPa for 8% $\text{H}_2\text{O}_2$ -Sep-AAM sample and 2.1 MPa for 1% $\text{H}_2\text{O}_2$ -MKGP sample are very promising and show that these materials can be utilized for different practical applications and may offer a high regeneration capability.

### 4.3.2. MB Adsorption Tests

As stated earlier, negatively charged surface hydroxyl groups provide a suitable environment for the attraction of cationic MB molecules. The presence of these functional groups was verified by FTIR analysis both for MK- and Sep-based samples (Figure 4.2). To be able to understand the change in the nature of surface charge on adsorption capacity for the samples with highest porosity levels (8% $\text{H}_2\text{O}_2$ -Sep-AAM and 1% $\text{H}_2\text{O}_2$ -MKGP), pH of the MB solution was measured at initial ( $t=0$ ) and equilibrium conditions ( $t=24$  h). The initial pH of the 30  $\text{mg L}^{-1}$  MB solution was recorded as 7. At the end of 24 hours of adsorption experiment, pH of the MB solution was measured as 10.6 and 10.1 for 8% $\text{H}_2\text{O}_2$ -Sep-AAM and 1% $\text{H}_2\text{O}_2$ -MKGP, respectively. Zeta potential evolution for these two samples as a function of pH was recorded and presented in Figure C.4. Results suggest that zeta potentials of 8% $\text{H}_2\text{O}_2$ -Sep-AAM and 1% $\text{H}_2\text{O}_2$ -MKGP are negative for all of the studied pH values (pH = 2-12). Zeta potential being negative for the equilibrium pH values (pH = 10.1-10.6) implies that the adsorption occurs as a result of electrostatic interaction [97, 192] between the adsorbate and the adsorbent.

#### 4.3.2.1. Effect of Contact Time, $C_0 = 70 \text{ mg L}^{-1}$

The effect of contact time that is required to obtain adsorption-desorption equilibrium was determined for all of the synthesized porous AAMs by setting the initial concentration of MB solution to 70  $\text{mg L}^{-1}$ .

Changes observed in the uptake values with time are shown in Figure 4.5 both for Sep-AAMs and MKGPs having different porosity levels. Patterns presented in this figure demonstrate that a similar exponential increase in MB uptake values over time is detected for all samples and an adsorption-desorption equilibrium is reached within 24 h. Same experiments were also conducted for different initial MB concentrations ( $C_0 = 30\text{-}110 \text{ mg L}^{-1}$ ) and results showed that equilibrium time of 24 h is sufficient enough both for the highest and the lowest initial MB concentration values.

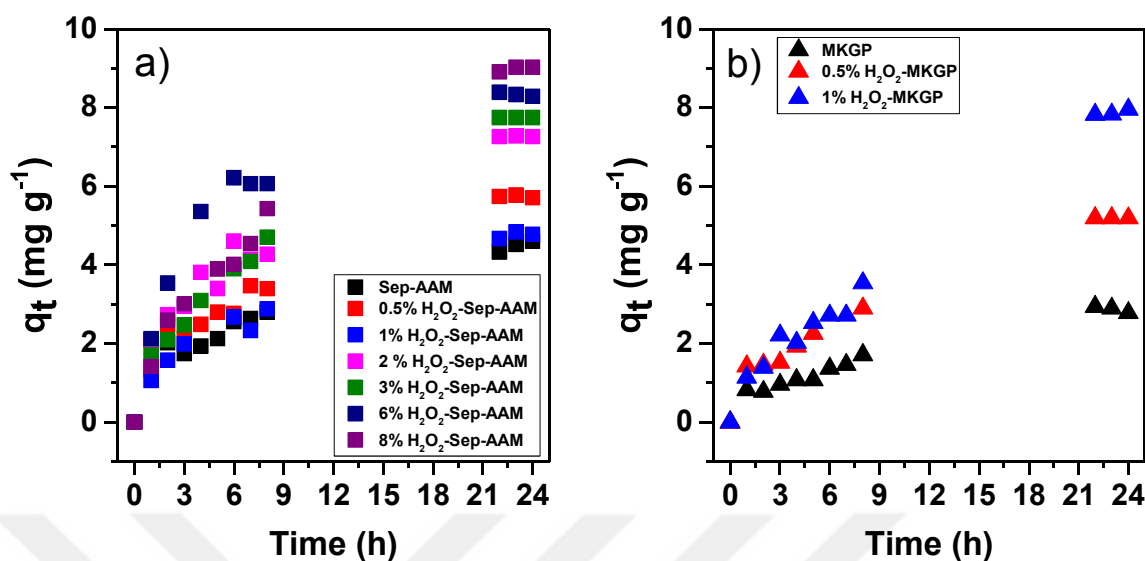


Figure 4.5. The effect of contact time on uptake of a) Sep-AAMs and b) MKGPs with different H<sub>2</sub>O<sub>2</sub> content.

#### 4.3.2.2. Effect of Initial MB Concentration

Figure 4.6 displays the change of uptake capacity with initial MB concentration for Sep-AAM, 8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM, MKGP, and 1% H<sub>2</sub>O<sub>2</sub>-MKGP. For the sake of brevity, only the samples with no H<sub>2</sub>O<sub>2</sub> content (Sep-AAM and MKGP), and highest H<sub>2</sub>O<sub>2</sub> content (8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM and 1% H<sub>2</sub>O<sub>2</sub>-MKGP) are included in this figure. As it is evident from this figure, both for Sep-AAM and MKGP samples, uptake capacity enhances with an increase in initial MB concentration and adding H<sub>2</sub>O<sub>2</sub> have a positive effect on the adsorption performance. Within the studied highest initial MB concentration of 110 mg L<sup>-1</sup>, uptake values at the end of 24 hours for Sep-AAM and 8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM are 6.6 and 10.3 mg g<sup>-1</sup>, respectively. For MK-based counterparts on the other hand, uptake values reach to 4.3 and 7.8 mg g<sup>-1</sup> for MKGP and 1% H<sub>2</sub>O<sub>2</sub>-MKGP, respectively with an initial MB concentration of 110 mg L<sup>-1</sup>. When the initial MB concentration was 110 mg L<sup>-1</sup>, the pH of the solution at the end of 24 hours of adsorption experiments had reached to 8.3 and 7.9 for 8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM and 1% H<sub>2</sub>O<sub>2</sub>-MKGP, respectively. In a similar manner, when the initial MB concentration was 30 mg L<sup>-1</sup>, the pH of the solution had reached to 10.6 and 10.1 for 8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM and 1% H<sub>2</sub>O<sub>2</sub>-MKGP, respectively.

The effect of initial MB concentration on uptake performance and removal efficiency for all of the synthesized materials are provided in Table C.6. For the sample with the highest  $\text{H}_2\text{O}_2$  content of Sep-AAM samples, namely 8% $\text{H}_2\text{O}_2$ -Sep-AAM, 3.67-fold increase in initial MB concentration caused 2.34-fold enhancement in the uptake value. In a similar manner, for 1% $\text{H}_2\text{O}_2$ -MKGP, same amount of increase in initial MB concentration resulted a 1.56-fold increase in uptake capacity. A concomitant decrease in removal efficiency (%) is detected for all of the samples (Figure 4.6 and Table C.6) upon an increase in MB concentration. This situation points out that at lower initial MB concentrations, the number of active sites available per adsorbent is higher, explaining the favored interaction between adsorbents and MB dye at low concentrations. However, with the increase in MB concentration, available active sites are occupied with MB molecules and hinders the further adsorption of MB. This situation is in accordance with the results reported for FA-based geopolymers, MK-based geopolymers [19], and powder-formed Sep-based geopolymers with no  $\text{H}_2\text{O}_2$  content [97].

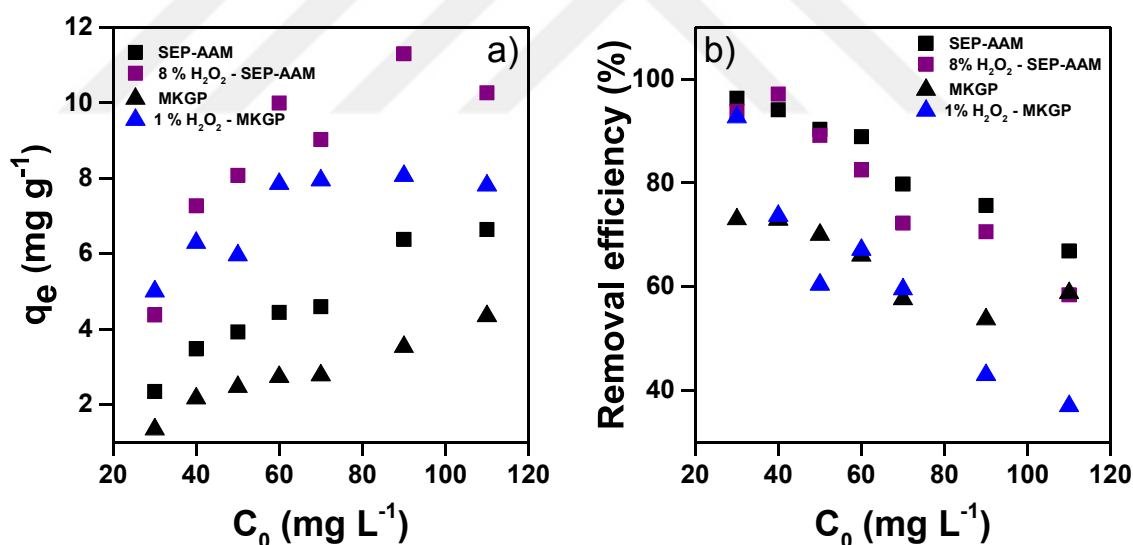


Figure 4.6. Effect of initial MB concentration on a) uptake ( $q_e$ ) and b) removal efficiency (%) of MB for Sep-AAM, 8% $\text{H}_2\text{O}_2$ -Sep-AAM, MKGP, and 1% $\text{H}_2\text{O}_2$ -MKGP.

#### 4.3.2.3. Adsorption Kinetics Modeling and Mechanism

Adsorption data were further studied by fitting experimental data to pseudo-first- and pseudo-second-order kinetic models, as presented in Table 4.3 for an initial MB concentration of  $70 \text{ mg L}^{-1}$ , and in Table C.7 for all of the studied initial MB concentrations.

Obtaining higher compatibility for pseudo-second-order kinetic model is mostly attributed to rate limiting step being the chemisorption process [21, 25], whereas presence of a higher correlation for pseudo-first-order kinetic model refers to existence of physisorption process [25, 223].

Table 4.3. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto synthesized AAMs. (*Contact time* = 24 h,  $C_0 = 70 \text{ mg L}^{-1}$ ).

| Adsorbent                            | $q_{e,exp}$<br>( $\text{mg g}^{-1}$ ) | Pseudo-first-order adsorption kinetics<br>( $C_0 = 70 \text{ mg L}^{-1}$ ) |                                       |       | Pseudo-second-order adsorption kinetics<br>( $C_0 = 70 \text{ mg L}^{-1}$ ) |                                       |       | Removal<br>(%) |
|--------------------------------------|---------------------------------------|----------------------------------------------------------------------------|---------------------------------------|-------|-----------------------------------------------------------------------------|---------------------------------------|-------|----------------|
|                                      |                                       | $k_{1,ads,app}$<br>( $\text{min}^{-1}$ )                                   | $q_{e,cal}$<br>( $\text{mg g}^{-1}$ ) | $R^2$ | $k_{2,ads,app}$<br>( $\text{g mg}^{-1} \text{ min}^{-1}$ )                  | $q_{e,cal}$<br>( $\text{mg g}^{-1}$ ) | $R^2$ |                |
| Sep-AAM                              | 4.59                                  | $2.5 \times 10^{-3}$                                                       | 4.44                                  | 0.93  | $6.8 \times 10^{-4}$                                                        | 5.22                                  | 0.93  | 79.8           |
| 0.5% $\text{H}_2\text{O}_2$ -Sep-AAM | 5.70                                  | $1.7 \times 10^{-3}$                                                       | 4.86                                  | 0.87  | $4.3 \times 10^{-4}$                                                        | 6.90                                  | 0.93  | 76.98          |
| 1% $\text{H}_2\text{O}_2$ -Sep-AAM   | 4.77                                  | $2.8 \times 10^{-3}$                                                       | 5.24                                  | 0.96  | $5.6 \times 10^{-4}$                                                        | 5.67                                  | 0.93  | 65.74          |
| 2% $\text{H}_2\text{O}_2$ -Sep-AAM   | 7.26                                  | $1.7 \times 10^{-3}$                                                       | 5.98                                  | 0.87  | $4.2 \times 10^{-4}$                                                        | 8.31                                  | 0.93  | 82.75          |
| 3% $\text{H}_2\text{O}_2$ -Sep-AAM   | 7.41                                  | $1.9 \times 10^{-3}$                                                       | 8.85                                  | 0.98  | $2.7 \times 10^{-4}$                                                        | 9.49                                  | 0.92  | 73.67          |
| 6% $\text{H}_2\text{O}_2$ -Sep-AAM   | 8.28                                  | $2.3 \times 10^{-3}$                                                       | 6.24                                  | 0.96  | $7 \times 10^{-4}$                                                          | 9.06                                  | 0.99  | 77.45          |
| 8% $\text{H}_2\text{O}_2$ -Sep-AAM   | 9.02                                  | $3.3 \times 10^{-3}$                                                       | 11.94                                 | 0.95  | $2.2 \times 10^{-4}$                                                        | 11.17                                 | 0.88  | 72.26          |
| MKGP                                 | 2.78                                  | $1.6 \times 10^{-3}$                                                       | 2.49                                  | 0.91  | $6.2 \times 10^{-4}$                                                        | 3.64                                  | 0.88  | 57.62          |
| 0.5% $\text{H}_2\text{O}_2$ -MKGP    | 5.69                                  | $1.8 \times 10^{-3}$                                                       | 5.56                                  | 0.99  | $3.4 \times 10^{-4}$                                                        | 6.82                                  | 0.89  | 58.56          |
| 1% $\text{H}_2\text{O}_2$ -MKGP      | 7.95                                  | $3 \times 10^{-3}$                                                         | 11.52                                 | 0.92  | $1 \times 10^{-4}$                                                          | 11.52                                 | 0.63  | 59.51          |

As it is seen from these tables, both of these kinetic models demonstrate a good fit for the studied concentrations and none of these models have a superiority on providing a better fit to experimental data; showing that both of these adsorption processes occur simultaneously. Furthermore, according to Table C.7, both  $k_{1,ads,app}$  and  $k_{2,ads,app}$  values show a non-monotonous decreasing trend upon an increase in initial MB concentration, implying that both physical and chemical adsorption processes govern the adsorption process [224] and further analysis is needed to determine the dominating adsorption mechanism.

To evaluate the diffusion mechanism and have an understanding on the rate limiting step, experimental results were further studied by considering intraparticle diffusion model.

Intraparticle diffusion model for the adsorption of MB onto synthesized AAMs are presented for Sep and MK-based samples with highest H<sub>2</sub>O<sub>2</sub> contents as an example in Figure C.5. Obtained parameters for all of the synthesized AAMs are also provided in detail in Table C.8. As it is seen from Figure C.5 and Table C.8, the fit of experimental data to intraparticle diffusion does not show a single linear trend over the time, indicating multiple processes taking place during the adsorption [225].

It is challenging to identify the exact rate controlling mechanisms during adsorption. However, two different patterns obtained in Figure C.5 implies that the main rate controlling mechanism in first eight hours includes combined effects of boundary layer diffusion and gradual adsorption stage due to intraparticle diffusion [199]. As also shown in Table C.8, the numerical values of intercepts in the first linear region (*C*) are very low and obtained linear fit almost passes through the origin, showing that the effect of initial boundary layer resistance is low. This situation might be related with the sufficient agitation of the solution medium, minimizing the external diffusion resistance [226]. The slope of the first region increases upon H<sub>2</sub>O<sub>2</sub> addition both for Sep-AAM and MKGP samples, showing the increased rate of adsorption upon boosted porosity levels introduced by H<sub>2</sub>O<sub>2</sub> addition within first eight hours. On the other hand, as presented in Table C.8, the numerical values of the intercepts (*C*) shows a non-monotonous and still increasing trend upon H<sub>2</sub>O<sub>2</sub> content increase both for Sep and MK-based AAMs, showing the higher uptake values detected for more porous samples, which is consistent with the values of experimental uptake values given in Table 4.3. This situation is related with the presence of viscous drag between the adsorbent surface and MB solution diffusing through the boundary layer thickness [199] and similar findings were reported also for powder formed Sep-based AAMs [97]. The second portion of the data presented in Figure C.5 provides information on the equilibrium stage of the intraparticle diffusion where adsorption starts to slow down due to presence of fewer available adsorption sites and low adsorbate concentration [199, 226]. Second portion of these patterns not passing through the origin also supports that intraparticle diffusion is not the only rate controlling step for this system and the adsorption of MB onto monolith formed Sep and MK-based AAMs is a complex process.

### 4.3.3. Adsorbent Regeneration

A feasibility study was conducted to explore the regeneration ability of the spent adsorbents that will bring economical profit and gives an idea on the sustainability of the adsorbents by minimizing the need for landfilling procedure and reducing carbon emissions. Among various types of regeneration methods, thermal regeneration is a widely applied and regarded as the most cost-effective procedure in wastewater treatment facilities [205, 207]. This procedure is extensively studied for the regeneration of AAMs in the literature [19, 63, 97]. From this respect, regeneration by calcination at 400 °C in static air for 2 hours in between each consecutive adsorption cycle is performed for Sep and MK-based samples with highest H<sub>2</sub>O<sub>2</sub> content, 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM and 1%H<sub>2</sub>O<sub>2</sub>-MKGP, respectively. Reusability of these samples was evaluated at an initial MB concentration of 110 mg L<sup>-1</sup>, which is the highest concentration value investigated in this study. Figure 4.7 summarizes the findings obtained at the end of four regeneration cycles for both 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM and 1%H<sub>2</sub>O<sub>2</sub>-MKGP. As it is seen from Figure 4.7a, for 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM, removal efficiency (%) shows a non-monotonous decreasing trend upon regeneration cycles. The uptake capacity, on the other hand, displays a non-monotonous but increasing trend upon regeneration cycles. After the first adsorption test (before conducting regeneration experiments) the mass of 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM monolith was decreased by ~40%. The main reason for this situation is related with geopolymers involving free alkalis in their structure that are available for leaching. In fact this observation was also verified by pH measurements. Recorded pH value at the beginning of the first regeneration cycle was 10.4, and dropped to 8.55 at the end of the fourth cycle. Similar mass reduction was also reported for FA-based geopolymer spheres [22]. Between first and fourth regeneration cycles on the other hand, 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM sample had lost further 6% of its mass. Previous interferences on the thermogravimetric analysis applied on Sep-AAM samples showed that this mass reduction is related with the removal of physically adsorbed and structural water [25]. Even though the mass of the adsorbent decreased upon adsorption and thermal regeneration, recorded uptake values show that this reduction in mass for 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM sample is thought to be compensated by the increase in porosity as a result of thermal treatment [19]. The initial concentration of MB solution was kept constant at 110 mg L<sup>-1</sup> during the regeneration experiments and results imply that after the fourth cycle, the uptake

value for the sample 8% $\text{H}_2\text{O}_2$ -Sep-AAM is  $16.4 \text{ mg g}^{-1}$ , showing the high regeneration ability of this sample without any compromise in adsorption performance.

As shown in Figure 4.7b, for 1% $\text{H}_2\text{O}_2$ -MKGP, both the uptake capacity and removal efficiency display a decreasing pattern upon regeneration cycles. After the first adsorption test, the mass of 1% $\text{H}_2\text{O}_2$ -MKGP monolith was decreased by  $\sim 21\%$  which is associated with leaching of alkalis present in the geopolymer structure. pH of the MB solution at the beginning of the first regeneration cycle was recorded as 10.1, which dropped to 8.1 at the end of the fourth cycle. For this sample, further mass loss of 1.2% was recorded in between first and fourth regeneration cycle, related with the removal of water molecules. The uptake capacity of 1% $\text{H}_2\text{O}_2$ -MKGP had decreased from  $7.8$  to  $6.2 \text{ mg g}^{-1}$  during the regeneration experiments, however, as evident from Figure 4.7-b, after the first regeneration cycle, there is a stabilization in the adsorption performance and only very minor changes are detected both in removal efficiency and uptake values, revealing that porous MKGP samples can be evaluated as adsorbents for consecutive adsorption cycles without a significant loss in adsorption performance.

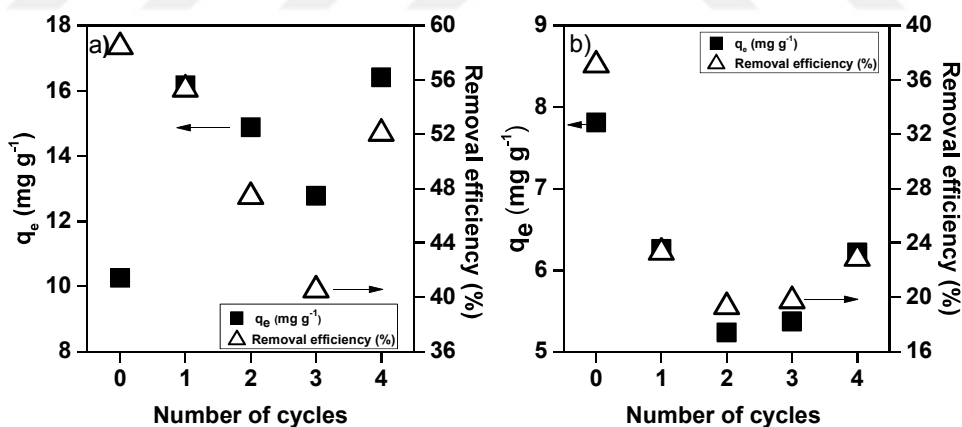


Figure 4.7. MB uptake ( $\text{mg g}^{-1}$ ) removal efficiency (%) values for a) 8% $\text{H}_2\text{O}_2$ -Sep-AAM and b) 1% $\text{H}_2\text{O}_2$ -MKGP after regeneration cycles.

FTIR spectra of MB, 8% $\text{H}_2\text{O}_2$ -Sep-AAM, and 1% $\text{H}_2\text{O}_2$ -MKGP before and after adsorption, and after thermal regeneration are provided in Figure C.6. As it is seen from this figure, FTIR spectrum of MB displays contributions that are positioned at  $3342$ ,  $1592$ ,  $1464$ ,  $1379$ ,  $1322$ ,  $1145$ , and  $876 \text{ cm}^{-1}$ , corresponding to bonded  $-\text{OH}$  groups, stretching vibrations

of C=N and C=C groups, CH<sub>2</sub> deformation vibration, C–N bonds, C–S bonds, and wagging vibration of C–H in aromatic ring, respectively [97], [208].

FTIR spectrum of 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM shown in Figure C.6a shows that peaks located at 1649 and 983 cm<sup>-1</sup> had shifted to 1615 and 1003 cm<sup>-1</sup>, upon MB adsorption, corresponding the the possible participation of C=O and C–O groups [208] and also nitrogen containing functional groups and Si–O–Si groups [143] in the adsorption of MB onto 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM. New peaks that have appeared around 1464 cm<sup>-1</sup> denote to the existence of MB on the surface of 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM, indicating –CH<sub>3</sub> and aromatic nitro groups of MB caused an interaction between MB dye and adsorbent [143].

According to Figure C.6b, the peak positioned at 1646 cm<sup>-1</sup> of 1%H<sub>2</sub>O<sub>2</sub>-MKGP had shifted to 1653 cm<sup>-1</sup> upon MB adsorption. On the other hand, the contribution centered at 983 cm<sup>-1</sup>, which corresponds to the main band of a geopolymeric network denoted to the asymmetric stretching vibrations of Si–O–T (T: Si or Al) [38], remained constant and no position change was detected for this contribution.

The effect of pH of the solution medium on surface charge and the functional group dissociation had previously been reported [97, 209, 210]. In this respect, as both Sep and MK-based AAMs synthesized in this study are alkaline in nature causing high basicity in the solution medium, high pH values cause an enhancement in the electrostatic interactions between functional groups of MB dye and adsorbents of this study. FTIR analyses conducted before and after adsorption process are also in line with this observation as observed shifts confirm the presence of electrostatic interactions between adsorbents and MB dye [228] and shows that chemisorption dominates the adsorption process.

#### 4.3.4. Adsorption Isotherm Model Studies

For all of the synthesized samples, adsorption data were fitted using Langmuir and Freundlich models. Table 4.4 shows the Langmuir and Freundlich parameters for adsorption of MB dye onto synthesized AAMs. Comparatively higher  $R^2$  values are obtained for Langmuir isotherm than they are for Freundlich isotherm for all of the AAMs.

Table 4.4. Langmuir and Freundlich isotherm constants for MB adsorption on synthesized AAMs.

| Adsorbents             | Langmuir Model                 |                                    |       | Freundlich Model               |                             |       |
|------------------------|--------------------------------|------------------------------------|-------|--------------------------------|-----------------------------|-------|
|                        | $K_L$<br>(L mg <sup>-1</sup> ) | $q_{max}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $K_F$<br>(mg g <sup>-1</sup> ) | $n$<br>(g L <sup>-1</sup> ) | $R^2$ |
| Sep-AAM                | 0.94                           | 4.97                               | 1     | 2.55                           | 3.82                        | 0.91  |
| 0.5% $H_2O_2$ -Sep-AAM | 0.34                           | 7.09                               | 0.99  | 3.19                           | 4.81                        | 0.88  |
| 1% $H_2O_2$ -Sep-AAM   | 0.15                           | 7.67                               | 0.94  | 3.37                           | 3.37                        | 0.66  |
| 2% $H_2O_2$ -Sep-AAM   | 0.24                           | 10.86                              | 0.98  | 3.57                           | 3.42                        | 0.99  |
| 3% $H_2O_2$ -Sep-AAM   | 0.17                           | 10.54                              | 0.99  | 2.98                           | 3.10                        | 0.96  |
| 6% $H_2O_2$ -Sep-AAM   | 0.31                           | 10.53                              | 1     | 4.17                           | 4.40                        | 0.96  |
| 8% $H_2O_2$ -Sep-AAM   | 0.68                           | 10.80                              | 0.99  | 5.63                           | 5.40                        | 0.64  |
| MKGP                   | 0.04                           | 5.70                               | 0.90  | 0.54                           | 1.90                        | 0.90  |
| 0.5% $H_2O_2$ -MKGP    | 0.06                           | 8.85                               | 0.93  | 1.34                           | 2.43                        | 0.71  |
| 1% $H_2O_2$ -MKGP      | 0.37                           | 8.24                               | 0.99  | 4.58                           | 7.16                        | 0.76  |

The Langmuir isotherm model showing a better fit for these materials imply that the surface of the adsorbents are homogeneous in terms of functional groups and these active sites have identical binding ability to the adsorbate [67, 97, 142]. Furthermore, Langmuir model assumes that there is no interaction between adsorbate molecules on adjacent sites and each active site can hold only one molecule of the adsorbate when an adsorbate molecule occupies a site on the surface of the adsorbent, this site becomes unavailable for adsorption; suggesting a formation of a monolayer structure [25, 142]. It is reported in the literature that Langmuir isotherm model is convenient for defining chemisorption process, where there is a chemical interaction between molecules or ions of the adsorbate and surface of the adsorbent [201, 229]. Therefore, from a theoretical point of view, it can be said that AAMs synthesized in this study have finite adsorption capabilities.

These observations are in line with the existing literature on MB adsorption of geopolymers as C-type FA-based cubic-shaped geopolymer samples also showed a better fit to Langmuir isotherm and adsorption was described by a chemisorption process [63]. In a

similar manner, MK-based geopolymers also demonstrated a better fit to Langmuir isotherm model for MB adsorption and chemisorption was also found to be the main mechanism for the adsorption process [18]. Table C.9 shows the values of the Langmuir separation factor,  $R_L$ , calculated for all MB concentrations. As it is evident from Table C.9,  $R_L$  values are in between 0 and 1, showing that adsorption within the considered experimental conditions is favorable.

Considering high and similar correlation coefficients obtained from fitting the experimental data to pseudo-first, pseudo-second-order and intraparticle diffusion models (Table C.7 and Table C.8), the adsorption mechanism between MB dye and monolith formed AAMs is found to be affected synergistically from physisorption, chemisorption and diffusion. However, isotherm model studies and regeneration experiments pointed out that chemisorption has a dominant effect on the adsorption mechanism.

Our previous findings on powder formed Sep-based AAMs showed that natural presence of surface hydroxyl groups on AAMs presents a good environment for chemical adsorption as there occurs a chemical attraction between the anionic surface hydroxyl groups and cationic portion of MB dye [97]. This electrostatic interaction between cationic MB dye and the adsorbent is also accounted for MK-based counterparts of Sep-AAMs. In fact, the finding of this study is in accordance with the existing literature, where FA [63], RM and MK-based [25] AAMs displayed chemical adsorption to MB dye, revealing that adsorption process between AAMs are mostly controlled by chemisorption.

Even though  $H_2O_2$  addition does not provide an increased surface area (Table 4.1), it leads to an increase in the availability of MB molecules due to increased level of total porosity values (Table 4.2). The enhanced porosity due to  $H_2O_2$  addition helps MB molecules to reach to inside of the each monolith, and therefore increase the accessible surface area for MB molecules to be adsorbed. This situation is also verified by the micrographs obtained from stereo microscope (Figure C.7). As Figure C.7 shows, both for MKGP and Sep-AAM,  $H_2O_2$  addition induces an increase in the length of MB molecules that have entered into the monolith structure. According to digital stereo microscope results, the highest path length of MB molecules that have entered into the monolith are 287.2,

1343.9, 2105.5, and 3587.8  $\mu\text{m}$  for Sep-AAM, 8% $\text{H}_2\text{O}_2$ -Sep-AAM, MKGP, and 1% $\text{H}_2\text{O}_2$ -MKGP, respectively (Figure C.7).

Larger pore size formation with  $\text{H}_2\text{O}_2$  addition has previously been reported for coal FA-based geopolymers and it was concluded that increased pore size values resulted a faster diffusion rate and MB molecules have more access into the pore and therefore be adsorbed on the adsorbents surface [63]. Similar case is also observed in our system. The length of MB molecule is reported to be in the range between 13.82-14.47 Å, depending on the location of the chloride ion [230]. Regarding the length of MB molecule and pore size values of synthesized AAMs (Table 4.1), it may be suggested that MB molecules can enter into the pores of AAMs synthesized in this study.

Maximum adsorption capacities of AAMs synthesized from various raw materials together with their corresponding mechanical performance are shown in Table 4.5. This table shows that MK-based and Sep-based AAMs with the highest  $\text{H}_2\text{O}_2$  content (1% $\text{H}_2\text{O}_2$ -MKGP and 8% $\text{H}_2\text{O}_2$ -Sep-AAM, respectively) in this study show comparable uptake values to that of other counterparts in this table. Adsorption performance of these samples in powder form is also provided as an example in this table. Relatively higher uptake capacities obtained in powder forms is an expected situation as the amount of accessible adsorption sites are higher for powder formed samples. Compressive strength values of these monoliths, especially 8% $\text{H}_2\text{O}_2$ -Sep-AAM, also show superior mechanical performance and therefore offers a huge potential for future practical water remediation applications.

Making an optimization by taking two different parameters; uptake and compressive strength, showed that adsorption performance of both MK and Sep-based AAM's uptake capacity can be enhanced by increasing the porosity levels. However, the trade-off between these two parameters should be well adjusted in order to obtain an adsorbent with good mechanical performance. As mentioned earlier, increased porosity levels cause a decrease in mechanical performance values.

Table 4.5. MB adsorption capacity of various AAMs.

| Adsorbent                                               | Form of the adsorbent | $q_e$ (mg g <sup>-1</sup> ) | Compressive strength (MPa) | Reference          |
|---------------------------------------------------------|-----------------------|-----------------------------|----------------------------|--------------------|
| Biomass FA-geopolymer                                   | Cylindrical monolith  | 15.4                        | 8                          | [19]               |
| Modified bauxite residue-based porous inorganic polymer | Cylindrical monolith  | 17                          | 1                          | [80]               |
| FA-based geopolymer                                     | Sphere                | 30.1                        | -                          | [22]               |
| Potassium activated FA based geopolymer                 | Cubic monolith        | 84                          | 1.7                        | [63]               |
| MK-based geopolymer with expanded glass aggregates      | Monolith              | 4.9                         | 1.6                        | [21]               |
| MK-based geopolymer spheres                             | Sphere                | 0.9                         | 3.3                        | [17]               |
| MK-based ice-templated geopolymer beads                 | Bead                  | 5                           | 5.9                        | [214]              |
| Sep-AAM                                                 | Cubic monolith        | 6.6                         | 37                         | <i>This thesis</i> |
| 0.5% $H_2O_2$ -Sep-AAM                                  | Cubic monolith        | 6.5                         | 15.8                       | <i>This thesis</i> |
| 1% $H_2O_2$ -Sep-AAM                                    | Cubic monolith        | 7.1                         | 16.3                       | <i>This thesis</i> |
| 2% $H_2O_2$ -Sep-AAM                                    | Cubic monolith        | 10.1                        | 11.7                       | <i>This thesis</i> |
| 3% $H_2O_2$ -Sep-AAM                                    | Cubic monolith        | 9.4                         | 9.2                        | <i>This thesis</i> |
| 6% $H_2O_2$ -Sep-AAM                                    | Cubic monolith        | 9.8                         | 6.9                        | <i>This thesis</i> |
| 8% $H_2O_2$ -Sep-AAM                                    | Cubic monolith        | 10.3                        | 6.5                        | <i>This thesis</i> |
| 8% $H_2O_2$ -Sep-AAM                                    | Powder                | 62.5                        | -                          | <i>This thesis</i> |
| MKGP                                                    | Cubic monolith        | 4.3                         | 28                         | <i>This thesis</i> |
| 0.5% $H_2O_2$ -MKGP                                     | Cubic monolith        | 7.2                         | 4.2                        | <i>This thesis</i> |
| 1% $H_2O_2$ -MKGP                                       | Cubic monolith        | 7.8                         | 2.1                        | <i>This thesis</i> |
| 1% $H_2O_2$ -MKGP                                       | Powder                | 19.5                        | -                          | <i>This thesis</i> |

#### 4.4. Concluding Remarks

Monolith formed Sep-based AAMs with distinct porosity levels are synthesized in this study. The MB adsorption capacity of these materials is compared to MK-based geopolymers with different porosity levels. The effect of binder nature and porosity in terms of microstructural properties, mechanical performance, and also adsorption performance were explored. Results showed that Sep-based AAMs are less sensitive to foaming agent addition when compared to MK-based counterparts and they can carry higher  $\text{H}_2\text{O}_2$  amounts with good mechanical performance values. Zeta potential measurements demonstrated that surface of both Sep and MK-based AAMs with the highest  $\text{H}_2\text{O}_2$  content surface is negatively charged within the studied pH region. Both pseudo-first-order and pseudo-second-order adsorption kinetics showed a good fit to experimental data, showing that both physical and chemical adsorption processes govern the adsorption process. However, adsorption isotherm model studies revealed that Langmuir isotherm model shows a better fit and therefore chemisorption process has a dominating effect on the adsorption mechanism and supported by FTIR analyses. Regeneration experiments conducted on samples with the highest porosity levels show that both MK and Sep-based AAMs can be regenerated up to four cycles without any loss in their integrity. Current part of this thesis shows that  $\text{H}_2\text{O}_2$  addition induces different porosity levels in Sep and MK-based AAMs and binder nature has an effect on the porosity levels of the end material. Still, these AAMs synthesized from different sources are sustainable options with a promising potential and their adsorption capacity can be tuned by arranging the porosity levels. In comparison to previous study where Sep-AAMs in powder forms were used effectively as MB adsorbents [97], results of this chapter is an important step forward since monolith formed AAMs can easily be regenerated without compromising from the adsorption performance.

## 5. GRAPHITIC CARBON NITRIDE INCORPORATED RED-MUD- AND METAKAOLIN-BASED GEOPOLYMERS FOR ENHANCED WASTEWATER TREATMENT CAPABILITY

### 5.1. Introduction

Graphitic carbon nitride ( $g\text{-C}_3\text{N}_4$ ) is one of the prospective adsorbent candidates that has a potential to be used for wastewater remediation systems. It is a 2D material consisting of s-triazine or s-heptazine units that are bonded by tertiary or secondary amino groups [231, 232]. It is known from the literature that  $g\text{-C}_3\text{N}_4$  preserves its stability up to 600 °C and shows resistance to weak acids and bases, dissoluble in water, acetone, ethanol, and diethyl ether [231, 233]. It can be synthesized via a thermal procedure by using different nitrogen-rich organic precursors including melamine [35, 234], urea [235], cyanamide [236], dicyandiamide [237, 238], and thiourea [238]. Due to its unique structure and the presence of conjugated  $\pi$  regions,  $g\text{-C}_3\text{N}_4$  has the ability to adsorb organic pollutants [232] and used for the removal of organic pollutants in the literature [35, 239]. This material has different morphological forms that can be produced by different methods depending on its final application area. Different morphological forms of  $g\text{-C}_3\text{N}_4$  include bulky  $g\text{-C}_3\text{N}_4$ , 3D porous  $g\text{-C}_3\text{N}_4$ , 2D nanosheets of  $g\text{-C}_3\text{N}_4$ , 1D nanorods of  $g\text{-C}_3\text{N}_4$ , and 0D quantum dots of  $g\text{-C}_3\text{N}_4$  [240]. One of the mostly studied morphological form of  $g\text{-C}_3\text{N}_4$  is its bulky form; this form of  $g\text{-C}_3\text{N}_4$  can easily be produced by thermally condensating the nitrogen-rich precursors [240, 241].

Owing to its band gap, oxidation and reduction potential, and flexibility of modification with metals and non-metals [232, 233],  $g\text{-C}_3\text{N}_4$  is also a widely studied visible-light active photocatalyst, especially for water splitting and oxidation of hydrocarbons [242]. As stated previously,  $g\text{-C}_3\text{N}_4$ -based materials are prospective candidates as adsorbents for wastewater treatment applications. In this regard, Shi et al. had studied RM and  $g\text{-C}_3\text{N}_4$ -based composites for their synergistic adsorption and photocatalysis performance for wastewater treatment [35]. Results of this study had shown that both adsorption and photocatalytic performance of the synthesized composite is increased compared to pure  $g\text{-C}_3\text{N}_4$ .

$C_3N_4$ , which was related with the increased surface area, increased visible-light absorption capability, and enhanced separation of photogenerated electron-hole pairs [35].

Adsorbents that are based on g- $C_3N_4$  require specific attention as the adsorption capacity of these materials can be improved by increasing the porosity via soft and hard templates, chemical functionalization, or synthesis of functional composites [231]. Bulk g- $C_3N_4$  does not show high adsorption performance due to its low surface area, however functionalizing the surface of this material with different techniques offers good opportunities for evaluating these materials in adsorption [243] and also in photocatalysis research area [35].

The adsorption performance of geopolymers towards organic pollutants depends on electrostatic or ionic interactions and also on oxygen containing groups. Electrostatic or ionic interactions between the geopolymer and target pollutant imply a process where negatively charged geopolymer sourcing from the Al atom in tetrahedral position attracts the positively charged portion of the cationic dye in the aqueous medium.

For MB, which is one of the most commonly known cationic dye for instance, cationic portion of MB exchange sites with  $Na^+$  charge balancing cations of the geopolymer structure [21]. Additionally, oxygen containing groups such as surface hydroxyls, also produce affinity for MB adsorption [21, 97] and therefore responsible for the adsorption performance of geopolymers in general.

For g- $C_3N_4$ , alkaline  $-NH-$  and  $-NH_2-$  functional groups present at the edges induce electrostatic interactions and contributes to the adsorption of pollutants [243]. In this regard, in this chapter a new composite consisting of red mud (RM) and metakaolin (MK)-based geopolymer and g- $C_3N_4$  is introduced for the first time. To the best of our knowledge, this is the first attempt of investigating the adsorption capacity of geopolymer and g- $C_3N_4$ -based composites for the removal of MB dye from wastewaters. The manuscript form of Chapter 5 is to be submitted as a publication.

## 5.2. Experimental

### 5.2.1. Materials

MK and RM are the aluminosilicate sources utilized for the geopolymers. Chemical compositions of MK, RM, and calcined RM are given in Table D.1 (in the Appendix D). To synthesize MK and RM-based geopolymers, sodium silicate ( $\text{Na}_2\text{Si}_3\text{O}_7$ ) solution and sodium hydroxide pellets was used. Urea (Merck,  $1.34 \text{ g/cm}^3$ ) was used as a  $\text{g-C}_3\text{N}_4$  precursor.

### 5.2.2. Synthesis of Geopolymers

The ratio of MK to RM was optimised based on our previous studies [25, 38]. 20 wt% RM and 80 wt% MK were used in solid raw material basis [38] and synthesis conditions together with molar Si/Al and Na/Al ratios are given in Table D.2. Powdered and sieved (#70 mesh sieve,  $200 \mu\text{m}$ ) RM and MK were mixed with alkali activators and then thermally treated at  $60^\circ\text{C}$  for 24 hours.

### 5.2.3. Synthesis of $\text{g-C}_3\text{N}_4$ Incorporated RMGP

$\text{g-C}_3\text{N}_4$  incorporated RMGP composites ( $\text{g-C}_3\text{N}_4/\text{RMGP}$ ) were produced by a calcination method. 30 g urea and 0.5 g of RMGP were mixed thoroughly and the mixture was grinded for 30 mins. Grinded mixture was then transferred into a crucible with a cap. The solid powder-formed mixture was heated from room temperature to  $550^\circ\text{C}$  with a heating rate of  $3^\circ\text{C/min}$ , and then kept at  $550^\circ\text{C}$  for further two hours. At the end of this thermal procedure, a two phased material is obtained. The upper part of the material was red in color and consists of RMGP and  $\text{g-C}_3\text{N}_4$ , whereas the lower part was pure  $\text{g-C}_3\text{N}_4$  with a yellow color. These two phases were easily separated from each other and evaluated for adsorption experiments separately.

### 5.2.4. Characterization

Chemical compositions of raw materials were analyzed by XRF spectrometer that is used in standardless mode under He atmosphere. XRD patterns of the materials were

determined by utilizing a Bruker D8 Discover Diffraction system with a Cu  $K\alpha_1$  radiation source with a wavelength of 1.5418 Å. FTIR spectroscopy was performed on a Bruker Alpha II with an ATR cell, in absorption mode. A Zeiss Ultra Plus FE-SEM coupled with an EDS was performed to determine the microstructure and morphology of materials. Micromeritics ASAP 2020 –Physisorption Analyzer was used to determine the BET surface area, pore size, and pore volume values of materials. Pore size distribution of the materials were identified by using BJH model utilizing desorption adsorption isotherms. XPS analyses were performed on a Thermo Scientific K-Alpha X-ray Photoelectron Spectrometer and XPS data fitting were established by employing Avantage 5.9 software. A lab pH meter was used to measure the pH of the MB solutions. Zeta potential measurements were performed on a Malvern Zetasizer Nano ZS.

#### **5.2.5. Adsorption Experiments**

To understand the adsorption behaviour of the materials, sieved (200  $\mu\text{m}$ , #70 mesh sieve) and powdered adsorbents were immersed into 50 ml of MB solution with different specified MB concentrations (10-70  $\text{mg L}^{-1}$ ), and magnetically stirred at 700 rpm until an equilibrium was obtained. Samples were syringed at definite time intervals, centrifuged, and their concentration was evaluated with a Flame-S-UV-Vis-ES spectrometer (Ocean Optics, USA) by collecting the absorbance values at  $\lambda = 664 \text{ nm}$ . The amount of MB adsorbed by the adsorbents were calculated by Equation (1.1). The removal efficiency (%) was calculated using Equation (1.2). Linearized forms of pseudo-first- (Equation (1.3)) and pseudo-second-order (Equation (1.4)) adsorption kinetic models were employed to interpret the kinetics data. To determine the individual effects of adsorbed amount and adsorbent amount on the adsorption rate, Equation (1.8) was used. Intraparticle diffusion model (Equation (1.10)) was also used to determine the diffusion mechanism: Langmuir and Freundlich adsorption isotherm models were applied to equilibrium adsorption data of the adsorbents.

##### **5.2.5.1. Adsorbent Reusability Experiments**

Reusability of newly introduced composite (g- $\text{C}_3\text{N}_4/\text{RMGP}$ ) was investigated for four successive adsorption experiments of three hours. As thermal treatment was known to be an

efficient technique that is applicable both to geopolymers and g-C<sub>3</sub>N<sub>4</sub> itself [80, 244], after each adsorption experiment g-C<sub>3</sub>N<sub>4</sub>/RMGP was kept at 400 °C in static air for two hours to remove adsorbed MB molecules [97]. At the beginning of these experiments adsorbent amount was 100 mg and the initial MB concentration was 70 mg L<sup>-1</sup> (500 ml). MB concentration was arranged between each cycle to compensate the reduction in powder-formed adsorbent amount. Therefore, MB amount per g-C<sub>3</sub>N<sub>4</sub>/RMGP amount was kept constant within each cycle.

### 5.3. Results and Discussion

#### 5.3.1. Morphological Properties

BET surface areas, pore volumes, and average pore sizes of RMGP and calcined RMGP are given in Table D.3. As it is seen from Table D.3, there is a slight decrease in surface area of RMGP as a result of calcination due to removal of water molecules. Table 5.1 presents the BET surface area, average pore size, and pore volume of g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP. Data implies that g-C<sub>3</sub>N<sub>4</sub>/RMGP has a comparatively lower surface area and pore volume to that of g-C<sub>3</sub>N<sub>4</sub>. Incorporation of RMGP causing a reduction in surface area is related with the formation of a denser structure with the introduction of a geopolymer into graphitic carbon nitride.

Table 5.1. BET surface area, average pore size, and pore volume of samples.

| Sample                                | Surface area<br>(m <sup>2</sup> /g) | Pore volume<br>(cm <sup>3</sup> /g) | Pore size<br>(Å) |
|---------------------------------------|-------------------------------------|-------------------------------------|------------------|
| g-C <sub>3</sub> N <sub>4</sub>       | 62.02                               | 0.261                               | 254.25           |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 13.92                               | 0.081                               | 410.15           |

SEM images together with corresponding EDS spectra of RMGP, calcined RMGP, g-C<sub>3</sub>N<sub>4</sub>, and g-C<sub>3</sub>N<sub>4</sub>/RMGP are presented in Figure D.1. Atomic % of different surface elements in these materials are calculated and provided in Table D.4. SEM images and EDS spectra of RMGP and calcined RMGP (FigureD.1a&b) imply that both of these materials display a homogeneous surface microstructure and consist of different elements including

O, Si, Na, and Al atoms, constituting the main geopolymeric network. Due to removal of surface adsorbed water upon calcination of RMGP, the amount of surface oxygen atoms had decreased from 62.3 to 59.8 % (Table D.4).

SEM image of g-C<sub>3</sub>N<sub>4</sub> shown in Figure D.1c demonstrates that the surface of g-C<sub>3</sub>N<sub>4</sub> is porous and composes of flake-like and fluffy structures, consistent with the existing literature on the morphology of urea-derived g-C<sub>3</sub>N<sub>4</sub>s [245-247]. As it is evident from Table D.4, the surface of g-C<sub>3</sub>N<sub>4</sub> consists mainly of C and N atoms. With the incorporation of RMGP, the morphology changed significantly and the newly synthesized g-C<sub>3</sub>N<sub>4</sub>/RMGP composite shows a more homogeneous morphology that holds morphological fingerprints of both g-C<sub>3</sub>N<sub>4</sub> and RMGP. Surface atomic % of C and N decreased for the newly synthesized composite whereas surface O, Si, Al, and Na amounts resulting from RMGP increased (Table D.4). The alteration observed in the morphology for g-C<sub>3</sub>N<sub>4</sub>/RMGP and the formation of a more homogeneous system is consistent with the decrease in surface area and pore volume values from BET analyses (Table 5.1).

XRD patterns of RMGP, calcined RMGP, g-C<sub>3</sub>N<sub>4</sub>, and g-C<sub>3</sub>N<sub>4</sub>/RMGP are provided in Figure 5.1. To obtain calcined RMGP, the same thermal procedure to produce g-C<sub>3</sub>N<sub>4</sub>/RMGP was followed; powdered form of RMGP was heated from room temperature to 550 °C with a heating rate of 3 °C/min, and then kept at 550 °C for additional two hours.

XRD pattern shown in Figure 5.1c denotes to the XRD pattern of yellow part that is obtained from the lower part of the crucible as a result of thermal treatment procedure and is mainly pure g-C<sub>3</sub>N<sub>4</sub>. The pattern at the bottom in Figure 5.1d shows the XRD spectrum of the red part that was collected from the upper part of the crucible and includes footprints sourcing from RMGP and g-C<sub>3</sub>N<sub>4</sub>.

As it is evident from Figure 5.1, RMGP and calcined RMGP display an amorphous structure and there is a main feature located at 28°, demonstrating the formation of an amorphous geopolymer [39]. Crystalline phases for RMGP was quartz (SiO<sub>2</sub>) and hematite (Fe<sub>2</sub>O<sub>3</sub>) phases and crystalline structure did not change by calcination, as calcined RMGP (Figure 5.1c) also showed similar XRD pattern to that of RMGP. RM is an aluminosilicate

source with high iron oxide content and the XRD pattern of as-received RM consists mainly of hematite phase [25].

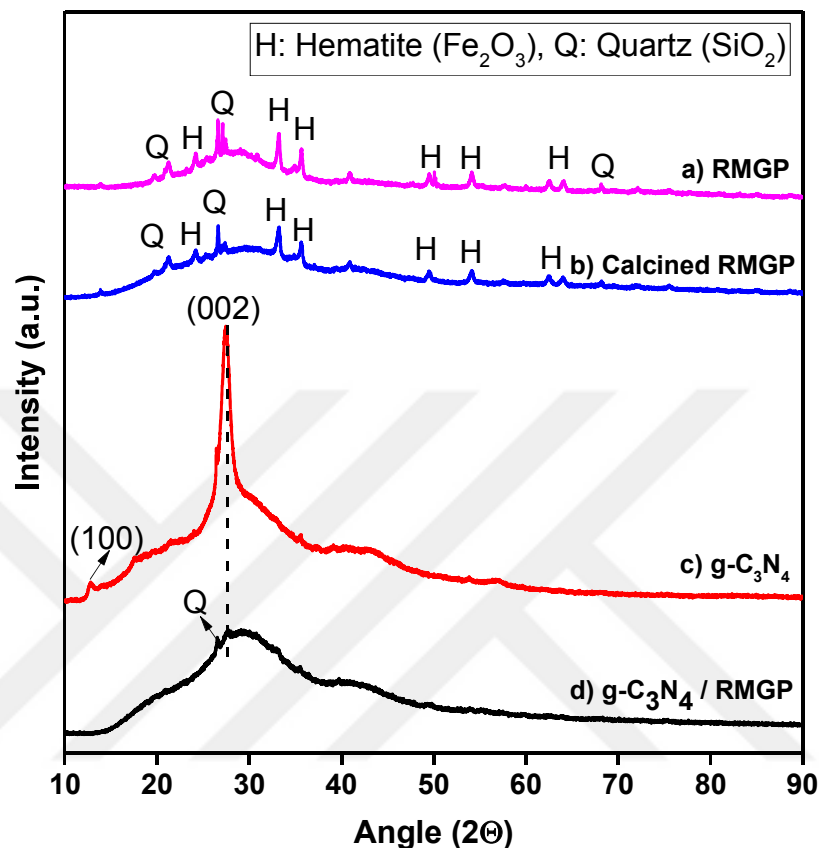


Figure 5.1. XRD patterns of a) RMGP, b) Calcined RMGP, c)  $\text{g-C}_3\text{N}_4$ , and d)  $\text{g-C}_3\text{N}_4/\text{RMGP}$ .

MK on the other hand is also an aluminosilicate source, and dominating crystalline phase in its XRD spectrum is quartz phase [25]. In this respect, hematite and quartz phases present in RMGP are sourced from RM and MK, respectively. The crystallographic structure of the synthesized  $\text{g-C}_3\text{N}_4$  demonstrates two characteristic peaks of pure  $\text{g-C}_3\text{N}_4$  located at  $12.7^\circ$  and  $27.4^\circ$  that correspond to (100) and (002) diffraction planes of the  $\text{g-C}_3\text{N}_4$  [248], [249]. The main diffraction peak positioned at  $27.4^\circ$  is associated with the interplanar structural packing of aromatic units of  $\text{g-C}_3\text{N}_4$  [246], [249]. The presence of the low angle diffraction peak located at  $12.7^\circ$  denotes to the crystal plane of repeating tri-s-triazine units of  $\text{g-C}_3\text{N}_4$  [246, 249, 250]. Crystallographic structure of  $\text{g-C}_3\text{N}_4/\text{RMGP}$  is similar to RMGP, and the intensity of the diffraction peak related with the (002) diffraction plane of pure  $\text{g-C}_3\text{N}_4$ , is only partly detectable.

FTIR spectra of RMGP, calcined RMGP, g-C<sub>3</sub>N<sub>4</sub>, and g-C<sub>3</sub>N<sub>4</sub>/RMGP are shown in Figure 5.2. FTIR spectrum of RMGP displays typical characteristic feature in the region positioned between 900-1200 cm<sup>-1</sup>, denoting to the formation of geopolymer structure [38, 251] and the main feature located at 980 cm<sup>-1</sup> is ascribed to the asymmetric stretching vibrations of T–O–Si bonds (T: Al or Si) that are formed during geopolymer production as a consequence of TO<sub>4</sub> reorganization [38, 110]. This main contribution verifies the presence of geopolymeric network with tetrahedral SiO<sub>4</sub><sup>4-</sup> and AlO<sub>4</sub><sup>5-</sup> monomers together with exchangeable charge balancing cations (Na<sup>+</sup> or K<sup>+</sup>) [220].

For RMGP, shoulders located at 1139 cm<sup>-1</sup> and 885 cm<sup>-1</sup> correspond to asymmetric stretching vibrations of Si–O–Si bonds sourcing from MK [25] and Si–OH bending vibrations [112], respectively. Weak contributions at 1653 cm<sup>-1</sup> and 1415 cm<sup>-1</sup> can be attributed to the H–O–H bending vibrations of adsorbed H<sub>2</sub>O molecule [113] and stretching vibrations of C–O groups sourcing from the carbonate impurities [37], respectively. The features related with the presence of water molecules disappeared upon calcination of RMGP (Figure 5.2b). Weak contribution at 1415 cm<sup>-1</sup> had also disappeared upon calcination and indicates the dissolution of carbonate impurities as a result of thermal treatment procedure.

FTIR spectrum of g-C<sub>3</sub>N<sub>4</sub> consists of several different peaks. The feature located in between 3000-3500 cm<sup>-1</sup> is resulted from N–H stretching vibrations of uncondensed amino functional groups primary amine (–NH<sub>2</sub>) and absorbed hydroxyl groups [241, 246]. Intense contributions in the region between 1200 and 1650 cm<sup>-1</sup> are sourced from stretching vibrations of C–N and C=N units in aromatic ring of g-C<sub>3</sub>N<sub>4</sub> [35, 241, 243]. More specifically, intense features at 1400 and 1600 cm<sup>-1</sup> can be assigned to stretching vibrations of heptazine derived units, whereas contributions at lower wavenumber 1200 and 1400 cm<sup>-1</sup> are sourced from out of plane bending vibrations of heptazine rings [235, 246]. Peaks positioned at 1446 and 1313 cm<sup>-1</sup>, also correspond to the presence of C=O and C–OH surface functional groups, respectively [252]. Feature detected at 807 cm<sup>-1</sup> is assigned to breathing mode of tri-s-triazine units of g-C<sub>3</sub>N<sub>4</sub> [35, 246, 253].

The characteristic bands of g-C<sub>3</sub>N<sub>4</sub>/RMGP are similar to those of RMGP and g-C<sub>3</sub>N<sub>4</sub>. The main band of RMGP positioned at 980 cm<sup>-1</sup> is still visible for g-C<sub>3</sub>N<sub>4</sub>/RMGP. Additionally, contributions in the region between 1200 and 1600 cm<sup>-1</sup>, and 807 cm<sup>-1</sup> still

exist in the newly formed g-C<sub>3</sub>N<sub>4</sub>/RMGP composite. In this regard, synthesized composite holds fingerprints of both RMGP and g-C<sub>3</sub>N<sub>4</sub>.

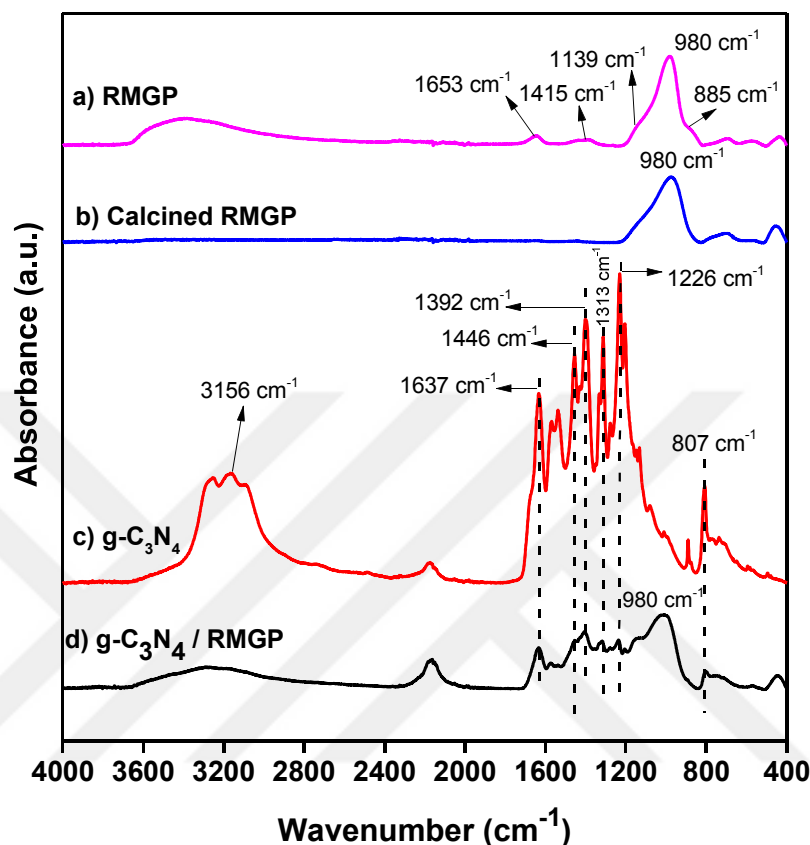


Figure 5.2. FTIR spectra of a) RMGP, b) Calcined RMGP, c) g-C<sub>3</sub>N<sub>4</sub>, and d) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

### 5.3.2. Surface Characteristics

To determine the alterations in surface elemental compositions for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, XPS analysis was conducted. XP survey spectra of RMGP, calcined RMGP, g-C<sub>3</sub>N<sub>4</sub>, and g-C<sub>3</sub>N<sub>4</sub>/RMGP are provided in Figure D.2. As is evident from these graphs, the surface of RMGP and calcined RMGP consists of same elements. g-C<sub>3</sub>N<sub>4</sub>/RMGP, on the other hand displays fingerprints of both RMGP and g-C<sub>3</sub>N<sub>4</sub>.

Deconvoluted C 1s, O 1s, and N 1s XP spectra of g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP and surface atomic % obtained from XPS results regarding all surface elements for RMGP, calcined RMGP, g-C<sub>3</sub>N<sub>4</sub>, and g-C<sub>3</sub>N<sub>4</sub>/RMGP were given in Figure D.3 and Table D.5,

respectively. C 1s spectrum of g-C<sub>3</sub>N<sub>4</sub> consists primarily of three peaks located at 284.5, 286.2, and 287.9 eV. Major contribution positioned at higher binding energy corresponds to sp<sup>2</sup> hybridized carbon (N–C=N) of g-C<sub>3</sub>N<sub>4</sub> [253]. Weaker contributions at 284.5 eV and 286.2 eV are assigned to graphitic C=C bonds and C–NH<sub>2</sub> species [254]. O 1s spectrum of g-C<sub>3</sub>N<sub>4</sub> displays two peaks at 531.9 eV and 535.03 eV. These peaks are related with the OH<sup>–</sup> groups on the surface due to absorbed water [245] and oxygen in molecular water [160], respectively. N 1s spectrum of g-C<sub>3</sub>N<sub>4</sub> was deconvoluted into three peaks at the binding energies of 398.4, 399.8, and 400.9 eV. The main contribution at 398.4 eV is associated with sp<sup>2</sup> hybridized nitrogen groups [245, 254, 255]. Peaks at 399.8 and 400.9 eV are related with the presence of tertiary nitrogen atoms (N–(C)<sub>3</sub>) [246, 255] and hydrogen bonded nitrogen groups (C–N–H) [253, 255].

Even though C 1s and N 1s spectra of g-C<sub>3</sub>N<sub>4</sub>/RMGP show similar characteristics and peaks to that of g-C<sub>3</sub>N<sub>4</sub>, it can be seen that the effect of surface oxygen atoms is more obvious for g-C<sub>3</sub>N<sub>4</sub>/RMGP. O 1s spectrum of g-C<sub>3</sub>N<sub>4</sub>/RMGP demonstrate that main peak is observed at a binding energy value of 531.5 eV and this significant contribution is related with the presence of surface hydroxyls for this material [25, 118]. As stated previously, g-C<sub>3</sub>N<sub>4</sub>/RMGP composite is a combination of g-C<sub>3</sub>N<sub>4</sub> and RMGP, therefore shows characteristics of both of these materials. The increased contribution of surface hydroxyl groups for g-C<sub>3</sub>N<sub>4</sub>/RMGP is also evident from Table D.5, where surface atomic % of oxygen element was detected as 3.4 and 38.6% for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, respectively.

### 5.3.3. Adsorption Measurements

The change of zeta potential with pH is shown in Figure D.4 for both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP. For both of these materials, zeta potential values were found to be negative within the studied pH region (2-12). This situation implies that surface of these adsorbents are negatively charged in these pH interval. For g-C<sub>3</sub>N<sub>4</sub>, with the increase of pH from 2 to 4, there is a significant decrease in zeta potential value from -12.1 to -36.3 eV. Further increase in pH did not cause major alterations, however, minor but systematic decrease in zeta potential values were observed. The trend for g-C<sub>3</sub>N<sub>4</sub>/RMGP is similar with a steeper decline from -5.7 to -38.8 eV when pH is increased from 2 to 4. When pH was equal to 12, zeta potential values of g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP were -49.6 and 50 eV, respectively.

Initial pH of the solutions during adsorption experiments were arranged to be neutral and results point out that zeta potential of g-C<sub>3</sub>N<sub>4</sub>/RMGP composite is systematically lower than it is for g-C<sub>3</sub>N<sub>4</sub> for a wide range of pH values. Existence of higher electrostatic interactions between negatively charged surface of g-C<sub>3</sub>N<sub>4</sub>/RMGP composite and positively charged MB molecules increases the adsorption performance.

Surface of the geopolymers synthesized from different raw materials is known to have a negative charge that is associated with the presence of different oxygen-rich hydroxyl groups [192, 256, 257]. Additionally, the surface of geopolymers contains silanol groups and therefore have a negative charge in an alkaline environment [194, 258]. On these grounds, existence of surface hydroxyl groups and silanol groups, make geopolymers suitable candidates especially for the removal of cationic molecules from wastewater. Surface functional groups evaluated by FTIR and XPS analyses also shows that C and O involving surface functional groups results in a negatively charged surface leading to an enhanced interaction for cationic adsorbates [259].

#### 5.3.3.1. Influence of Contact Time

The influence of contact time on the adsorption performance of g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub> were determined by setting the adsorbent amount to 10 mg and initial MB concentration to 20 mg L<sup>-1</sup>. Uptake capacities ( $q_t$  (mg g<sup>-1</sup>)) and  $C_t/C_0$  ratio were followed by measuring the concentration of MB by taking samples at regular time intervals and presented in Figure 5.3. As it is evident from Figure 5.3, for both of these adsorbents, adsorption-desorption equilibrium was reached within the first one hour. Since only very minor changes in adsorption performance were observed after one hours, optimum contact time for these adsorbents were taken as 180 minutes (3 h). At the end of three hours, uptake and  $C_t/C_0$  ratio for g-C<sub>3</sub>N<sub>4</sub>/RMGP were 92.9 mg g<sup>-1</sup> and 0.13, respectively. The adsorption performance of g-C<sub>3</sub>N<sub>4</sub> was found to be lower than that of g-C<sub>3</sub>N<sub>4</sub>/RMGP and uptake and  $C_t/C_0$  were determined as 34.6 mg g<sup>-1</sup> and 0.67, respectively. As mentioned previously, presence of surface functional groups were verified by XPS and FTIR analyses. In this regard, g-C<sub>3</sub>N<sub>4</sub>/RMGP composite demonstrating higher performance upon MB removal is in accordance with these information, and shows that surface functional groups are of great importance.

The same measurements were conducted also for RMGP and calcined RMGP for comparison and results are provided in Figure D.5. Uptake values for RMGP and calcined RMGP were measured as 18.9 and 9.5 mg g<sup>-1</sup>. The decrease from 18.9 mg g<sup>-1</sup> to 9.5 mg g<sup>-1</sup> is most possibly related with the loss of surface Si–OH hydroxyl groups upon calcination, which was also verified by FTIR measurements (Figure 5.2) Adsorption measurements for these materials implied that both g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub> exhibit superior performance than RMGP and calcined RMGP.

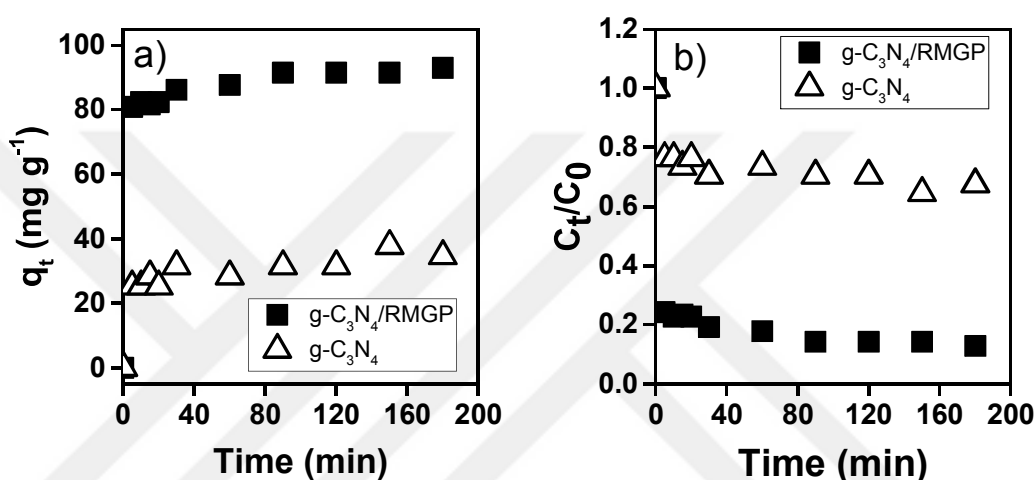


Figure 5.3. The influence of contact time on a) Uptake and b)  $C_t/C_0$  of g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub>.

### 5.3.3.2. Influence of Initial MB Concentration

The effect of initial MB concentration on uptake and removal efficiency of g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub> are presented in Figure 5.4 by setting sample amount to 10 mg for each run. Patterns presented in this figure imply that for both of these samples, removal efficiency decreases with an increase in the initial MB concentration. The quantity of available active sites for adsorption per adsorbate is lower at high MB concentrations to that of at low initial MB concentrations. As the available active sites for adsorption are not sufficient, removal efficiency decreases at higher concentrations both for g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub>. Similar observations had also been made for FA and MK-based geopolymers [19] and activated carbon [260]. As mentioned previously, g-C<sub>3</sub>N<sub>4</sub>/RMGP exhibits superior adsorption performance and Figure 5.4 shows that uptake capacity of g-C<sub>3</sub>N<sub>4</sub>/RMGP increases upon an increase in initial MB concentration and nearly reaches a plateau for MB

concentrations equal and higher than  $40 \text{ mg L}^{-1}$ . Initial MB concentration increase from 10 to  $70 \text{ mg L}^{-1}$  resulted a 3.8-fold enhancement in the uptake value of g-C<sub>3</sub>N<sub>4</sub>/RMGP from  $44.6 \text{ mg g}^{-1}$  to  $170.9 \text{ mg g}^{-1}$ .

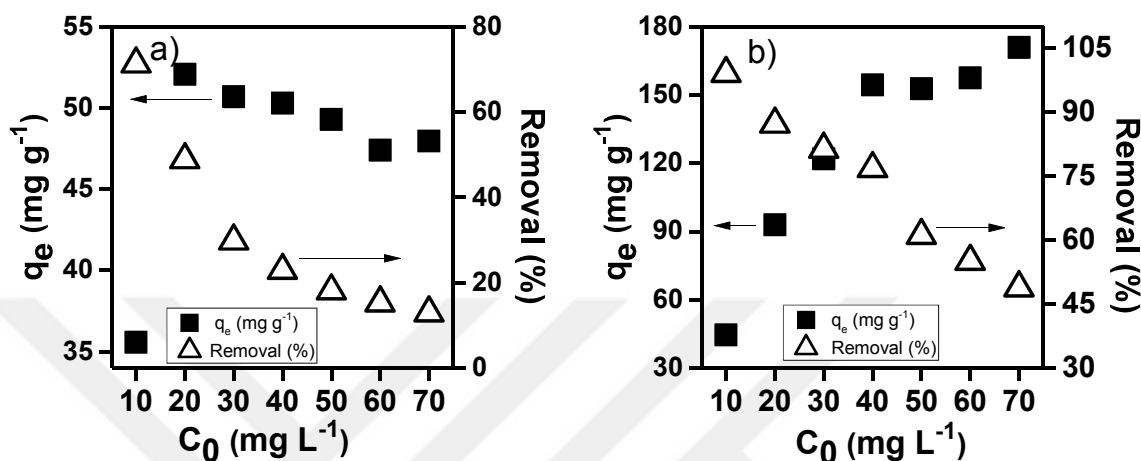


Figure 5.4. The influence of initial MB concentration on uptake and removal (%) of MB for a) g-C<sub>3</sub>N<sub>4</sub> and b) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

Surface functional groups of this adsorbent compensate the increase in adsorbate amount up to a certain level, and then uptake capacity reaches a saturation point where further adsorbate molecules cannot be adsorbed as all of the active sites had already been occupied by MB molecules. The effect of initial MB concentration was less profound for g-C<sub>3</sub>N<sub>4</sub>; 7-fold increase in initial MB concentration was found to cause an increase in the uptake value from 35 to  $47.9 \text{ mg L}^{-1}$ .

#### 5.3.3.3. Influence of Adsorbent Amount

The influence of adsorbent amount on uptake capacity and removal efficiency results are shown in Figure 5.5 for both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP. Figure 5.5. implies that for both of these adsorbents, MB uptake capacity decreases with an increase in the adsorbent amount. This decrease in uptake capacity upon change in adsorbent amount is more obvious for g-C<sub>3</sub>N<sub>4</sub>/RMGP sample. When the amount of adsorbent is increased from 0.006 g to 0.012 g, the uptake capacity ( $\text{mg g}^{-1}$ ) had decreased from 143.5 to  $72.7 \text{ mg g}^{-1}$ .

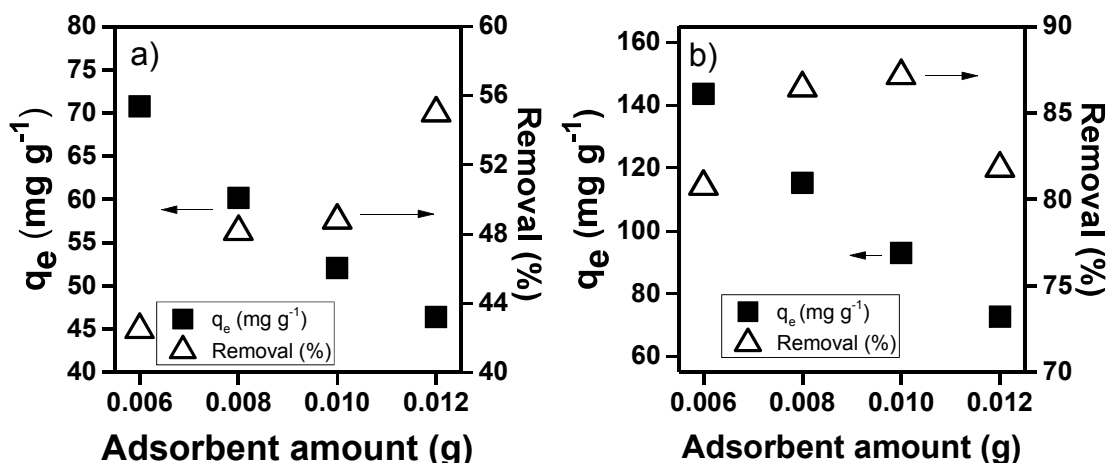


Figure 5.5. The influence of adsorbent amount on uptake and removal (%) of MB for a) g-C<sub>3</sub>N<sub>4</sub> and b) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

Similar patterns were observed for geopolymer materials and activated carbon used for dye adsorption [22, 196,261]. This pattern was explained by the increased presence of unsaturated adsorption sites with an increase in adsorbent amount [261]. Removal efficiency displays a different trend than uptake capacity; with the increase in adsorbent amount removal efficiency enhances for both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP. This enhancement in removal efficiency is more profound for g-C<sub>3</sub>N<sub>4</sub> and this trend is related with the increased quantity of available adsorption sites with an increase in adsorbent amount [22, 262].

#### 5.3.3.4. Influence of pH

pH of the solution medium also has an influence on the adsorption occurring at the water-adsorbent interfaces [263]. To identify the effect of changes in pH values on adsorption efficiency, pH of the effluent was adjusted by using 0.1 M HCl and NaOH solutions. Adsorption experiments at distinct initial pH values of 2, 3, 4, 7, 8, and 9 were conducted both for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP by using 10 mg adsorbent and 50 ml of MB solutions with definite concentrations (20 mg L<sup>-1</sup>). pH measurements of these effluents were performed on a lab pH-meter. The pH of MB solution with 20 mg L<sup>-1</sup> initial concentration was measured as 7.0 without any adjustment. Figure 5.6 shows the adsorption performance of g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP at different initial pH values.

Experimental results pointed out that increase in the initial pH value results similar trends for both of these adsorbents. Adsorption performance of g-C<sub>3</sub>N<sub>4</sub>/RMGP is superior to that of g-C<sub>3</sub>N<sub>4</sub> within all studied pH values (pH = 2-9), however these two adsorbents behave in a similar manner under different pH conditions. Uptake capacity increases with an increase in the initial pH and stabilizes when pH exceeds 7. The reason of this enhancement in adsorption performance for g-C<sub>3</sub>N<sub>4</sub>/RMGP is sourced from the synergistic effect of surface functional groups from g-C<sub>3</sub>N<sub>4</sub> itself and negatively charged geopolymeric framework of RMGP, which is equipped with exchangeable charge balancing cations (Na<sup>+</sup>).

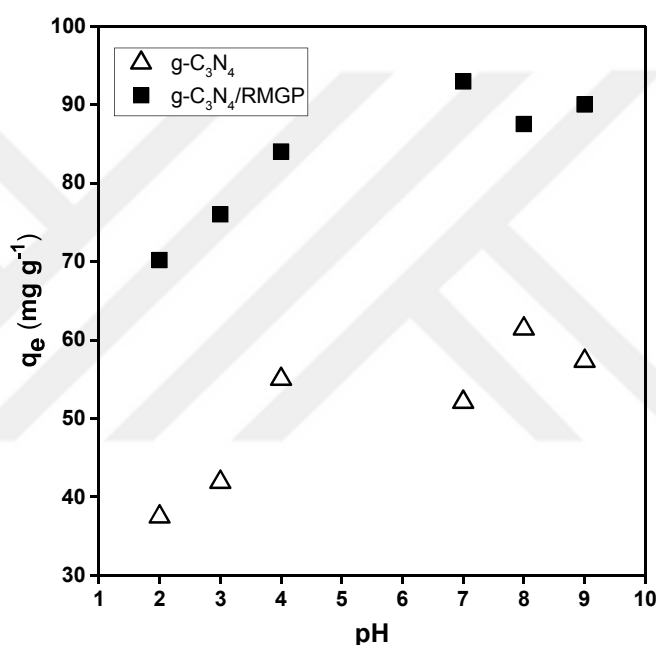


Figure 5.6. The influence of pH on MB uptake by g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP (*Contact time* = 3h, *C*<sub>0</sub> = 20 mg L<sup>-1</sup>).

It was reported that both surface area and surface functional groups have an effect on the adsorption properties of the materials [252]. In this respect, the enhanced adsorption capacity of g-C<sub>3</sub>N<sub>4</sub>/RMGP composite is sourced from its unique surface structure. Increased amount of surface functional groups, and the existence of a geopolymeric framework, which were previously identified by both FTIR and XPS analyses, are the main performance determining parameters for this system. As there are more OH<sup>-</sup> ions in the medium at higher pH values, these negatively charged anions attract cationic MB dye molecules more than they attract in lower pH values. Alkalinity of the effluent provides a suitable environment and causes an increase in the electrostatic attraction between these positively and negatively

charged ions. Therefore, adsorption performance is higher at alkaline conditions. This finding conforms with the existing literature where MB adsorption density is favored at higher pH values when geopolymers [23] and g-C<sub>3</sub>N<sub>4</sub> [264] were used as an adsorbent.

#### 5.3.3.5. Adsorption Kinetics Modeling and Mechanism

Results of adsorption experiments were further analyzed by using pseudo-first- and pseudo-second-order kinetic models and provided in Table 5.2 and Figure D.6 for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP samples. For both of these adsorbents, pseudo-second-order adsorption kinetic model demonstrated a better fit and Figure D.6 shows that experimental data display linearity with very high correlation coefficients ( $R^2=1$ ). Additionally, as it is seen from Table 5.2, there is a high consistency between experimental and calculated values of uptake values, implying that adsorption mechanism for both of these adsorbents are better defined by pseudo-second-order kinetics, and pseudo-first-order kinetics model did not show a good fit to experimental data.

In this regard, it is deduced that MB adsorption onto g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP samples conform with pseudo-second-order adsorption model and adsorption is mostly due to chemisorption. This situation signifies that there is an electron sharing or exchange between MB dye molecules and the adsorbent [198]. Similar findings was also observed for RMGP and calcined RMGP (Table D.6), however as it can also be seen from this table, uptake performance of these two materials are limited and are not further considered.

The adsorption mechanism between geopolymer samples and cationic MB dye was previously studied for MK-based geopolymers [214] and experimental data suited well to pseudo-second-order adsorption kinetics, showing that chemical adsorption takes place [214]. Surface functional groups were reported as being the main parameter determining the adsorption capacity of geopolymers [6]. In a similar manner, adsorption of cationic molecules onto urea-based g-C<sub>3</sub>N<sub>4</sub> was studied, and it was asserted that adsorption is dominated by chemisorption as adsorption process involves electron exchange and transfer [265, 266].

Table 5.2. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP (*Contact time* = 3 h,  $C_0 = 20 \text{ mg L}^{-1}$  and  $m = 10 \text{ mg}$ ).

| Adsorbent                             | $q_{e,exp}$<br>( $\text{mg g}^{-1}$ ) | Pseudo-first-order adsorption kinetics   |                                    |       | Pseudo-second-order adsorption kinetics                    |                                    |       | Removal (%) |
|---------------------------------------|---------------------------------------|------------------------------------------|------------------------------------|-------|------------------------------------------------------------|------------------------------------|-------|-------------|
|                                       |                                       | $k_{1,ads,app}$<br>( $\text{min}^{-1}$ ) | $q_{e,cal}$ ( $\text{mg g}^{-1}$ ) | $R^2$ | $k_{2,ads,app}$<br>( $\text{g mg}^{-1} \text{ min}^{-1}$ ) | $q_{e,cal}$ ( $\text{mg g}^{-1}$ ) | $R^2$ |             |
| g-C <sub>3</sub> N <sub>4</sub>       | 52.07                                 | $1.25 \times 10^{-2}$                    | 12.43                              | 0.56  | $1.1 \times 10^{-2}$                                       | 50.0                               | 0.99  | 48.82       |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 92.96                                 | $1.84 \times 10^{-2}$                    | 17.61                              | 0.77  | $5.06 \times 10^{-3}$                                      | 93.45                              | 1     | 87.15       |

To determine the real pseudo-second-order adsorption rate constant ( $k_{2,ads}$ ) for both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, the dependency of adsorption rate on the adsorbent amount should be taken into consideration. For this reason, for both of these adsorbents, the adsorbent amount was varied and corresponding apparent pseudo-second-order adsorption rate constant values were recorded and presented in Table D.7. This table shows that for both of these samples apparent pseudo-second-order rate constant ( $k_{2,ads,app}$ ) increases as adsorbent amount is increased from 0.006 g to 0.012 g. Corresponding changes in  $k_{2,ads,app}$  ( $\text{g mg}^{-1} \text{ min}^{-1}$ ) values as a result of variation in adsorbent amount (g) are shown in Figure D.7. As it is seen from this figure, data for g-C<sub>3</sub>N<sub>4</sub>/RMGP displays comparatively higher correlation coefficient with an  $R^2$  value of 0.95. Still, the systematic enhancement as a result of an increase in adsorbent amount was detected for both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP. The actual pseudo-second-order adsorption rate constant ( $k_{2,ads}$ ) and the order of adsorption rate in regard to adsorbent amount were calculated by using Equation (1.8). The slope and intercept values of Figure D.7 were used and the actual second-order adsorption rate constants ( $k_{2,ads}$ ) for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP were calculated based on these values. These calculations showed that  $k_{2,ads}$  for g-C<sub>3</sub>N<sub>4</sub> is  $639.06 ((\text{g adsorbent})^{-1.31} (\text{mg MB})^{-1} \text{ min}^{-1})$ , whereas  $k_{2,ads}$  for g-C<sub>3</sub>N<sub>4</sub>/RMGP was found as  $64.71 ((\text{g adsorbent})^{-1.08} (\text{mg MB})^{-1} \text{ min}^{-1})$ .

To help understanding the rate limiting step of the adsorption and to designate the diffusion mechanism, adsorption data were further studied by applying intraparticle diffusion model in addition to pseudo-first-order and pseudo-second-order adsorption kinetic models. Experimental data showing the intraparticle diffusion model for MB adsorption on g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, together with the corresponding intraparticle

diffusion model parameters are given in Figure D.8 and Table D.8, respectively. As it is seen from Table 5.2 and Table D.8, comparably very higher correlation coefficients were observed for the pseudo-second-order adsorption model, designating that responsible adsorption mechanism between g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP and MB dye is chemisorption [200, 267]. During chemisorption there occurs a bond interaction between anionic ends of adsorbents and the cationic adsorbate molecules [201, 231]. As stated by many researchers in the literature, surface of g-C<sub>3</sub>N<sub>4</sub> and also surface of geopolymers are negatively charged due to the presence of negatively charged nitrogen atoms for g-C<sub>3</sub>N<sub>4</sub> [231, 263, 268] and surface hydroxyl groups for geopolymers [25, 109]. This fact was also verified in this study, as both FTIR and XPS analyses implies the presence of different types of surface functional groups of these adsorbents. The content of active sites, and therefore surface chemistry is a very important parameter that has a huge effect on the correct decision of adsorbent towards a specific adsorbate [231]. In our case, the adsorbate MB molecule is a cationic dye that is dissolved into a cationic portion and a chlorine ion in aqueous solutions [202]. In this respect, it is assumed that the advanced adsorption capacity of g-C<sub>3</sub>N<sub>4</sub>/RMGP, to that of g-C<sub>3</sub>N<sub>4</sub>, is sourced from the increased amount of surface functional groups for this adsorbent. These negatively charged surface active sites cause an increased level of electrostatic interaction between MB dye molecules and enhances the adsorption capacity.

#### 5.3.3.6. Adsorbent Regeneration

To be able to perform an adsorption that is both sustainable and durable, reusability of the adsorbents should also be taken into consideration. The g-C<sub>3</sub>N<sub>4</sub>/RMGP composite with very high adsorption capacity towards MB dye molecules introduced in this study holds imprints of geopolymers and graphitic carbon nitride. Therefore, a regeneration procedure that is effective for both of these materials should be conducted. Our previous observations showed that thermal treatment applied on spent geopolymer materials is an effective procedure [97] and this had previously been verified by researchers of this area [205], [269]. It was shown that a temperature of 400 °C applied for geopolymer samples is sufficient enough to remove the adsorbed MB molecules [19, 80] and geopolymers regenerated within this procedure can successfully be re-used. Additionally, regeneration ability of graphitic carbon nitride-based adsorbents' used for methyl blue adsorption was also investigated by carrying out a thermal treatment during regeneration [244, 270]. In the light of these

information, reusability of g-C<sub>3</sub>N<sub>4</sub>/RMGP in this study was investigated by calcination at 400 °C in static air with an isothermal step of 2 h to remove an thermally degenerate MB molecules adsorbed on the surface of g-C<sub>3</sub>N<sub>4</sub>/RMGP. This procedure was applied in between each consecutive adsorption experiments and experimental results are provided in Figure D.9. Data presented in Figure D.9 demonstrates that regeneration with thermal treatment reduces the adsorption performance of g-C<sub>3</sub>N<sub>4</sub>/RMGP. Uptake capacity of g-C<sub>3</sub>N<sub>4</sub>/RMGP decreased from 170.9 to 20.8 mg g<sup>-1</sup>, at the end of the first experiment and fourth regeneration, respectively. One of the reasons of this reduction in adsorption performance is related with the loss of adsorbents during the regeneration experiments and this is accepted as one of the disadvantages of using powder-formed adsorbents. Nevertheless, after fourth regeneration, g-C<sub>3</sub>N<sub>4</sub>/RMGP still displays a better adsorption performance compared to calcined RMGP (please see Table D.6) and cumulative uptake value had reached 461.9 mg g<sup>-1</sup> during these four regeneration cycles.

FTIR spectra of MB, g-C<sub>3</sub>N<sub>4</sub>/RMGP, g-C<sub>3</sub>N<sub>4</sub>/RMGP after first and fourth regeneration and g-C<sub>3</sub>N<sub>4</sub>/RMGP after adsorption of MB are shown in Figure D.10. FTIR pattern of MB displays different peaks positioned mainly at 1591, 1322, 1145 and 876 cm<sup>-1</sup> [97]. The presence of these peaks were related with the existence of different functional groups such as stretching vibrations of C=N and C=C (1591 cm<sup>-1</sup>), N-CH<sub>3</sub> bond (1322 cm<sup>-1</sup>), C-S bonds (1142 cm<sup>-1</sup>), and wagging vibration of C-H in aromatic ring (876 cm<sup>-1</sup>) [208].

As it is seen from Figure D.10, the peak positioned at 1154 cm<sup>-1</sup> had shifted to 1145 cm<sup>-1</sup> upon MB adsorption, showing that C=O groups participate in the MB adsorption process. In a similar manner, peak located at 1637 cm<sup>-1</sup> had shifted to 1591 cm<sup>-1</sup>, and peak at 1406 cm<sup>-1</sup> had shifted to 1389 cm<sup>-1</sup> with adsorption, implying the participation of C-O groups and nitrogen containing functional groups [143, 208], and also participation of multiple peaks of carbon nitride heterocycles stretching modes [263] during MB adsorption. This finding was verified from FTIR and XPS analyses which show the presence of surface functional groups that have a positive effect on the adsorption capacity of an adsorbent. On the contrary, the peak located at 876 cm<sup>-1</sup> for MB adsorbed g-C<sub>3</sub>N<sub>4</sub>/RMGP was not available for g-C<sub>3</sub>N<sub>4</sub>/RMGP prior to adsorption and this shows that aromatic C-H groups of MB result in an increased interaction between the surface of for g-C<sub>3</sub>N<sub>4</sub>/RMGP and MB.

Additionally, Figure D.10 shows that FTIR spectrum at the end of first regeneration displays more contribution from g-C<sub>3</sub>N<sub>4</sub> (bands in the region between 1700-1250 cm<sup>-1</sup>), whereas at the end of the fourth regeneration very little contribution from g-C<sub>3</sub>N<sub>4</sub> was detected and adsorbent's FTIR spectrum at the end of fourth regeneration is very similar to that of calcined RMGP (Figure 5.2). g-C<sub>3</sub>N<sub>4</sub>/RMGP at the end of fourth regeneration still have a peak at 807 cm<sup>-1</sup>, sourcing from the breathing mode of tri-s-triazine units of g-C<sub>3</sub>N<sub>4</sub>, however it is clear that the reduction of g-C<sub>3</sub>N<sub>4</sub>-related surface functional groups during thermal regeneration causes a reduction in the uptake values.

#### 5.3.3.7. Adsorption Isotherm Model Studies

Experimental data collected at ambient temperatures were fitted by utilizing Langmuir and Freundlich adsorption isotherm models for both g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub>. Parameters obtained for the adsorption of MB dye molecules onto these two adsorbents are displayed in Table 5.3. According to this table, for both g-C<sub>3</sub>N<sub>4</sub>/RMGP and g-C<sub>3</sub>N<sub>4</sub>, Langmuir isotherm exhibits a better fit with very high correlation coefficients.  $R^2$  values for Langmuir isotherm model is 1 for both of these adsorbents, however for Freundlich isotherm  $R^2$  values were found to be 0.49 and 0.85 for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, respectively. Higher compatibility to Langmuir model suggests that surface functional groups of these adsorbents are homogeneously dispersed and therefore these adsorbents display monolayer adsorption with no sites being available for further adsorption when an active site is occupied by a MB molecule, and there are no interactions between MB molecules [232], [266]. Previously presented adsorption experiments revealed that g-C<sub>3</sub>N<sub>4</sub>/RMGP exhibits comparatively higher adsorption performance than g-C<sub>3</sub>N<sub>4</sub>. Concordantly,  $q_{max}$  values presented in Table 5.3 supports this finding and higher  $q_{max}$  values are determined for g-C<sub>3</sub>N<sub>4</sub>/RMGP, indicating the higher availability of surface functional groups in this material compared to g-C<sub>3</sub>N<sub>4</sub>. The value of Langmuir separation factor ( $R_L$ ) was also calculated at all the studied initial MB concentrations and provided in Table D.9.

Adsorption kinetic and isotherm model results determined for g-C<sub>3</sub>N<sub>4</sub>/RMGP are in accordance with the existing literature where carbon-doped graphitic carbon nitride adsorbents were found to exhibit higher compatibility to pseudo-second-order adsorption kinetics and Langmuir model for MB adsorption which was correlated with the electrostatic

interactions between the adsorbent and MB molecules [232]. Concordantly, urea-based graphitic carbon nitride was used as an adsorbent for Pb(II) and aniline removal and experimental data suited better to pseudo-second-order kinetics and Langmuir isotherm model which was attributed to the electrostatic interaction between g-C<sub>3</sub>N<sub>4</sub> and cationic adsorbates [266].

All of the  $R_L$  values presented in Table D.9 being in between 0 and 1 shows that adsorption is favorable within the given experimental conditions.

Table 5.3. Langmuir and Freundlich isotherm constants for MB adsorption on Sep-AAM at different temperatures.

| Adsorbents                            | Langmuir Model                 |                                    |       | Freundlich Model               |                             |       |
|---------------------------------------|--------------------------------|------------------------------------|-------|--------------------------------|-----------------------------|-------|
|                                       | $K_L$<br>(L mg <sup>-1</sup> ) | $q_{max}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $K_F$<br>(mg g <sup>-1</sup> ) | $n$<br>(g L <sup>-1</sup> ) | $R^2$ |
| g-C <sub>3</sub> N <sub>4</sub>       | 2.19                           | 48.07                              | 1     | 36.56                          | 12.47                       | 0.49  |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 0.36                           | 181.82                             | 1     | 56.81                          | 2.89                        | 0.85  |

Table 5.4 summarizes the reported maximum adsorption capacities of different graphitic carbon nitride-based adsorbents towards MB dye together with corresponding experimental conditions of the studies that uptake values were recorded.

According to this table, equilibrium experimental MB uptake value offered by g-C<sub>3</sub>N<sub>4</sub>/RMGP is very promising among various graphitic carbon nitride-based adsorbents. Remarkable uptake performance towards MB dye for g-C<sub>3</sub>N<sub>4</sub>/RMGP is due to presence of surface functional groups that are sourced from both RMGP and g-C<sub>3</sub>N<sub>4</sub>. This newly introduced composite offers a sustainable and easy-to-synthesize route for remediation of wastewaters with high adsorption performance. Simultaneous effects of surface functional groups from geopolymers and graphitic carbon nitride has been introduced for the first time, which proved that this combination may further be developed and brings in advantages including high adsorption performance, evaluation of industrial wastes, and providing an easy route for synthesis of effective adsorbents for MB removal.

Table 5.4. MB adsorption capacity of various graphitic carbon nitride-based adsorbents.

| Adsorbent                                             | $q_e$ (mg g <sup>-1</sup> ) | Experimental conditions                                                           | Reference          |
|-------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------------|--------------------|
| Carbon-doped graphitic carbon nitride                 | 57.87                       | $C_0 = 15$ mg L <sup>-1</sup> , pH- not given, $m_{ads}$ =not given               | [232]              |
| Biochar carbonitride carbon                           | 302.25                      | $C_0 = 50$ mg L <sup>-1</sup> , pH=11, $m_{ads}=0.16$ g L <sup>-1</sup>           | [265]              |
| Tetragonal C <sub>3</sub> N <sub>4</sub> hollow tubes | 7.0                         | $C_0 = 15$ mg L <sup>-1</sup> , pH- not given, $m_{ads}=1$ g L <sup>-1</sup> , RT | [271]              |
| Carbon nitride hydrogel                               | 402                         | $C_0 = 1000$ mg L <sup>-1</sup> $m_{ads}$ = not given, pH- not given, RT          | [272]              |
| Phosphorus-doped graphitic carbon nitride             | 100                         | $C_0 = 18$ mg L <sup>-1</sup> , pH=8, $m_{ads}$ = not given, T=18 °C              | [273]              |
| g-C <sub>3</sub> N <sub>4</sub>                       | 47.9                        | $C_0 = 70$ mg L <sup>-1</sup> , pH=7, $m_{ads}=0.2$ g L <sup>-1</sup> , RT        | <i>This thesis</i> |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP                 | 170.9                       | $C_0 = 70$ mg L <sup>-1</sup> , pH=7, $m_{ads}=0.2$ g L <sup>-1</sup> , RT        | <i>This thesis</i> |

\* $m_{ads}$  is the adsorbent dosage (g adsorbent/L MB solution), RT: room temperature.

#### 5.4. Concluding Remarks

In this chapter, a RM and MK-based geopolymer and urea-based graphitic carbon nitride were combined to obtain g-C<sub>3</sub>N<sub>4</sub>/RMGP composite for MB adsorption for the first time. This composite was utilized as an adsorbent for MB removal and its adsorption performance was compared with urea-based g-C<sub>3</sub>N<sub>4</sub>. The effect of surface functional groups on MB adsorption was investigated with the main focus being also on microstructural properties. Experimental results pointed out that g-C<sub>3</sub>N<sub>4</sub>/RMGP composite exhibits superior MB adsorption capacity than urea-based g-C<sub>3</sub>N<sub>4</sub> due to presence of higher amount of surface functional groups as also verified by XPS and FTIR analyses. Results showed that the adsorption of MB molecules onto g-C<sub>3</sub>N<sub>4</sub>/RMGP follows pseudo-second-order adsorption kinetics and according to adsorption isotherm model studies Langmuir model provides a better fit. Therefore, chemisorption was found to be the main controlling process during adsorption and electrostatic interaction between cationic MB molecules and negatively

charged surface of g-C<sub>3</sub>N<sub>4</sub>/RMGP created a suitable environment for chemical adsorption. Pseudo-second-order adsorption rate constant that is dependent on adsorbent amount was calculated and reusability of g-C<sub>3</sub>N<sub>4</sub>/RMGP was also investigated. Structure and adsorption performance relationship was established and it was observed that combining geopolymers and graphitic carbon nitride is an effective strategy towards MB removal for wastewater remediation applications.



## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1. Conclusions

The motivation of this thesis is to investigate the potential evaluation of geopolymers in adsorption and photocatalysis research area. Different raw materials used for geopolymer synthesis were introduced and their characteristics are discussed. Among various raw materials, particular emphasis was placed on MK, RM, and Sep. Geopolymers synthesized from these materials were used for MB removal from wastewaters. Ability of these materials' for MB removal and their structure-removal performance relations were investigated by using different characterization tools and techniques. Kinetic analyses were performed to be able to comment on the photocatalytic mechanism and/or adsorption mechanism.

In Chapter 2, performance of RM and MK-based geopolymers was investigated for the adsorption and photocatalytic degradation of MB to demonstrate their potential as self-cleaning, environmentally friendly construction materials. Compressive strength measurements showed that the mechanical performances of the synthesized RM- and MK-based geopolymers vary between 37.7 and 43.2 MPa, indicating that these materials are promising for construction applications. Next, the materials were tested for MB removal both under dark and UV-light conditions. Data showed that the RM- and MK-based geopolymer, without any anatase addition, worked both as an adsorbent and a photocatalyst for the removal of MB from wastewater. Systematic increase of anatase concentration resulted in an increase in the photocatalytic activity. For instance, the geopolymer with an anatase loading of 3.7 wt% provided more than three-times higher apparent photodegradation rate constant compared to that of pure anatase under identical conditions.

Chapter 3 focused on the introduction of a novel, cheap, and easy-to-synthesize Sep-AAM, that was synthesized by the reaction of a magnesium silicate source, sepiolite, with  $\text{Na}_2\text{Si}_3\text{O}_7$  solution, demonstrating high mechanical strength and MB removal performance. Kinetics data in this section indicated that MB adsorption occurs through pseudo-second-

order adsorption kinetics model, while the Langmuir isotherm model provided a better fit to adsorption isotherms. The Sep-AAM provided a removal capacity of  $99.92 \text{ mg g}^{-1}$  at  $50^\circ\text{C}$ , setting a new benchmark value among the materials used for this purpose. Thermodynamical parameters indicated that the adsorption of MB onto Sep-AAM was endothermic and the interaction between Sep-AAM and MB included weak chemical bonding. Regenerability of the Sep-AAM in powder and monolith forms was confirmed up to four-cycles. Structural parameters determined by several characterization tools demonstrated that the surface hydroxyl groups are responsible for the superior MB adsorption performance. The mechanical strength measurements showed that Sep-AAM in monolith form displayed a remarkable compressive strength value of 40 MPa.

In Chapter 4, Sep-AAM with varying porosities were introduced and their MB adsorption characteristics were comparatively evaluated for the first time. MK-based counterparts of these adsorbents were also produced to compare their structure and adsorption performance properties.  $\text{H}_2\text{O}_2$  was used as a foaming agent in these monoliths and varied in the range of 0-8 wt.% and 0-1 wt.% for Sep-AAMs and MKGPs, respectively. Experimental results pointed out that both MK and Sep-based AAMs display adsorption performance towards MB dye with comparatively higher adsorption capacity for Sep-based samples. As porosity of Sep-AAMs increased from about 13% to 40%, the uptake capacity rose from  $6.6$  to  $10.3 \text{ mg g}^{-1}$ . It is noteworthy that the compressive strength of the Sep based monolith with high uptake was 6 MPa which was much higher than most of the solid formed lightweight specimens reported. On the other hand, as the porosity of MKGP monoliths vary from 31.9% to 63.5%, corresponding uptake capacity increases from  $4.3$  to  $7.8 \text{ mg g}^{-1}$ . Zeta potential measurements indicated that the surface of the synthesized samples were negatively charged. Both pseudo-first-order and pseudo-second-order adsorption kinetics showed good fit to experimental data, signaling that both physical and chemical adsorption processes govern the adsorption process. Adsorption isotherm model studies show that Langmuir isotherm model showed a better fit indicating chemisorption process controls the adsorption mechanism, which was also verified FTIR analysis and zeta potential measurements. Regeneration experiments conducted on samples with the highest porosity levels showed that both MK and Sep-based AAMs could be regenerated up to four cycles without any loss in their integrity. Mechanical performance of these monoliths was strongly affected by increased porosity levels and compressive strength values were found to decrease with

increased porosity. For Sep-AAM and 8% $\text{H}_2\text{O}_2$ -Sep-AAM, compressive strength values were reported as 37 and 6.5 MPa, respectively. For MK-based samples, compressive strength values for MKGP and 1% $\text{H}_2\text{O}_2$ -MKGP were measured as 28 and 2.1 MPa, respectively. Results pointed out that it is possible to tune the adsorption performance of AAM monoliths by changing the porosity levels and these monoliths may display a certain level of mechanical performance, making these materials good candidates for wastewater remediation applications.

In Chapter 5, a novel composite consisting of an industrial waste RM and MK-based geopolymer ( $\text{g-C}_3\text{N}_4/\text{RMGP}$ ) and urea-derived  $\text{g-C}_3\text{N}_4$  was introduced and evaluated as an adsorbent for MB dye for the first time. The adsorption capacity of  $\text{g-C}_3\text{N}_4/\text{RMGP}$  was compared with urea-derived  $\text{g-C}_3\text{N}_4$ . Experimental data revealed that adsorption of MB onto  $\text{g-C}_3\text{N}_4/\text{RMGP}$  follows pseudo-second-order kinetics and chemisorption had an important effect on adsorption, which was verified also by FTIR analysis. Adsorption isotherm model studies demonstrated that Langmuir model offered a better fit. It was shown that, under same experimental conditions  $\text{g-C}_3\text{N}_4/\text{RMGP}$  showed an uptake capacity of  $170.9 \text{ mg g}^{-1}$ , whereas uptake capacity of  $\text{g-C}_3\text{N}_4$  was recorded as  $47.9 \text{ mg g}^{-1}$ . Regenerability of  $\text{g-C}_3\text{N}_4/\text{RMGP}$  was studied up to four consecutive cycles. Differences between the adsorption capacities of  $\text{g-C}_3\text{N}_4$  and  $\text{g-C}_3\text{N}_4/\text{RMGP}$  were investigated in detail by using different characterization tools. Results extracted from these analyses pointed out that surface functional groups sourcing from  $\text{g-C}_3\text{N}_4$  and surface hydroxyl groups and silanol groups of RMGP provided a unique structure for  $\text{g-C}_3\text{N}_4/\text{RMGP}$ , making it a strong candidate for MB adsorption.

These results demonstrate that a hazardous industrial waste, RM, globally produced in huge amounts, can be effectively utilized in the production of environmentally friendly construction materials with self-cleaning ability without sacrificing from mechanical performance. As presented in the final part, the adsorption performance of the geopolymer synthesized from RM and MK can be improved by incorporating graphitic carbon nitride. Furthermore, to establish a new approach forward on the development of AAMs for wastewater treatment, this thesis shows that Sep can effectively be utilized and Sep-AAM provides a sustainable solution for dye removal both in powder and monolith forms, with advanced mechanical properties.

## 6.2. Recommendations

AAMs are studied in detail in this thesis to understand their potential applicability in adsorption and photocatalysis research area. Aiming to overcome the limitations and challenges encountered during the experiments of this study, the following points can be further considered as recommendations for future studies. As observed by the results of Chapter 2, it is possible to produce mechanically strong and photocatalytically active geopolymers by using industrial waste RM, MK, and anatase as a photocatalyst. To expand these geopolymers usability for practical applications by ensuring visible-light photocatalytic activity, doping of anatase with metals and/or non-metals can be conducted.

Chapter 3 had shown that Sep mineral offers a huge potential as an adsorbent towards MB dye. In this regard, considering the findings from Chapters 2 and 3, to increase the MB removal efficiency, Sep-based AAMs with different anatase content can be further studied to benefit from combined effects of adsorption and photocatalysis for dye removal.

From the standpoint of mechanical performance and adsorption performance results that were found to be arranged by changing the porosity levels in Chapter 4, a coating procedure can be applied to these monolith-formed AAMs to make these materials beneficial for the utilization in construction, adsorption, and photocatalysis research area.

As mentioned in Chapter 5, graphitic carbon nitride has different morphological forms and bulky-graphitic carbon nitride were studied in this chapter. To ensure enhanced visible-light photocatalytic activity, various graphitic carbon nitride precursors and synthesis procedures may be further studied and resulting material can be tested for adsorption and visible-light activity.

In Chapters 2 and 5 of this thesis, an industrial waste, RM, was utilized for geopolymer synthesis. To make a contribution to circular economy, another widely produced industrial wastes such as FA and slags could also be used for geopolymer synthesis. Mechanical performance of these geopolymers can also be measured and their adsorption and photocatalysis potential can be evaluated to have a broader perspective on the importance of raw material type on different aspects of materials engineering.

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## APPENDIX A: SUPPLEMENTARY INFORMATION 1

Table A.1. Chemical compositions (wt%) of MK, raw RM, and calcined RM used in Chapter 2.

| Material    | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | CaO  | MgO  | Na <sub>2</sub> O |
|-------------|------------------|--------------------------------|------------------|--------------------------------|------------------|------|------|-------------------|
| MK          | 56.21            | 41.04                          | 1.15             | 0.36                           | 0.46             | 0.09 | 0.07 | -                 |
| RM          | 11.67            | 14.02                          | 5.78             | 37.1                           | 0.31             | 1.1  | 0.23 | 9.39              |
| Calcined RM | 12.59            | 16.85                          | 5.94             | 37.45                          | 0.31             | 1.44 | 0.2  | 10.55             |

Table A.2. The amounts of raw materials (in g) used in geopolymer synthesis, corresponding molar Si/Al and Al/Na ratios, and synthesis conditions used in RMGP synthesis in Chapter 2.

| Sample     | Anatase<br>(g) | RM<br>(g) | MK<br>(g) | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub><br>solution<br>(g) | NaOH<br>(g) | Molar<br>Si/Al | Molar<br>Al/Na | Activating<br>solution                                  | Thermal<br>treatment          |
|------------|----------------|-----------|-----------|-------------------------------------------------------------------|-------------|----------------|----------------|---------------------------------------------------------|-------------------------------|
| 0%A-RMGP   | 0              | 2         | 8         | 14.01                                                             | 1.69        | 2              | 0.83           | NaOH<br>&Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 60 °C<br>+ 1 week 25 °C |
| 0.4%A-RMGP | 0.1            | 2         | 8         | 14.01                                                             | 1.69        | 2              | 0.83           | NaOH<br>&Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 60 °C<br>+ 1 week 25 °C |
| 1.2%A-RMGP | 0.3            | 2         | 8         | 14.01                                                             | 1.69        | 2              | 0.83           | NaOH<br>&Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 60 °C<br>+ 1 week 25 °C |
| 1.9%A-RMGP | 0.5            | 2         | 8         | 14.01                                                             | 1.69        | 2              | 0.83           | NaOH<br>&Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 60 °C<br>+ 1 week 25 °C |
| 3.7%A-RMGP | 1              | 2         | 8         | 14.01                                                             | 1.69        | 2              | 0.83           | NaOH<br>&Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 60 °C<br>+ 1 week 25 °C |

Table A.3. BET surface area, average pore size, pore volume, and density of RMGP samples.

| Sample     | BET surface area<br>(m <sup>2</sup> /g) | Average pore size<br>(Å) | Pore volume<br>(cm <sup>3</sup> /g) | Density<br>(g/cm <sup>3</sup> ) |
|------------|-----------------------------------------|--------------------------|-------------------------------------|---------------------------------|
| 0%A-RMGP   | 15.9                                    | 409.2                    | 0.1                                 | 2.10 ± 0.01                     |
| 0.4%A-RMGP | 12.9                                    | 535.3                    | 0.1                                 | 2.13 ± 0.03                     |
| 1.2%A-RMGP | 17.2                                    | 472.6                    | 0.2                                 | 2.10 ± 0.01                     |
| 1.9%A-RMGP | 11.5                                    | 446.7                    | 0.1                                 | 2.11 ± 0.01                     |
| 3.7%A-RMGP | 14.0                                    | 443.2                    | 0.1                                 | 2.11 ± 0.03                     |

Figure A.1 shows the XRD patterns of the raw materials used as aluminosilicate sources for the geopolymer synthesis. XRD pattern of MK shows an amorphous feature located at approximately  $23^\circ$  together with quartz as an impurity. Calcined RM, on the other hand, has mainly an iron oxide phase, hematite. FTIR spectra of raw materials MK and RM are given in Figure A.2. FTIR band observed at  $1080\text{ cm}^{-1}$  in MK corresponds to the presence of Si–O bonds that is present in amorphous  $\text{SiO}_2$  and peak at  $811\text{ cm}^{-1}$  refers to the  $\text{AlO}_4$  tetrahedra in MK [1]. The feature at a lower frequency of  $445\text{ cm}^{-1}$  is related with the presence of Al–O–Si bridge aluminosilicates [2, 3]. A small contribution observed at a higher frequency of  $1436\text{ cm}^{-1}$  in RM is attributed to the presence of carbonate bonds [4], whereas band observed at  $980\text{ cm}^{-1}$  refers to the asymmetric stretching vibrations of Si–O–Si and Al–O–Si bonds. Features detected table at  $550$  and  $440\text{ cm}^{-1}$  are most possibly associated with stretching vibrations of Fe–O bonds sourcing from the iron content of RM [5]. The band located at  $680\text{ cm}^{-1}$  is assigned to the symmetric stretching vibrations of Si–O–Si and Al–O–Si bonds [6].

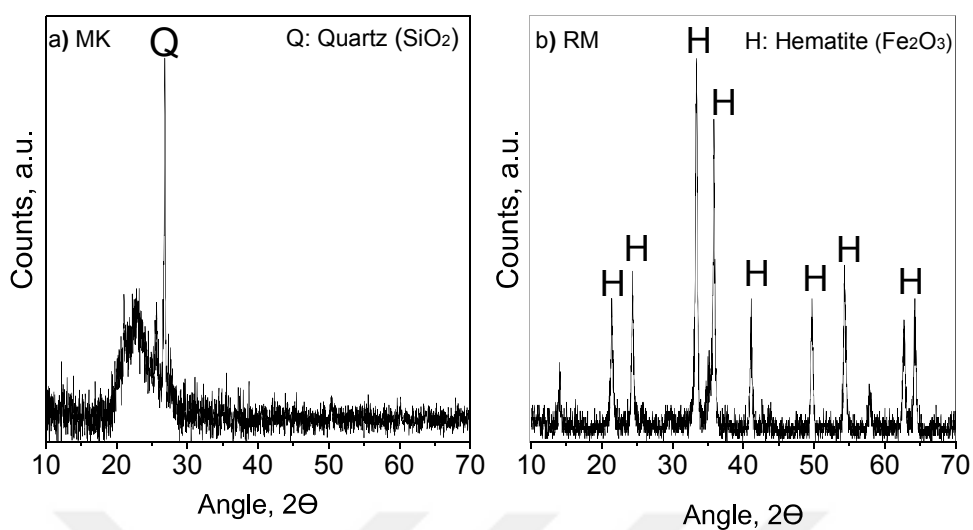


Figure A.1. XRD patterns of the aluminosilicate sources used for geopolymer synthesis: a) MK b) Calcined RM.

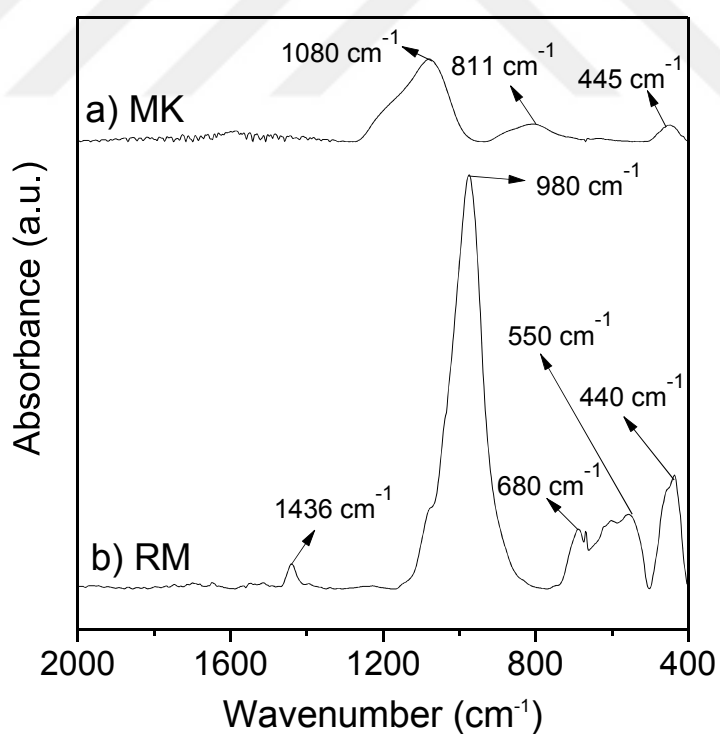


Figure A.2. FTIR spectra of raw materials a) MK and b) RM.

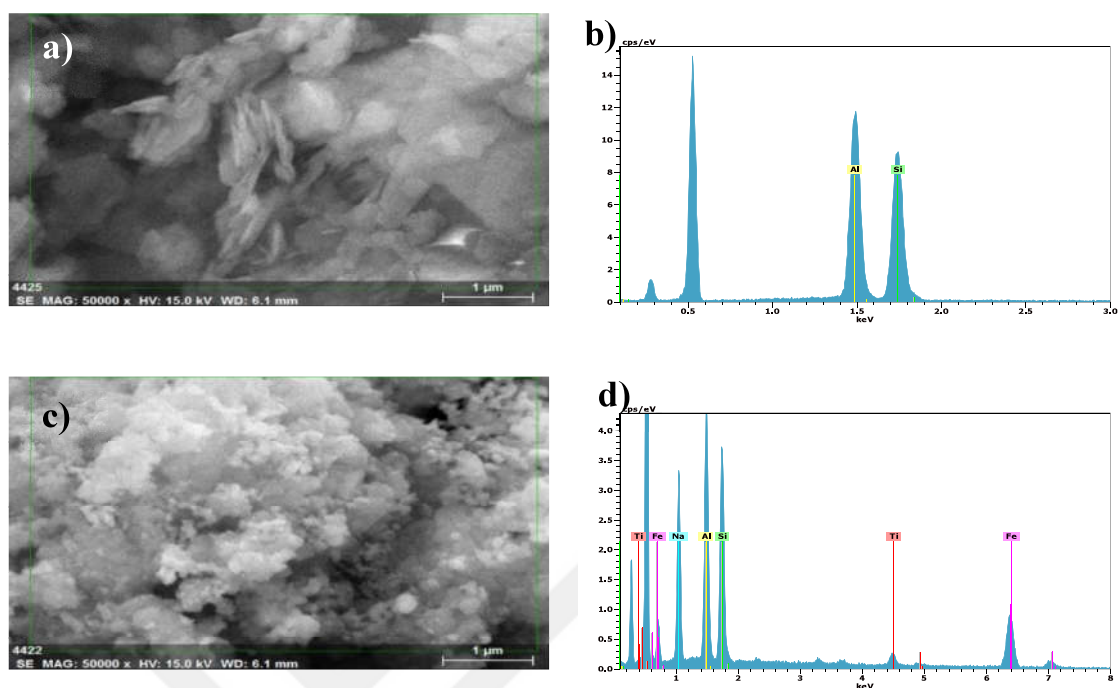


Figure A.3. SEM images and corresponding EDS spectrum of a) MK, b) EDS spectrum of MK, c) calcined RM, d) EDS spectrum of calcined RM.

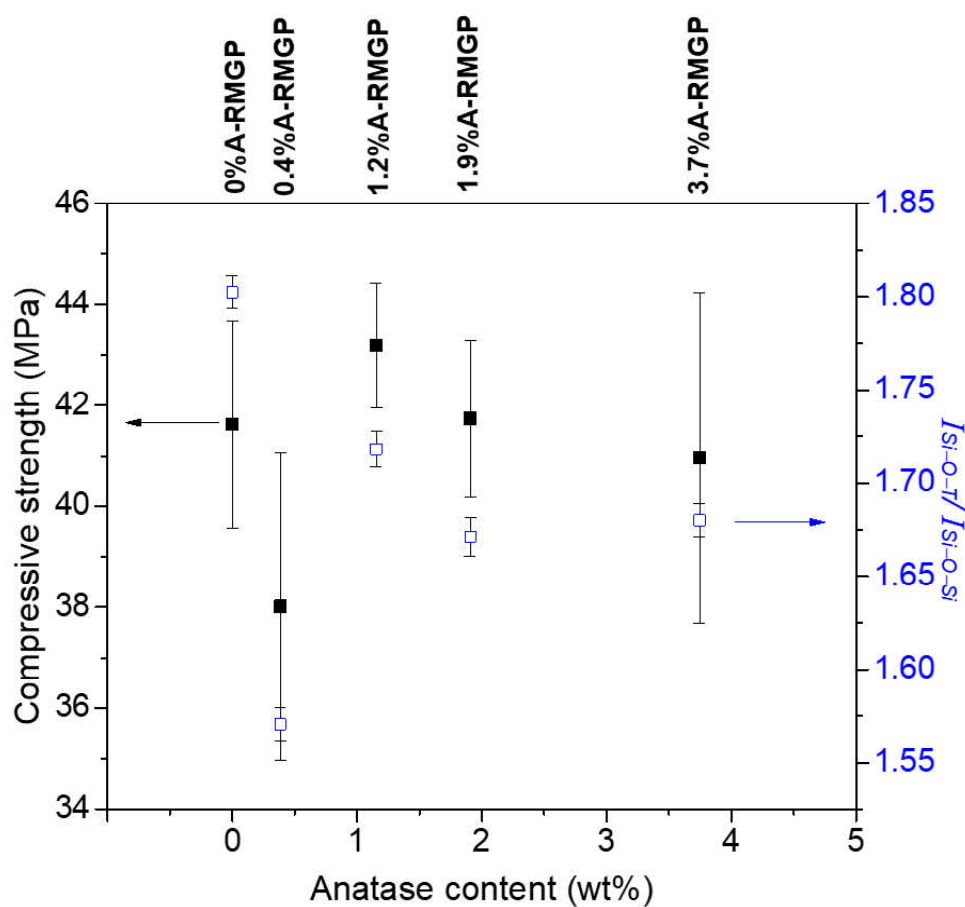


Figure A.4. Evolution of the ratios of the intensities of the bands corresponding to Si–O–T and Si–O–Si vibrations ( $I_{Si-O-T}/I_{Si-O-Si}$  ratio) and compressive strength of geopolymers as a function of anatase content (wt%) in the geopolymer pastes. Error bars represent the standard errors.

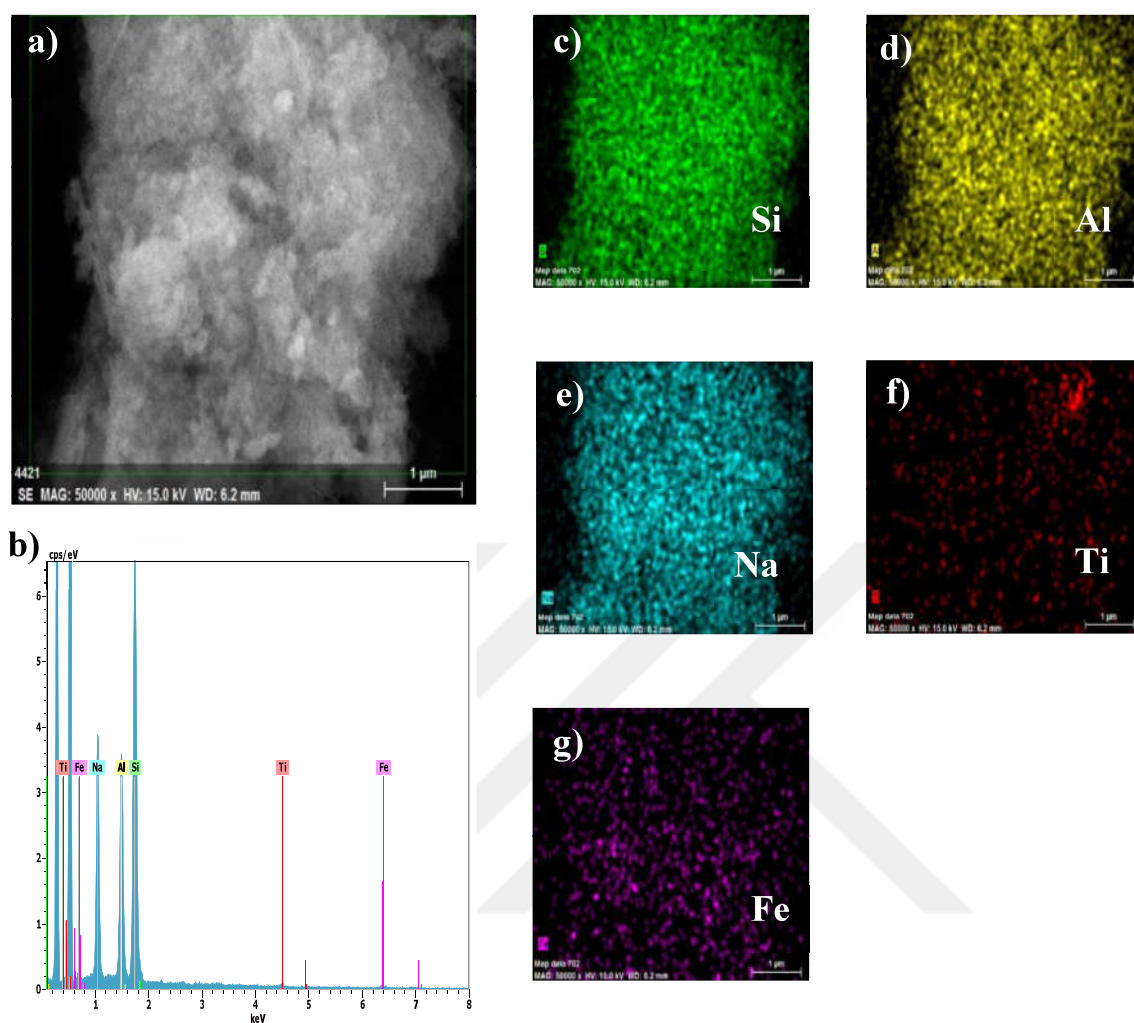


Figure A.5. SEM image, corresponding elemental analysis and EDS mapping of 0%A-RMGP: a) SEM image b) Elemental analysis and EDS mapping, including elemental analysis, c) Si, d) Al, e) Na, f) Ti, and g) Fe.

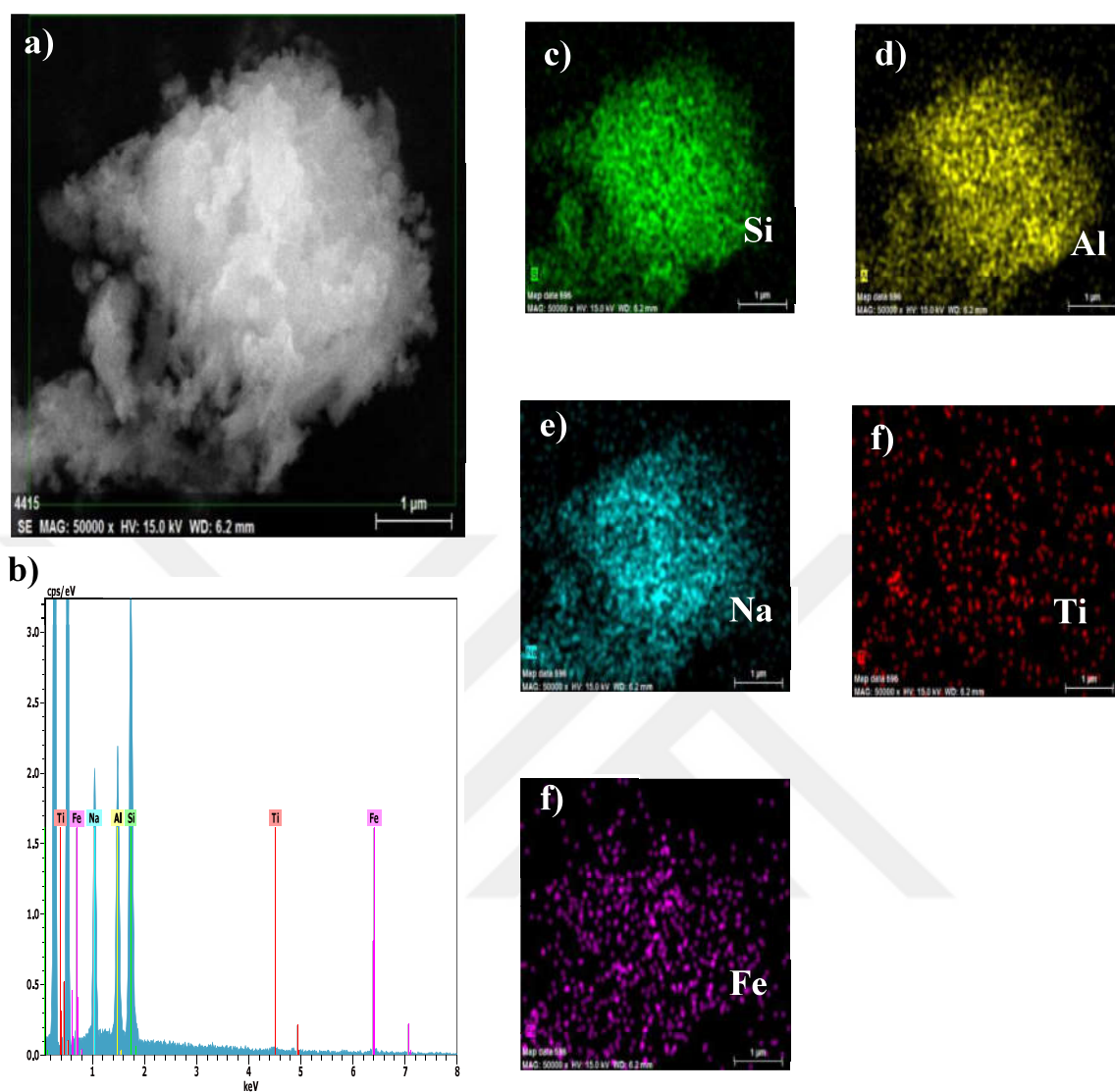


Figure A.6. SEM image, corresponding elemental analysis and EDS mapping of 0.4%A-RMGP: a) SEM image b) Elemental analysis and EDS mapping, including elemental analysis, c) Si, d) Al, e) Na, f) Ti, and g) Fe.

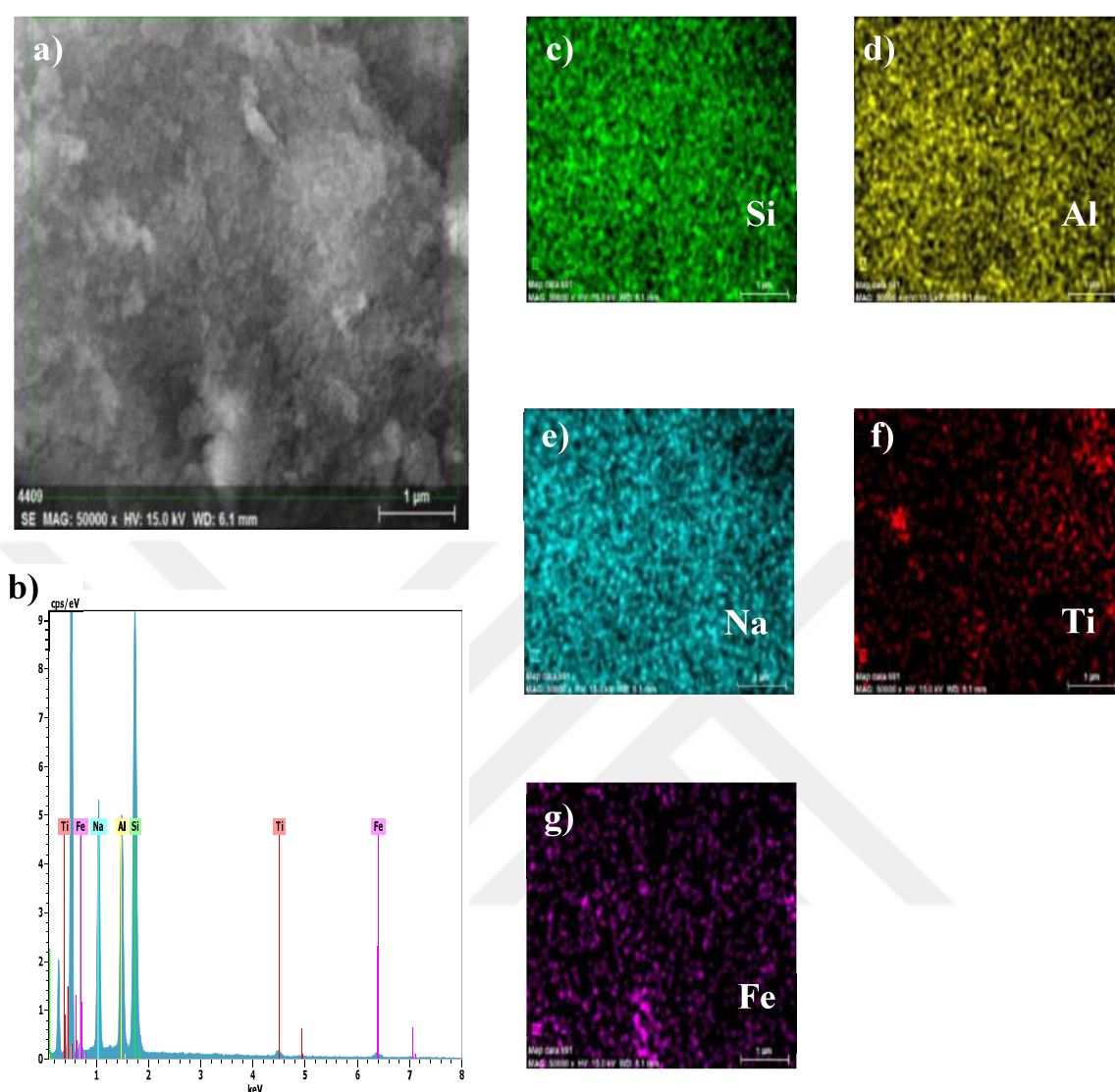


Figure A.7. SEM image, corresponding elemental analysis and EDS mapping of 1.2%A-RMGP: a) SEM image b) Elemental analysis and EDS mapping, including elemental analysis, c) Si, d) Al, e) Na, f) Ti, and g) Fe.

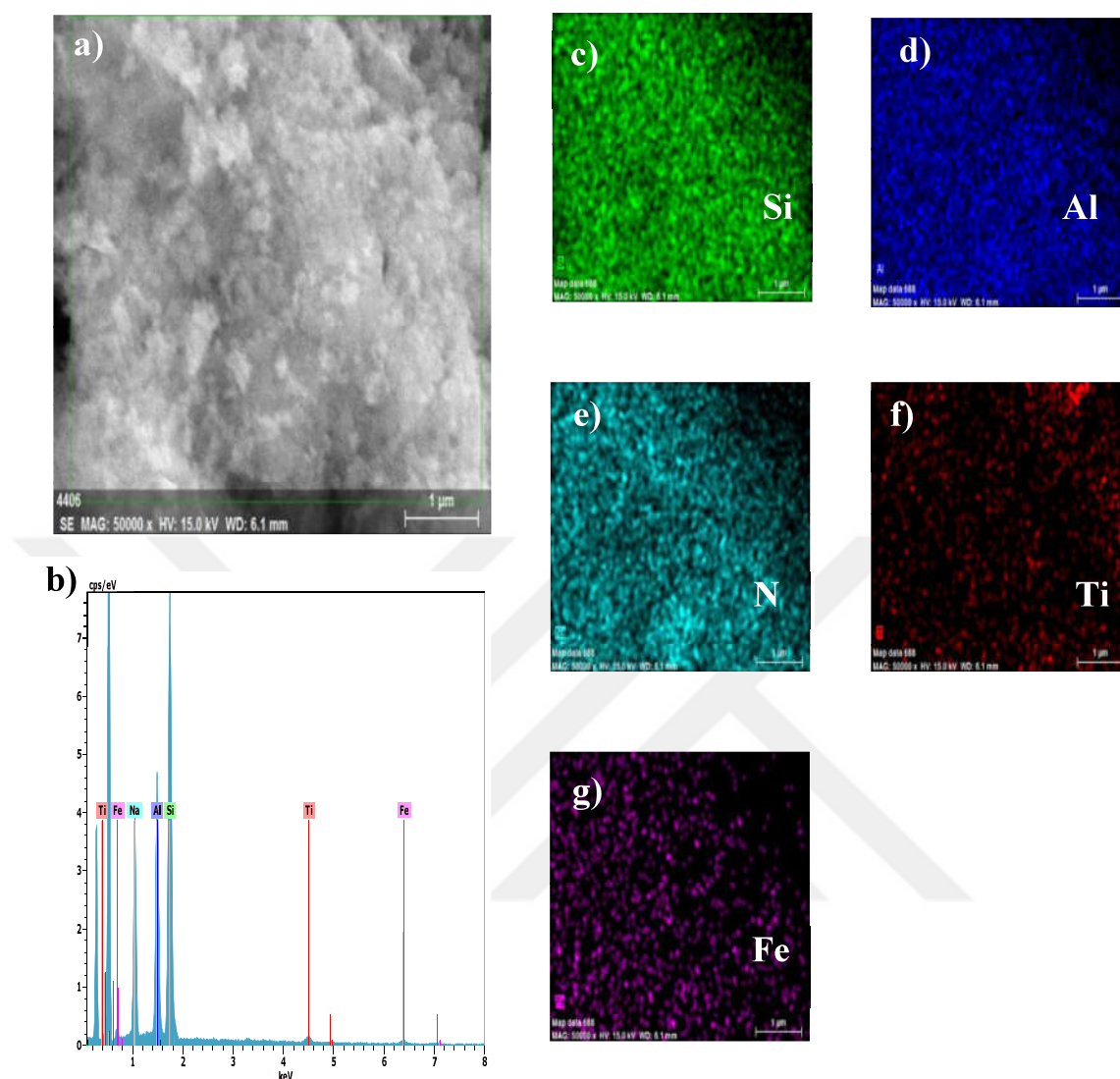


Figure A.8. SEM image, corresponding elemental analysis and EDS mapping of 1.9%A-RMGP: a) SEM image b) Elemental analysis and EDS mapping, including elemental analysis, c) Si, d) Al, e) Na, f) Ti, and g) Fe.

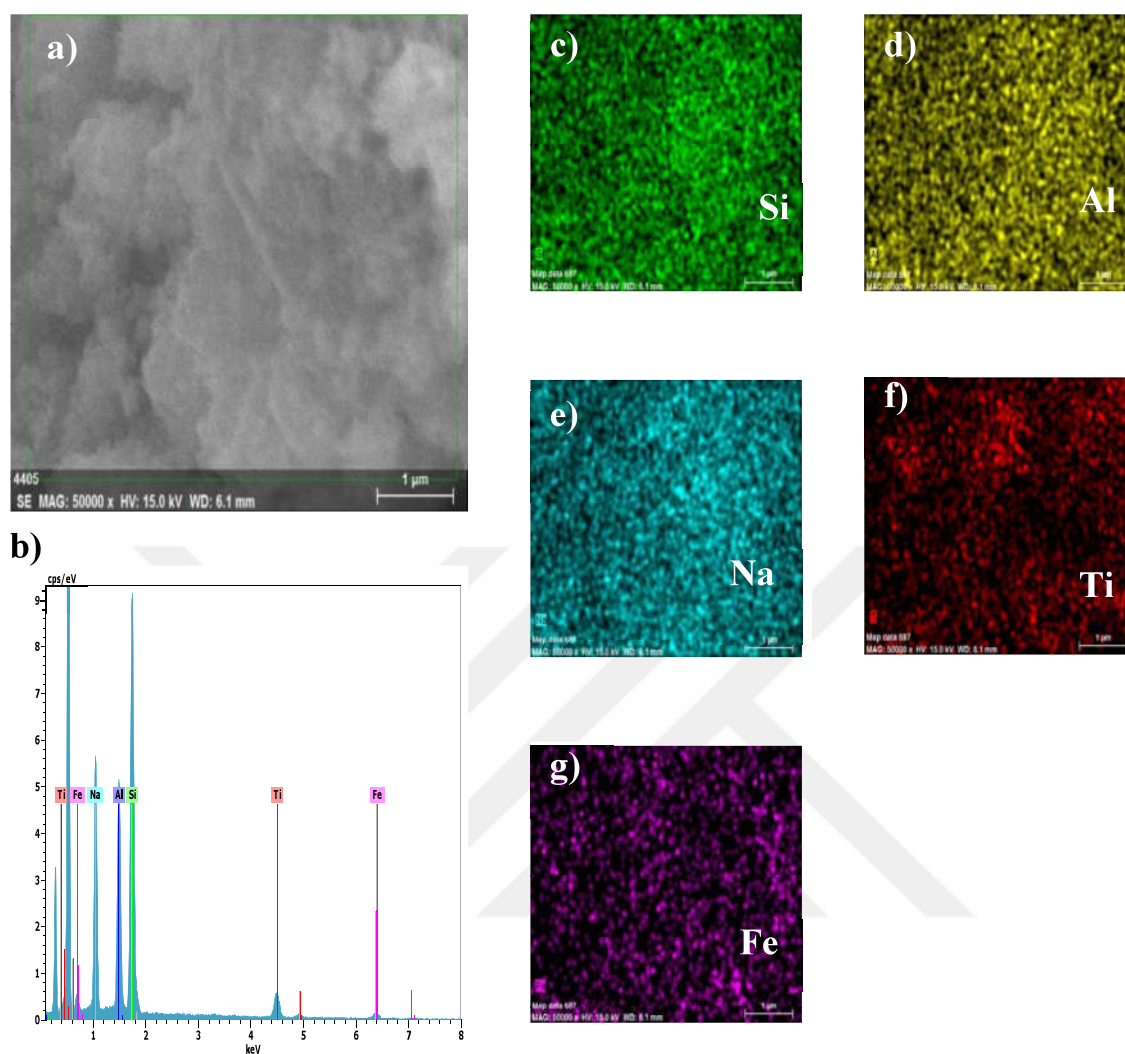


Figure A.9. SEM image, corresponding elemental analysis and EDS mapping of 3.7%A-RMGP: a) SEM image b) Elemental analysis and EDS mapping, including elemental analysis, c) Si, d) Al, e) Na, f) Ti, and g) Fe.

Table A.4. Atomic % of Si, Al, Na, Fe, and Ti in geopolymers which are calculated by taking the average of values from EDS spectra recorded from 3 spots.

| Sample     | Atomic % |      |      |      |      |
|------------|----------|------|------|------|------|
|            | Si       | Al   | Na   | Fe   | Ti   |
| 0%A-RMGP   | 48       | 21.9 | 26.3 | 3.56 | 0.74 |
| 0.4%A-RMGP | 46.2     | 20.5 | 28.3 | 3.18 | 1.79 |
| 1.2%A-RMGP | 46.2     | 20.5 | 26.1 | 3.54 | 2.18 |
| 1.9%A-RMGP | 43.2     | 21.8 | 24.9 | 2.48 | 3.08 |
| 3.7%A-RMGP | 42.4     | 18.8 | 23.9 | 3.19 | 6.99 |

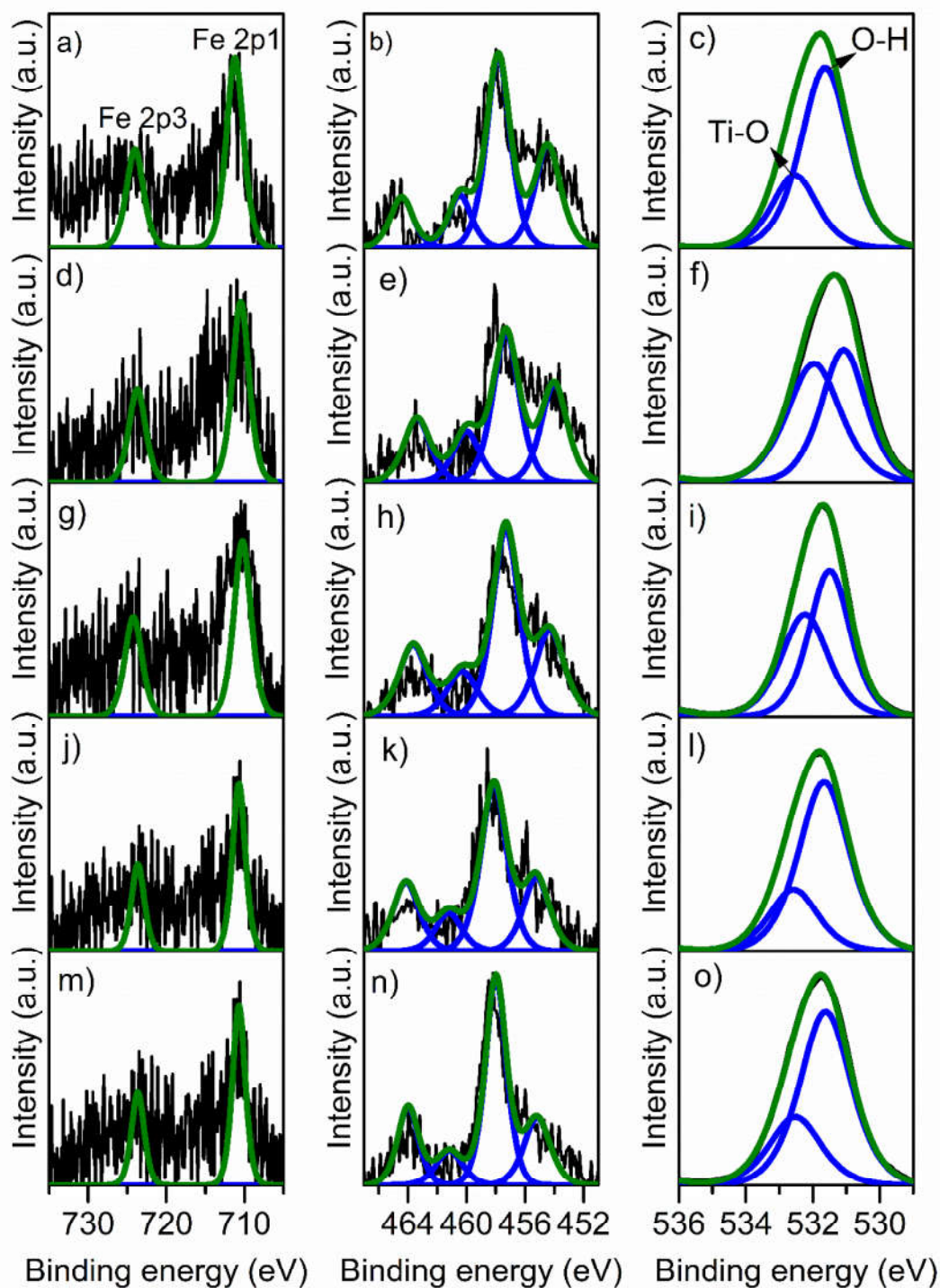


Fig A.10. XPS patterns of a) Fe 2p, b) Ti 2p, and c) O 1s spectrum of 0%A-RMGP, d) Fe 2p, e) Ti 2p and f) O 1s spectrum of 0.4%A-RMGP, g) Fe 2p, h) Ti 2p, and i) O 1s spectrum of 1.2%A-RMGP, j) Fe 2p, k) Ti 2p and l) O 1s spectrum of 1.9%A-RMGP, m) Fe 2p, n) Ti 2p, and o) O 1s spectrum of 3.7%A-RMGP (Blue lines: fitted individual peaks, green lines: envelope of all fitted peaks).

Table A.5. Binding energy values of geopolymers derived from XPS analysis.

| Sample     | O 1s position (eV) |               | Ti 2p positions (eV)         |                              |                              |                              | Fe 2p positions (eV)         |                              |
|------------|--------------------|---------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|
|            | ~531<br>Ti-O       | ~532<br>Ti-OH | ~454<br>Ti 2p <sub>3/2</sub> | ~457<br>Ti 2p <sub>3/2</sub> | ~460<br>Ti 2p <sub>1/2</sub> | ~464<br>Ti 2p <sub>1/2</sub> | ~711<br>Fe 2p <sub>3/2</sub> | ~723<br>Fe 2p <sub>1/2</sub> |
| 0%A-RMGP   | 531.63             | 532.54        | 454.45                       | 457.82                       | 460.45                       | 464.42                       | 711.21                       | 724.01                       |
| 0.4%A-RMGP | 530.98             | 531.87        | 454.01                       | 457.29                       | 460.01                       | 463.38                       | 710.48                       | 723.72                       |
| 1.2%A-RMGP | 530.86             | 531.7         | 454.31                       | 457.31                       | 460.31                       | 463.64                       | 710.07                       | 723.57                       |
| 1.9%A-RMGP | 531.66             | 532.57        | 455.22                       | 458.12                       | 461.22                       | 464.12                       | 710.71                       | 723.64                       |
| 3.7%A-RMGP | 531.62             | 532.52        | 455.17                       | 457.99                       | 461.17                       | 463.99                       | 710.55                       | 723.35                       |

Table A.6. Atomic % of Ti and Fe obtained from fitted peak information of Ti 2p and Fe 2p XP spectra.

| Sample     | Ti (at%) | Fe (at%) |
|------------|----------|----------|
| 0%A-RMGP   | 0.3      | 0.22     |
| 0.4%A-RMGP | 0.33     | 0.18     |
| 1.2%A-RMGP | 0.36     | 0.19     |
| 1.9%A-RMGP | 0.42     | 0.17     |
| 3.7%A-RMGP | 0.46     | 0.19     |

Table A.7. Band gap and maximum absorption wavelength values.

| Sample     | Band gap, E <sub>g</sub> (eV) | Maximum absorption wavelength, $\lambda_{\max}$ (nm) |
|------------|-------------------------------|------------------------------------------------------|
| MK         | 3.6                           | 390                                                  |
| RM         | 2.2                           | 590                                                  |
| 0%A-RMGP   | 2.9                           | 600                                                  |
| 0.4%A-RMGP | 2.9                           | 600                                                  |
| 1.2%A-RMGP | 2.9                           | 600                                                  |
| 1.9%A-RMGP | 3.2                           | 604                                                  |
| 3.7%A-RMGP | 3.2                           | 604                                                  |

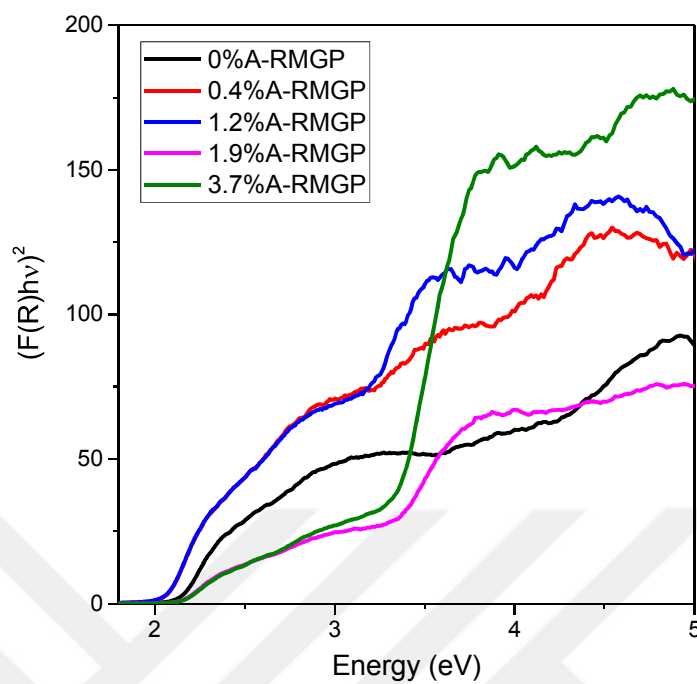


Fig A.11. Band gap values of geopolymers calculated by Kubelka Munk function.

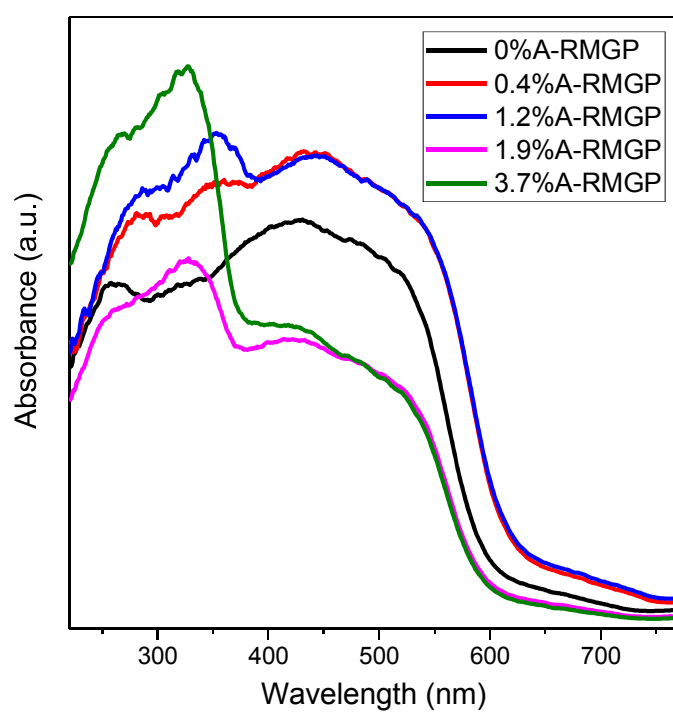


Fig A.12. Absorbance vs wavelength values of the geopolymers.

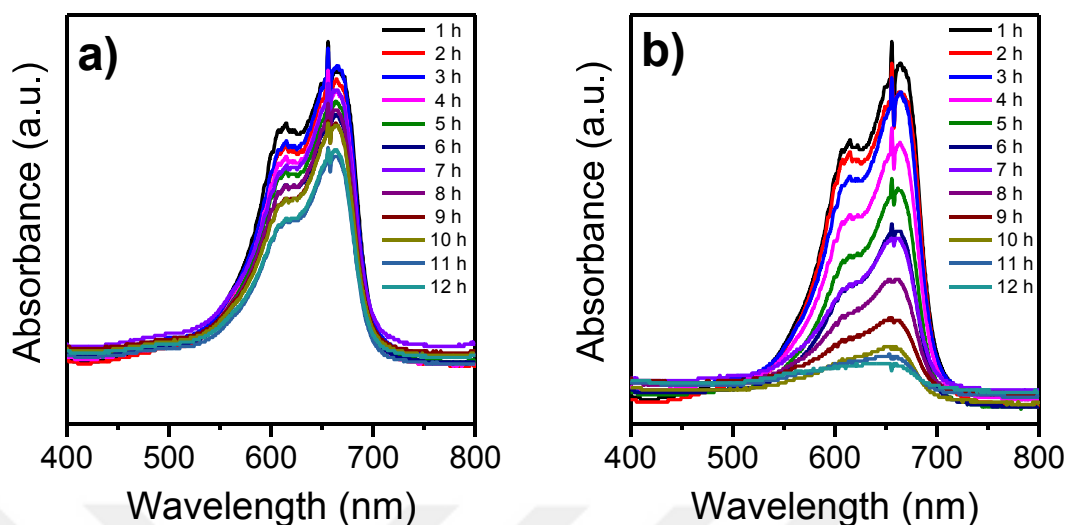


Figure A.13. UV-Vis spectrum of a) 0%A-RMGP and b) 10%A-RMGP.

- A1. Ozer, I. and S. Soyer-Uzun, “Relations Between the Structural Characteristics and Compressive Strength in Metakaolin Based Geopolymers with Different Molar Si/Al Ratios”, *Ceramics International*, Vol. 41, No. 8, pp. 10192–10198, 2015.
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- A5. Rendon, J. L. and C. J. Serna, “IR Spectra of Powder Hematite: Effects of Particle Size and Shape”, *Clay Minerals*, Vol. 16, No. 4, pp. 375–382, 1981.

- A6. Ye, N., J. Yang, X. Ke, J. Zhu, Y. Li, C. Xiang, H. Wang, and B. Xiao, "Synthesis and Characterization of Geopolymer from Bayer Red Mud with Thermal Pretreatment", *Journal of the American Ceramic Society*, Vol. 97, No. 5, pp. 1652–1660, 2014.



## APPENDIX B: SUPPLEMENTARY INFORMATION 2

Table B.1. Chemical compositions (wt%) of Sep and 1 h 750 °C calcined Sep used in this study, as determined by XRF spectroscopy.

| Material     | SiO <sub>2</sub> | MgO  | CaO   | Al <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | SO <sub>3</sub> |
|--------------|------------------|------|-------|--------------------------------|------------------|--------------------------------|------------------|-----------------|
| Sep          | 42.8             | 24.8 | 11    | 1.20                           | 0.10             | 0.50                           | 0.20             | 0.10            |
| Calcined Sep | 52.7             | 31.0 | 13.61 | 1.51                           | 0.07             | 0.59                           | 0.25             | 0.09            |

Table B.2. The amounts of raw materials (in g) used in the synthesis of Sep based AAM, corresponding molar Si/Mg and Na/Mg ratios, and synthesis conditions used in Sep-AAM synthesis in this study.

| Sample  | Calcined Sep (g) | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> solution (g) | Molar Si/Mg | Molar Na/Mg | Activating solution                            | Thermal treatment          |
|---------|------------------|-------------------------------------------------------------|-------------|-------------|------------------------------------------------|----------------------------|
| Sep-AAM | 6                | 19.08                                                       | 3           | 1           | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> | 1 day 40 °C + 1 week 25 °C |

Table B.3. Mix quantities per unit volume (kg m<sup>-3</sup>) calculated based on densities of the raw materials and assuming that the volumes of the components are additive. Corresponding wt% are given in parenthesis for the Sep-AAM paste.

| Sample  | Calcined Sep | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> solution | Total        |
|---------|--------------|---------------------------------------------------------|--------------|
| Sep-AAM | 368.2 (23.9) | 1171.2 (76.1)                                           | 1539.4 (100) |

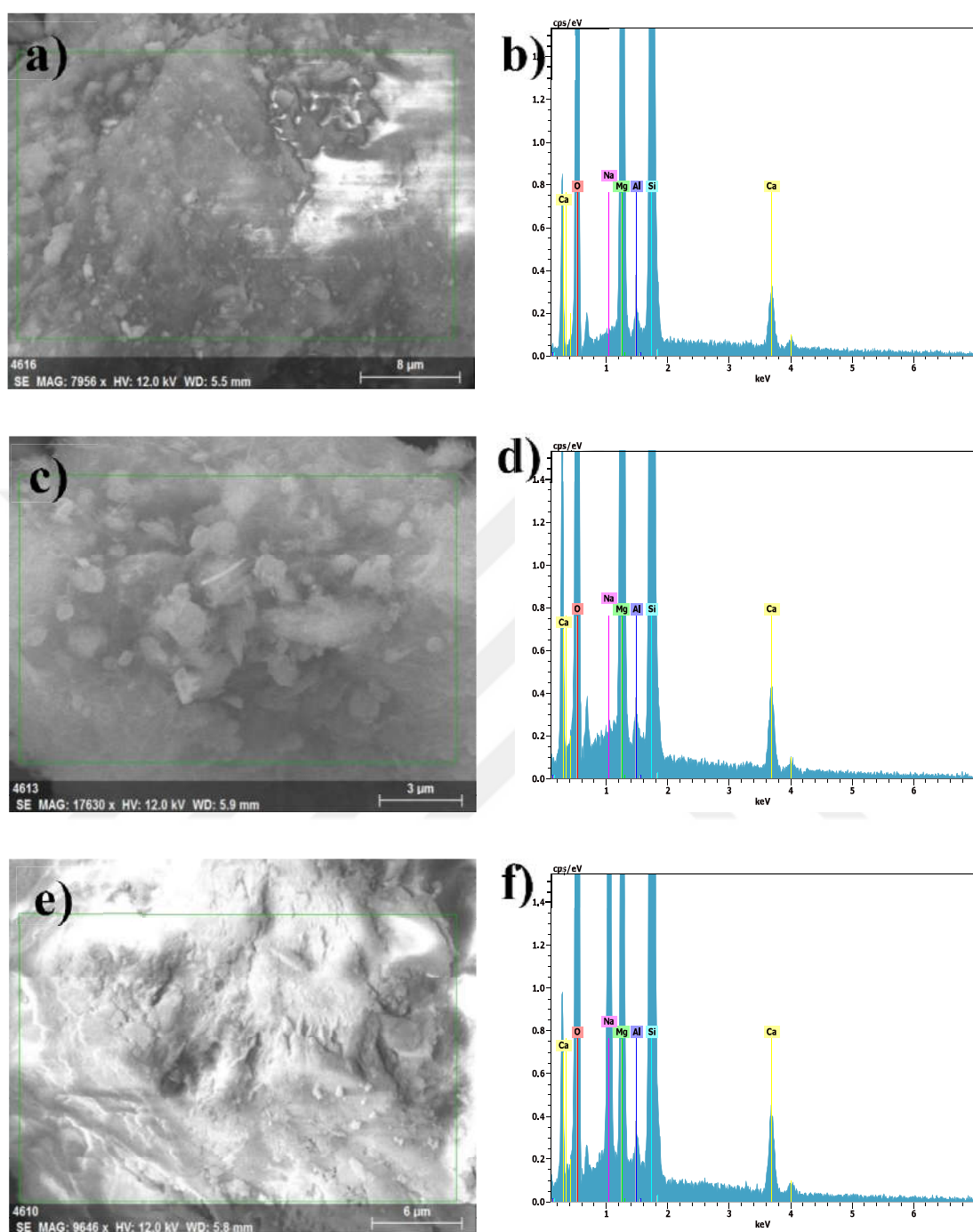


Figure B.1. SEM images and corresponding EDX spectra of materials: a) As-received Sep (at a magnification of 7956 $\times$ ), b) EDX spectrum of green  $\square$  in a), c) Calcined Sep (at a magnification of 17630 $\times$ ), d) EDX spectrum of green  $\square$  in c), e) Sep-AAM (at a magnification of 9646 $\times$ ), f) EDX spectrum of green  $\square$  in e).

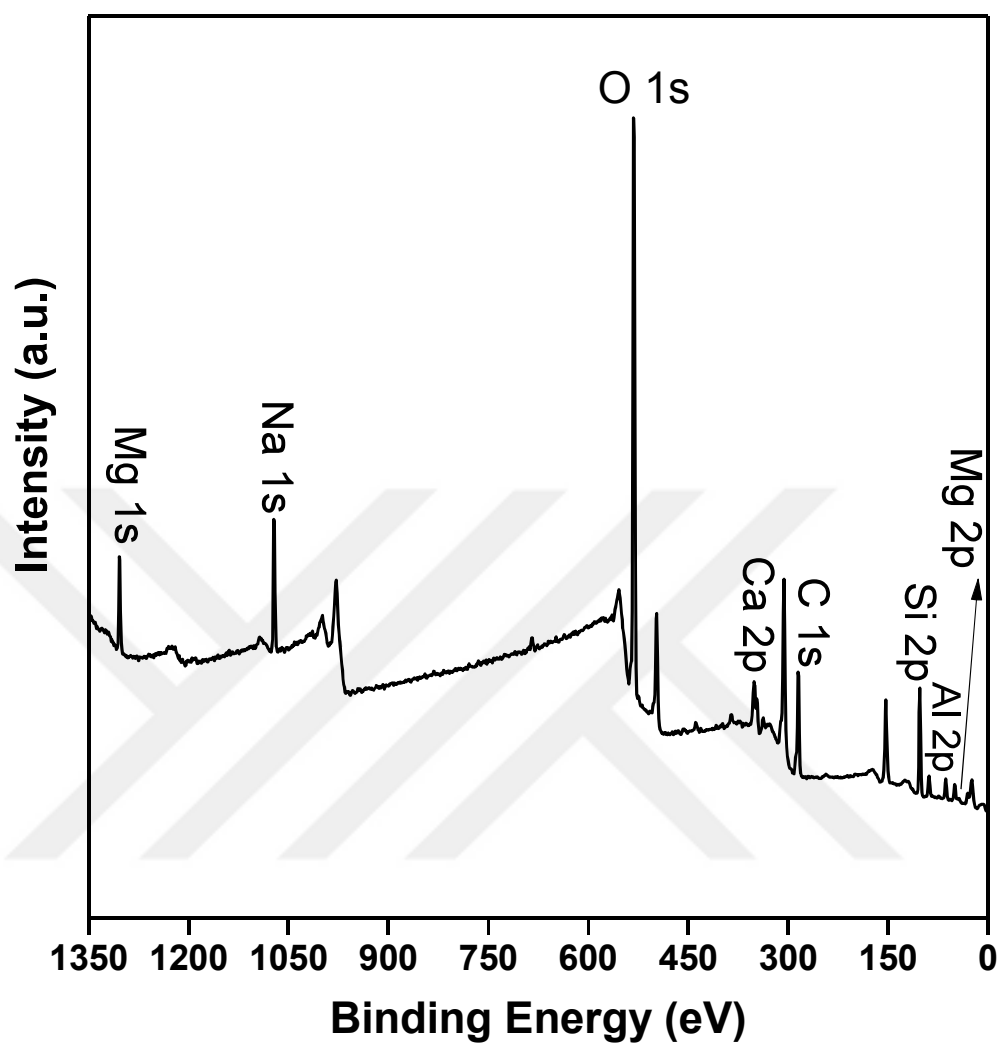


Figure B.2. XPS pattern of survey spectrum for Sep-AAM.

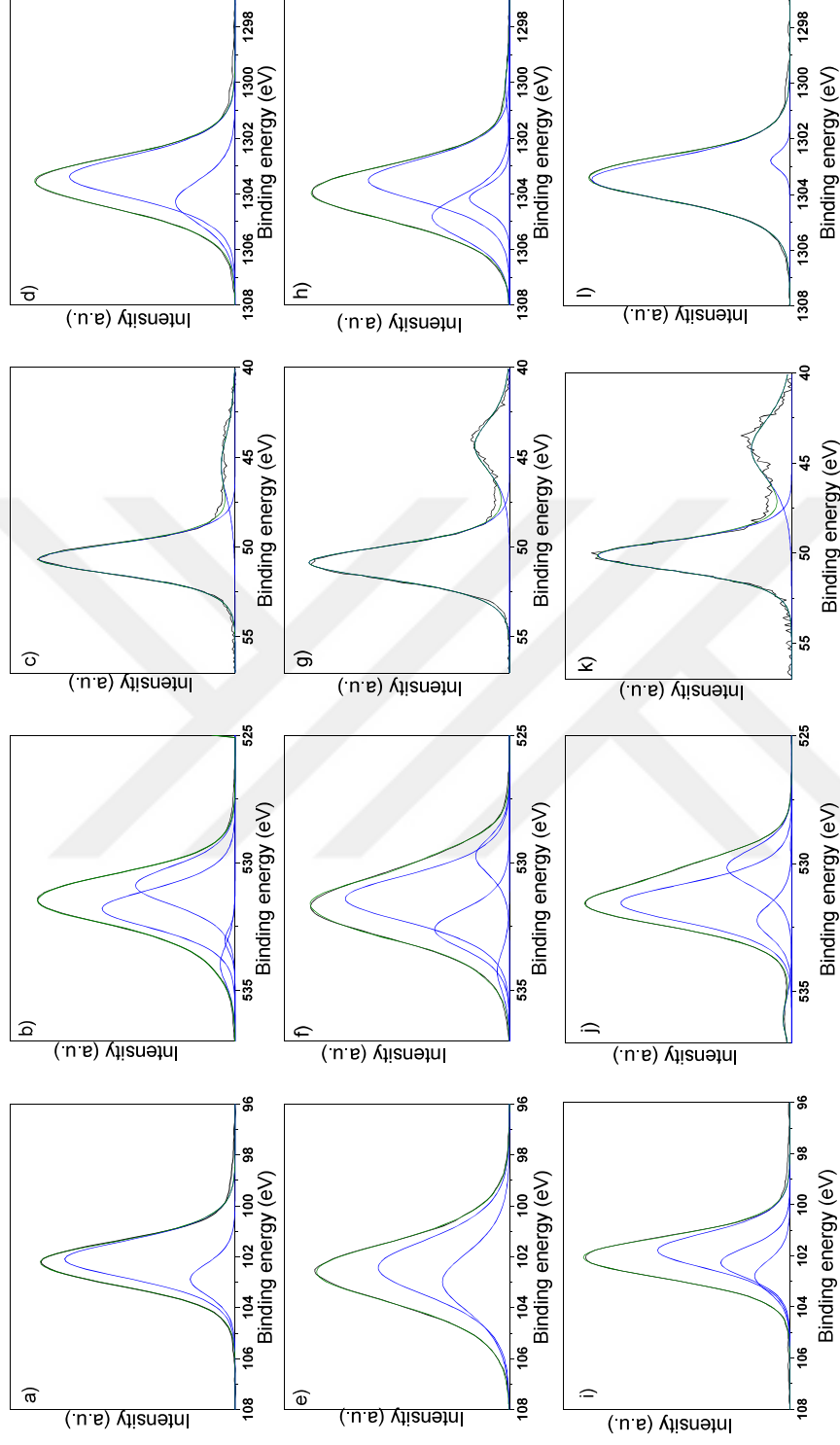


Figure B.3. XPS patterns of a) Si 2p, b) O 1s, c) Mg 2p, and d) Mg 1s spectrum of as-received Sep, e) Si 2p, f) O 1s, g) Mg 2p and h) Mg 1s spectrum of calcined Sep, i) Si 2p, j) O 1s, k) Mg 2p, and l) Mg 1s spectrum of Sep-

AAM (Blue lines: fitted individual peaks, green lines: envelope of all fitted peaks)

Table B.4. Binding energy values of samples derived from XPS analysis for O 1s spectrum.

| Sample       | O 1s position (eV) |        |        |        |        |        |        |
|--------------|--------------------|--------|--------|--------|--------|--------|--------|
|              | ~529               | ~530   | ~531   | ~532   | ~533   | ~534   | ~536   |
| Sep          | -                  | -      | 530.9  | 531.8  | 533.04 | 533.98 | -      |
| Calcined Sep | -                  | 529.54 | 531.2  | 532.4  | -      | 534.06 | -      |
| Sep-AAM      | 529.29             | 530.15 | 531.54 | 532.22 | -      | -      | 536.07 |

Table B.5. Binding energy values of samples derived from XPS analysis for Si 2p spectrum.

| Sample       | Si 2p position (eV) |        |
|--------------|---------------------|--------|
|              | ~102                | ~103   |
| Sep          | 102.09              | 102.88 |
| Calcined Sep | 102.42              | 102.98 |
| Sep-AAM      | 101.79              | 102.26 |
|              |                     | 102.79 |

Table B.6. Binding energy values of samples derived from XPS analysis for Mg 1s and Mg 2p spectrum.

| Sample       | Mg 1s and Mg 2p position (eV) |         |         |       |       |
|--------------|-------------------------------|---------|---------|-------|-------|
|              | ~1303                         | ~1304   | ~1305   | ~45   | ~50   |
| Sep          | 1303.39                       | 1304.3  | -       | 45.48 | 50.66 |
| Calcined Sep | 1303.52                       | 1304.17 | 1304.83 | 44.36 | 50.87 |
| Sep-AAM      | 1302.79                       | 1303.45 | -       | 44.22 | 50.13 |

Table B.7. Atomic % of Si, O, Mg, Ca, Al and Na obtained from fitted peak information of these elements' XP spectra.

| Sample       | Si<br>(at%) | O<br>(at%) | Mg<br>(at%) | Ca<br>(at%) | Al<br>(at%) | Na<br>(at%) |
|--------------|-------------|------------|-------------|-------------|-------------|-------------|
| Sep          | 32.97       | 48.39      | 11.61       | 4.84        | 2.2         | -           |
| Calcined Sep | 38.55       | 44.05      | 9.22        | 6.44        | 1.74        | -           |
| Sep-AAM      | 30.51       | 52.56      | 5.19        | 3.92        | 1.35        | 6.46        |

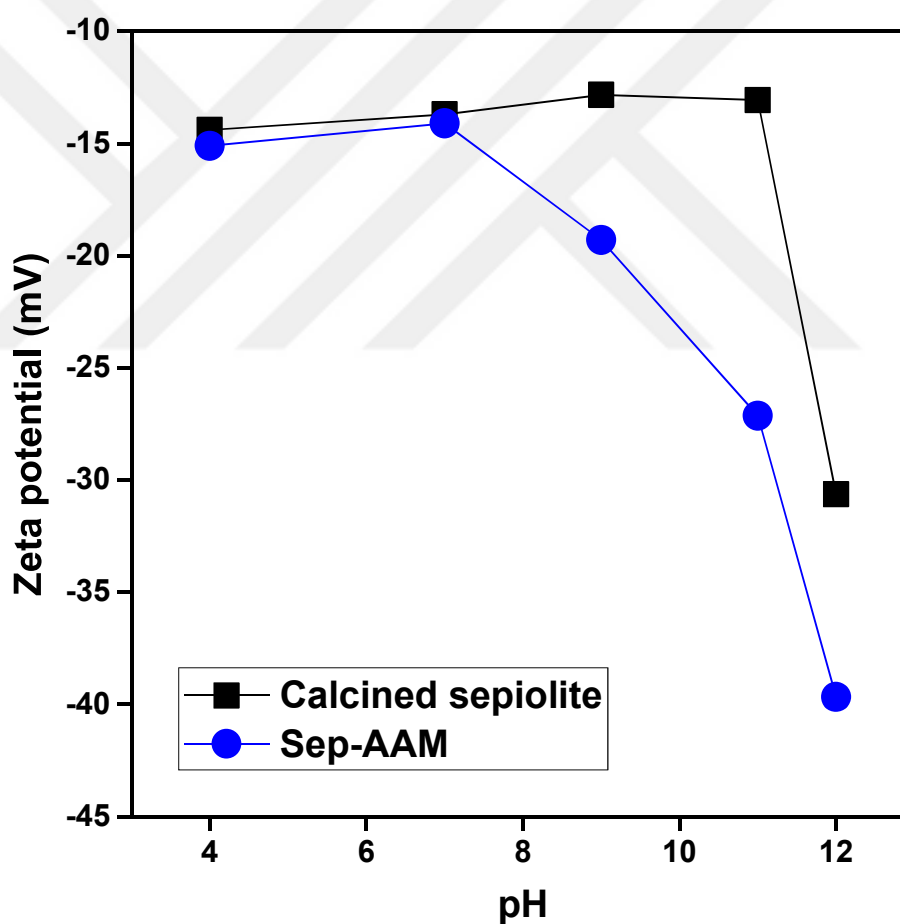


Figure B.4. The change of zeta potential with pH for calcined Sep and Sep-AAM.

Table B.8. The effect of temperature and adsorbent amount on the apparent pseudo-second-order adsorption kinetic rate constant and adsorption parameters for calcined Sep, and Sep-AAM (*Contact time* = 3.5 h,  $C_0 = 20 \text{ mg L}^{-1}$ ).

| Sample       | Temperature (°C) | Adsorbent amount (g) | $k_{2,ads,app}$ ( $\text{g mg}^{-1} \text{ min}^{-1}$ ) | $q_{e,exp}$ ( $\text{mg g}^{-1}$ ) | Removal (%) | $R^2$ |
|--------------|------------------|----------------------|---------------------------------------------------------|------------------------------------|-------------|-------|
| Calcined Sep | 31               | 0.006                | $3.8 \times 10^{-3}$                                    | 39.37                              | 23.17       | 0.99  |
|              |                  | 0.008                | $5.3 \times 10^{-3}$                                    | 39.37                              | 30.89       | 0.98  |
|              |                  | 0.01                 | $2.7 \times 10^{-2}$                                    | 47.25                              | 44.8        | 0.99  |
|              |                  | 0.012                | $3.2 \times 10^{-2}$                                    | 35.43                              | 41.71       | 0.99  |
|              | 40               | 0.006                | $2.8 \times 10^{-2}$                                    | 23.62                              | 13.9        | 0.94  |
|              |                  | 0.008                | $4.6 \times 10^{-2}$                                    | 29.53                              | 23.17       | 0.97  |
|              |                  | 0.01                 | $3.2 \times 10^{-1}$                                    | 49.02                              | 42.85       | 0.99  |
|              |                  | 0.012                | $3.8 \times 10^{-1}$                                    | 40.68                              | 47.89       | 0.98  |
|              | 50               | 0.006                | $9.2 \times 10^{-4}$                                    | 68.24                              | 40.8        | 0.98  |
|              |                  | 0.008                | $1.1 \times 10^{-3}$                                    | 64.96                              | 51.8        | 0.98  |
|              |                  | 0.01                 | $1.5 \times 10^{-2}$                                    | 63                                 | 54          | 0.98  |
|              |                  | 0.012                | $1.8 \times 10^{-2}$                                    | 45.1                               | 53          | 0.98  |
| Sep-AAM      | 31               | 0.006                | $4.4 \times 10^{-4}$                                    | 73.49                              | 40.10       | 0.96  |
|              |                  | 0.008                | $5.3 \times 10^{-4}$                                    | 74.80                              | 54.49       | 0.91  |
|              |                  | 0.01                 | $6.5 \times 10^{-4}$                                    | 74.64                              | 72.11       | 0.98  |
|              |                  | 0.012                | $7.8 \times 10^{-4}$                                    | 71.12                              | 73.5        | 0.99  |
|              | 40               | 0.006                | $6.0 \times 10^{-4}$                                    | 89.24                              | 47.4        | 0.98  |
|              |                  | 0.008                | $7.7 \times 10^{-4}$                                    | 78.74                              | 54.0        | 0.98  |
|              |                  | 0.01                 | $9.4 \times 10^{-4}$                                    | 79.06                              | 75.2        | 0.98  |
|              |                  | 0.012                | $1.0 \times 10^{-4}$                                    | 74.80                              | 79.48       | 0.98  |

Table B.8. The effect of temperature and adsorbent amount on the apparent pseudo-second-order adsorption kinetic rate constant and adsorption parameters for calcined Sep, and Sep-AAM (*Contact time* = 3.5 h,  $C_0 = 20 \text{ mg L}^{-1}$ ). (cont.)

|         |    |       |                      |       |       |      |
|---------|----|-------|----------------------|-------|-------|------|
| Sep-AAM | 50 | 0.006 | $6.1 \times 10^{-4}$ | 94.49 | 49.49 | 0.98 |
|         |    | 0.008 | $8.9 \times 10^{-4}$ | 75.50 | 55.8  | 0.98 |
|         |    | 0.01  | $9.8 \times 10^{-4}$ | 93.70 | 81.25 | 0.99 |
|         |    | 0.012 | $1.1 \times 10^{-3}$ | 80.87 | 84.72 | 0.99 |

Table B.9. Uptake performance and removal efficiency (%) for adsorption of MB onto as-received Sep at different temperatures (*Contact time* = 3.5h,  $C_0 = 20 \text{ mg L}^{-1}$ , and  $m = 10 \text{ mg}$ ).

| Adsorbent              | $q_{e,exp} (\text{mg g}^{-1})$ | Removal (%) |
|------------------------|--------------------------------|-------------|
| As-received Sep, 31 °C | 31.5                           | 30.9        |
| As-received Sep, 40 °C | 26.8                           | 26.3        |
| As-received Sep, 50 °C | 26.8                           | 26.3        |

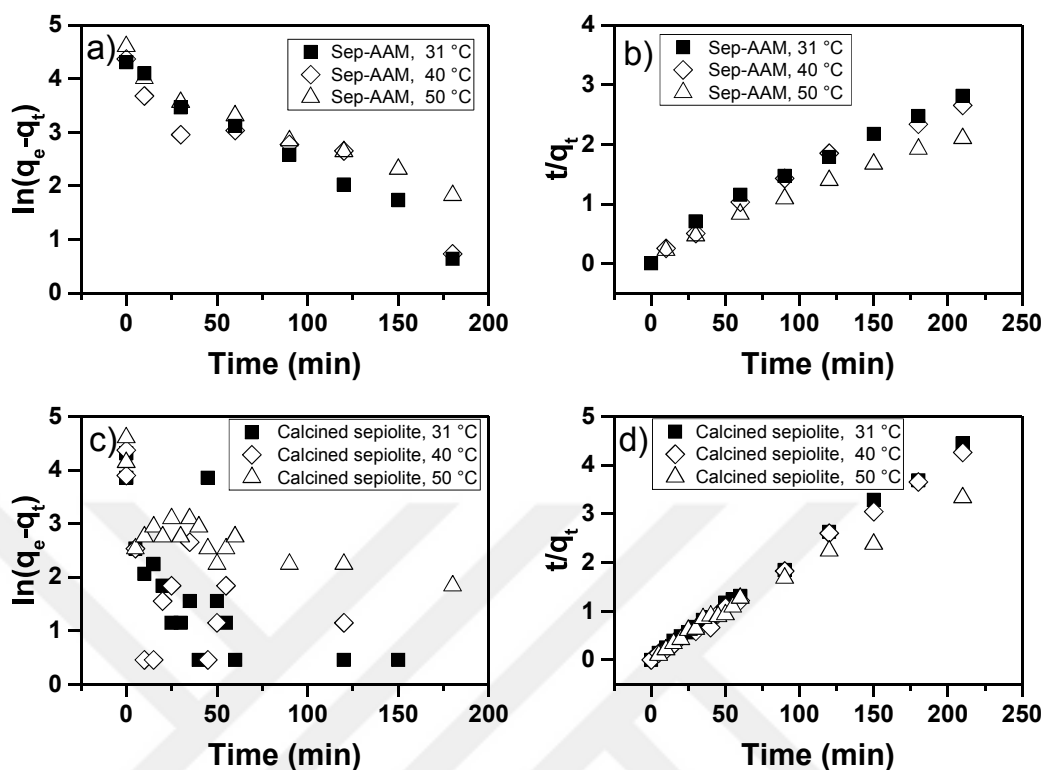


Figure B.5. Pseudo-first and pseudo-second-order kinetic models for the adsorption of MB onto a-b) Sep-AAM, and c-d) Calcined Sep, at different temperatures.

Table B.10. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto calcined Sep at different temperatures (*Contact time* = 3.5 h,  $C_0 = 20 \text{ mg L}^{-1}$  and  $m = 10 \text{ mg}$ ).

| Adsorbent           | $q_{e,exp}$<br>( $\text{mg g}^{-1}$ ) | Pseudo-first-order adsorption kinetics<br>( $C_0 = 20 \text{ mg L}^{-1}$ ) |                        |       | Pseudo-second-order adsorption kinetics<br>( $C_0 = 20 \text{ mg L}^{-1}$ ) |                        |       | Removal (%) |
|---------------------|---------------------------------------|----------------------------------------------------------------------------|------------------------|-------|-----------------------------------------------------------------------------|------------------------|-------|-------------|
|                     |                                       | $k_{1,ads,app}$                                                            | $q_{e,cal}$            | $R^2$ | $k_{2,ads,app}$                                                             | $q_{e,cal}$            | $R^2$ |             |
|                     |                                       | ( $\text{min}^{-1}$ )                                                      | ( $\text{mg g}^{-1}$ ) |       | ( $\text{g mg}^{-1} \text{ min}^{-1}$ )                                     | ( $\text{mg g}^{-1}$ ) |       |             |
| Calcined Sep, 31 °C | 47.25                                 | $1.48 \times 10^{-2}$                                                      | 7.0                    | 0.50  | $2.67 \times 10^{-2}$                                                       | 46.95                  | 0.99  | 44.80       |
| Calcined Sep, 40 °C | 49.28                                 | $9.7 \times 10^{-3}$                                                       | 7.15                   | 0.09  | $3.20 \times 10^{-1}$                                                       | 49.01                  | 0.99  | 42.85       |
| Calcined Sep, 50 °C | 63                                    | $7.8 \times 10^{-3}$                                                       | 22.02                  | 0.50  | $1.53 \times 10^{-1}$                                                       | 63.29                  | 0.98  | 54.0        |

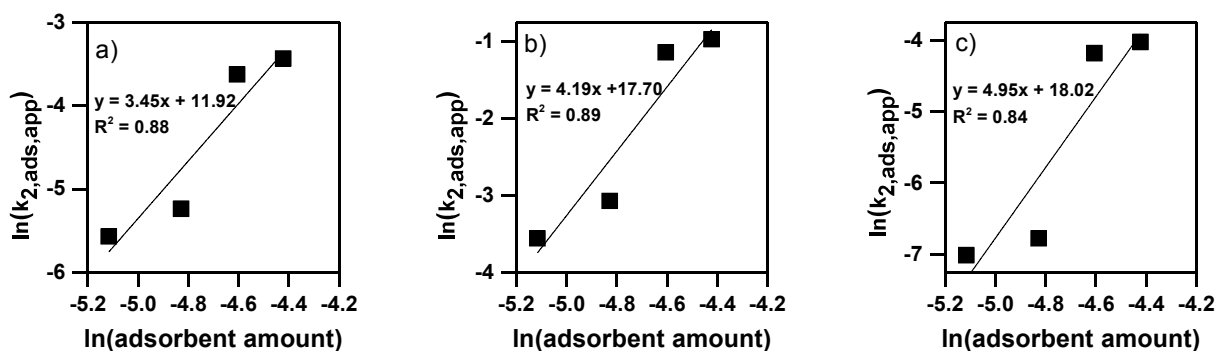


Figure B.6. Experimental data fit to pseudo-second-order adsorption kinetics for calcined Sep at a) 31 °C, b) 40 °C, and c) 50 °C.

Table B.11. Actual second-order adsorption rate constants ( $k_{2,ads}$ ) of calcined Sep at different temperatures.

| Temperature (°C) | $k_{2,ads} ((\text{g adsorbent})^{-3.2} (\text{mg MB})^{-1} \text{min}^{-1}) \times 10^{-5}$ |
|------------------|----------------------------------------------------------------------------------------------|
| 31               | 1.5                                                                                          |
| 40               | 484.5                                                                                        |
| 50               | 667.2                                                                                        |

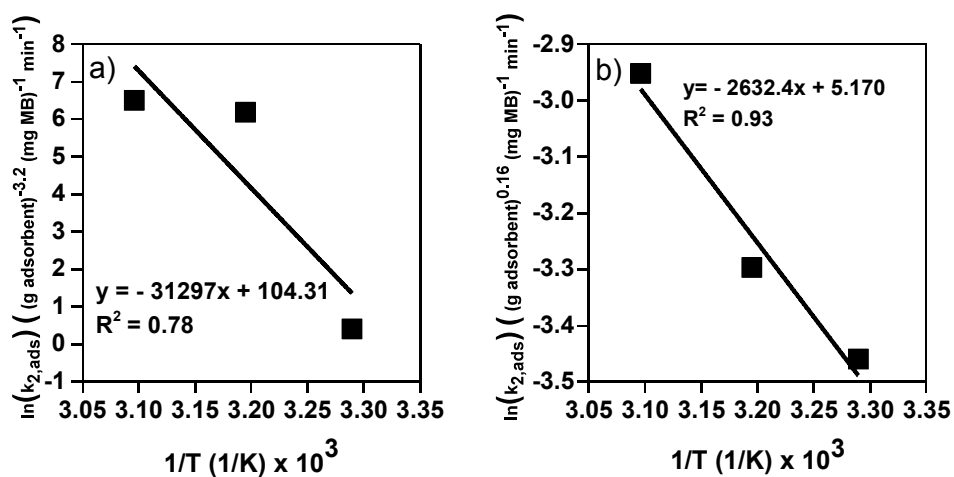


Figure B.7. The plot of  $\ln(k_{2,ads})$  vs  $1/T$  for a) calcined Sep and b) Sep-AAM.

According to the plot of  $\ln(k_{2,ads})$  vs  $1/T$ , pre-exponential factor  $A$  of Arrhenius equation is  $175.94 ((\text{g adsorbent})^{0.16} (\text{mg MB}^{-1}) (\text{min}^{-1}))$  and  $2 \times 10^{45} ((\text{g adsorbent})^{-3.2} (\text{mg MB}^{-1}) (\text{min}^{-1}))$ .

MB<sup>-1</sup>) (min<sup>-1</sup>), for Sep-AAM and calcined Sep, respectively.  $k_{2,ads}$  is the actual second-order adsorption rate constant.

The adsorption rate can be controlled by different processes involving external mass transfer or boundary layer diffusion that is followed by intraparticle diffusion, where adsorbate molecules diffuse from the surface to the internal sites. Therefore, this model gives information about the diffusion mechanism of adsorption process that can be dominated by film or pore diffusion [1]. The intraparticle diffusion model applied on Sep-AAM shown in Figure B.8 shows multilinearity that includes two steps pointing out the existence of boundary layer diffusion and intraparticle diffusion in the adsorption process of MB dyes onto Sep-AAM particles. The second line which represents the intraparticle diffusion range, not passing through the origin implies that intraparticle diffusion is not the only rate controlling step for this adsorption process [2–4]. In our system, boundary layer diffusion has the main effect on the adsorption process at initial time periods and at the later stages of adsorption, intraparticle diffusion controls the adsorption. However, for calcined Sep no such trend was observed and experimental data were found to be poorly fitted to this model. Table B.12 summarizes these findings for Sep-AAM samples operated at different temperatures. The first sharper region in Figure B.8 detected at the initial time values of adsorption process is related with the diffusion of MB dye molecules through the solution to the external surface of Sep-AAM and the boundary layer diffusion of MB molecules. The slope of the first region being high shows that there is a rapid adsorption within first 30 minutes. The intercept obtained from the second linear region is proportional to the boundary layer thickness and shows the presence of viscous drag between the adsorbate and the adsorbent [1]. This second step also defines the adsorption step, where the MB molecules are transported via intraparticle diffusion. For our system, as it can be seen from Table B.12, for the second step, the value of  $C$  increases with temperature revealing the higher uptake values detected at higher temperatures. As it can be seen from Figure B.8, this second stage, that covers the time region after first 30 minutes, is rather slow showing that intraparticle diffusion of MB molecules into Sep-AAM pores was rate limiting after first 30 minutes of the adsorption process [5]. Similar results were also reported by Künceket al. who also studied the intraparticle diffusion mechanism on the sonicated Sep [6]. For calcined Sep in this study, the correlation coefficient obtained from fitting experimental data to intraparticle diffusion model was low ( $R^2 = 0.63$ ).

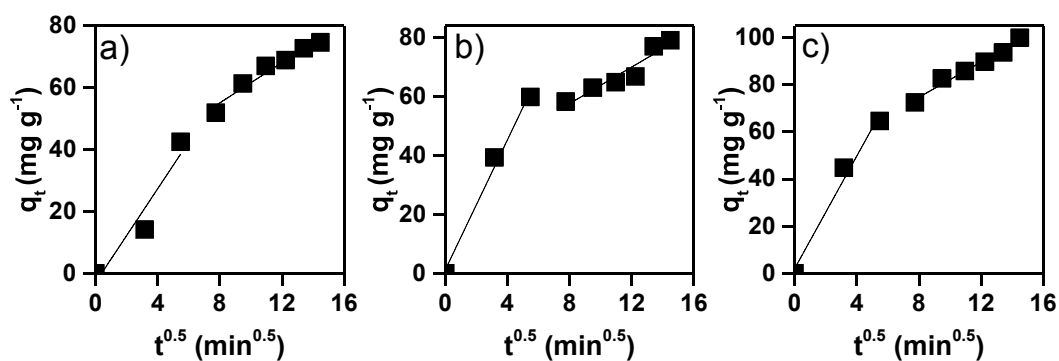


Figure B.8. Intraparticle diffusion model for the adsorption of MB onto Sep-AAM at a) 31 °C, b) 40 °C, and c) at 50 °C.

Table B.12. Parameters of intraparticle diffusion model for Sep-AAM at different temperatures.

| Temperature<br>(°C) | $k_{p,1}$<br>(mg g <sup>-1</sup> min <sup>-0.5</sup> ) | $C_1$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{p,2}$<br>(mg g <sup>-1</sup> min <sup>-0.5</sup> ) | $C_2$<br>(mg g <sup>-1</sup> ) | $R^2$ |
|---------------------|--------------------------------------------------------|--------------------------------|-------|--------------------------------------------------------|--------------------------------|-------|
| 31                  | 7.56                                                   | -2.90                          | 0.92  | 3.24                                                   | 1.34                           | 0.99  |
| 40                  | 11.01                                                  | 1.34                           | 0.99  | 3.09                                                   | 32.85                          | 0.91  |
| 50                  | 11.93                                                  | 2.12                           | 0.98  | 3.73                                                   | 44.85                          | 0.97  |

Table B.13. Concentration (ppm) of leached elements from adsorbent to MB solution measured by ICP-MS.

| Element concentration<br>(ppm) | Calcined Sep | Sep-AAM |
|--------------------------------|--------------|---------|
| Al                             | 0.048        | 0.026   |
| Mg                             | 4.073        | 2.098   |
| Fe                             | 0.186        | 0       |

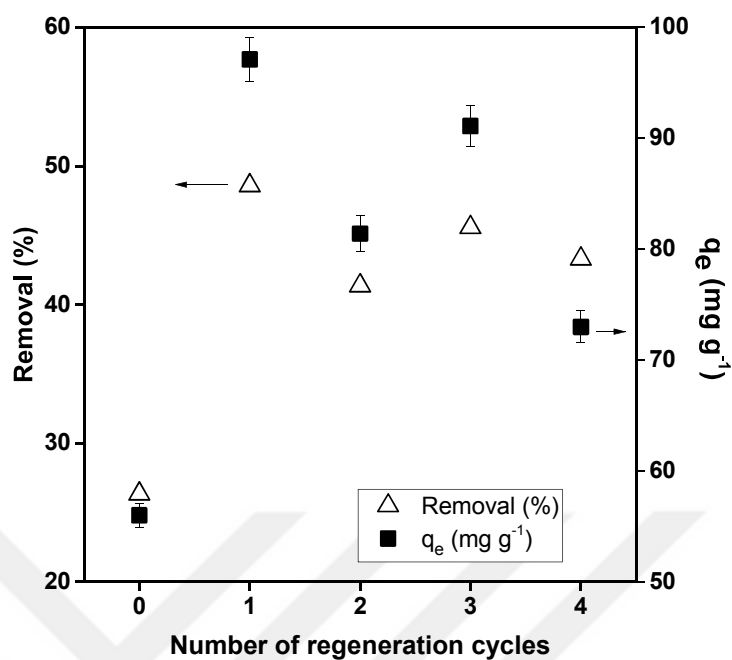


Figure B.9. MB removal (%) and uptake values for calcined Sep after regeneration cycles.

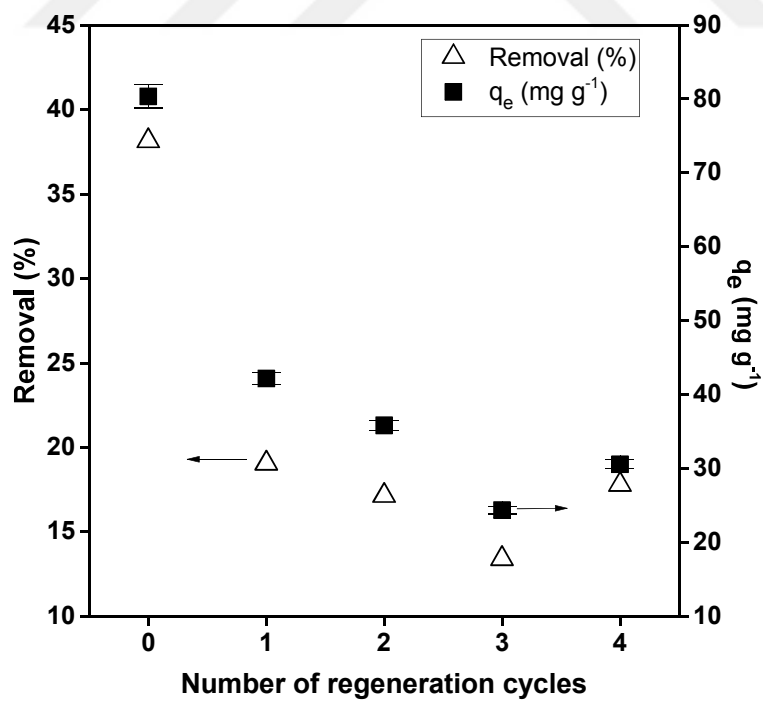


Figure B.10. MB removal (%) and uptake values for Sep-AAM after regeneration cycles.

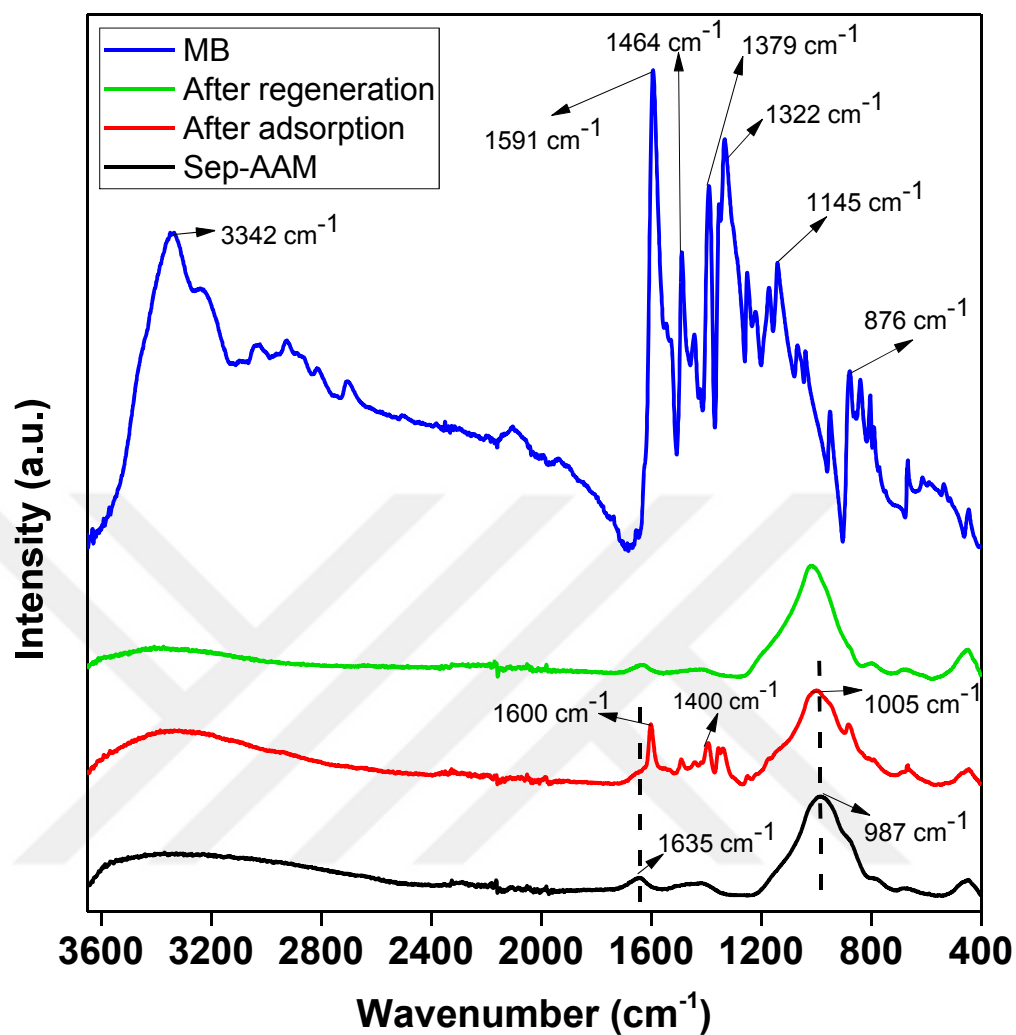


Figure B.11. FTIR spectra of MB and Sep-AAM sample before and after adsorption, and after 4 cycles of regeneration (*Contact time* = 3.5 h).

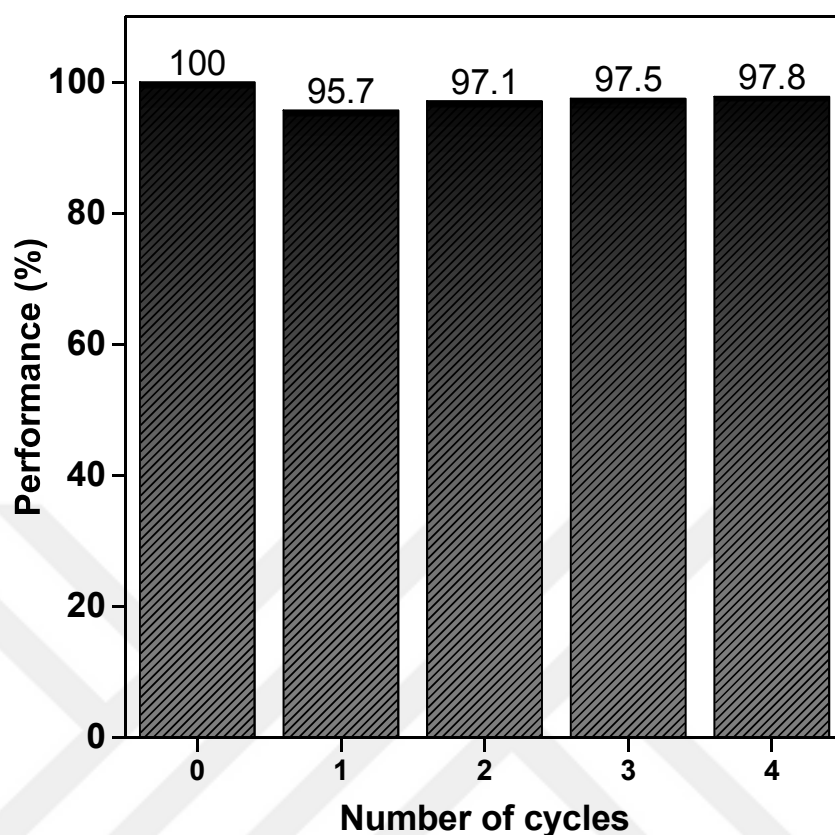


Figure B.12. The change in the performance (%) of Sep-AAM monoliths during regeneration experiments.

Table B.14. Langmuir and Freundlich isotherm constants for MB adsorption on calcined Sep at different temperatures.

| Adsorbents          | Langmuir Model                 |                                    |       | Freundlich Model               |                             |       |
|---------------------|--------------------------------|------------------------------------|-------|--------------------------------|-----------------------------|-------|
|                     | $K_L$<br>(L mg <sup>-1</sup> ) | $q_{max}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $K_F$<br>(mg g <sup>-1</sup> ) | $n$<br>(g L <sup>-1</sup> ) | $R^2$ |
| Calcined Sep, 31 °C | 1.25                           | 56.18                              | 0.99  | 34.17                          | 6.58                        | 0.89  |
| Calcined Sep, 40 °C | 1.29                           | 54.35                              | 0.99  | 30.26                          | 5.30                        | 0.68  |
| Calcined Sep, 50 °C | 1.48                           | 75.19                              | 0.98  | 42.19                          | 4.89                        | 0.78  |

Table B.15. Langmuir separation factor  $R_L$  for calcined Sep and Sep-AAM at different temperatures, at all the initial MB concentrations used.

| Sample       | Initial MB concentration<br>(mg L <sup>-1</sup> ) | $R_L$ |       |       |
|--------------|---------------------------------------------------|-------|-------|-------|
|              |                                                   | 31 °C | 40 °C | 50 °C |
| Calcined Sep | 5                                                 | 0.138 | 0.154 | 0.120 |
|              | 7                                                 | 0.102 | 0.110 | 0.089 |
|              | 10                                                | 0.074 | 0.077 | 0.064 |
|              | 15                                                | 0.050 | 0.051 | 0.044 |
|              | 20                                                | 0.038 | 0.038 | 0.033 |
|              | 30                                                | 0.026 | 0.026 | 0.022 |
|              | 35                                                | 0.022 | 0.022 | 0.019 |
|              | 40                                                | 0.019 | 0.019 | 0.017 |
| Sep-AAM      | 5                                                 | 0.095 | 0.079 | 0.061 |
|              | 7                                                 | 0.070 | 0.058 | 0.044 |
|              | 10                                                | 0.050 | 0.041 | 0.032 |
|              | 15                                                | 0.034 | 0.027 | 0.021 |
|              | 20                                                | 0.026 | 0.021 | 0.016 |
|              | 30                                                | 0.017 | 0.014 | 0.011 |
|              | 35                                                | 0.015 | 0.012 | 0.009 |
|              | 40                                                | 0.013 | 0.011 | 0.008 |

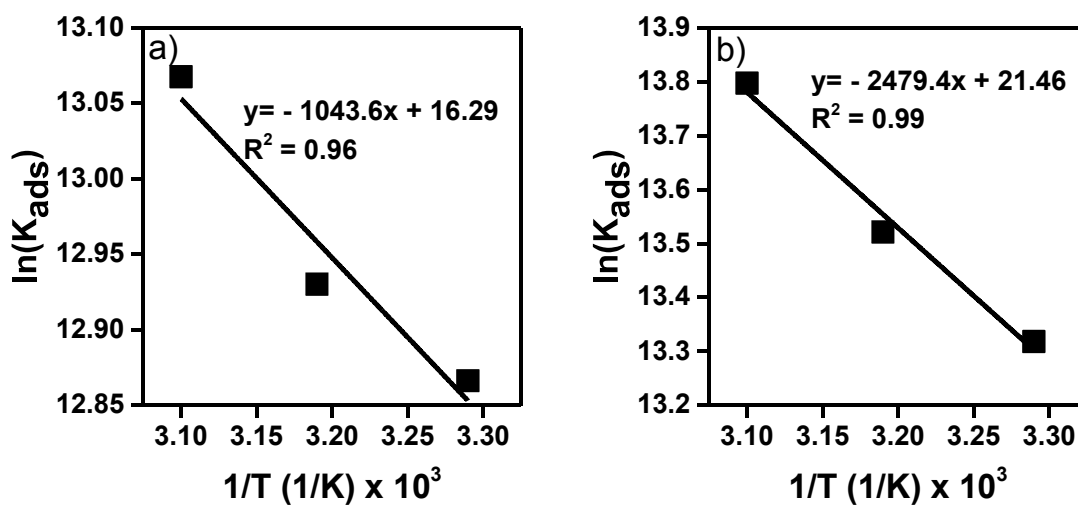


Figure B.13.  $\ln(K_{ads})$  vs  $1/T$  plot for MB adsorption onto a) Calcined Sep, and b) Sep-AAM.

Table B.16. Thermodynamic parameters for adsorption of MB onto calcined Sep for 31, 40, and 50 °C.

| Sample       | $T$ (°C) | Thermodynamic parameters |                                    |                              |                              |                               |
|--------------|----------|--------------------------|------------------------------------|------------------------------|------------------------------|-------------------------------|
|              |          | $K_L$ (L/mg)             | $K_{ads}$<br>(L/mol) $\times 10^4$ | $\Delta G^\circ$<br>(kJ/mol) | $\Delta H^\circ$<br>(kJ/mol) | $\Delta S^\circ$<br>(J/mol.K) |
| Calcined Sep | 31       | 1.25                     | 38.70                              | -41.08                       | 8.68                         | 135.41                        |
|              | 40       | 1.29                     | 41.26                              | -42.30                       |                              |                               |
|              | 50       | 1.48                     | 47.34                              | -43.65                       |                              |                               |

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### APPENDIX C: SUPPLEMENTARY INFORMATION 3

Table C.1. Chemical compositions (wt%) of 1 h 750 °C calcined Sep and MK used in this study, as determined by XRF spectroscopy.

| Material     | SiO <sub>2</sub> | MgO  | CaO   | Al <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O |
|--------------|------------------|------|-------|--------------------------------|------------------|--------------------------------|------------------|
| Calcined Sep | 52.7             | 31.0 | 13.61 | 1.51                           | 0.07             | 0.59                           | 0.25             |
| MK           | 56.2             | 0.07 | 0.09  | 41.0                           | 1.15             | 0.36                           | 0.46             |

Table C.2. The amounts of raw materials (in g) used in the synthesis of Sep-AAMs with distinct H<sub>2</sub>O<sub>2</sub> contents, corresponding molar Si/Mg and Na/Mg, and synthesis conditions.

| Sample                                     | Calcined Sep | H <sub>2</sub> O <sub>2</sub> | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> solution | NaOH | Si/Mg | Na/Mg | Thermal treatment              |
|--------------------------------------------|--------------|-------------------------------|---------------------------------------------------------|------|-------|-------|--------------------------------|
| Sep-AAM                                    | 12           | 0                             | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 0.5%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 12           | 0.25                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 1%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 12           | 0.51                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 2%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 12           | 1.01                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 3%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 12           | 1.52                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 6%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 12           | 3.04                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+1 week<br>25°C |
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 12           | 4.05                          | 38.17                                                   | 0.5  | 3     | 1.2   | 1 day 40 °C<br>+ 1 week 25 °C  |

Table C.3. The amounts of raw materials (in g) used in the synthesis of MKGPs with distinct  $\text{H}_2\text{O}_2$  contents, corresponding molar Si/Al and Na/Al ratios, and synthesis conditions.

| Sample                            | MK | $\text{H}_2\text{O}_2$ | $\text{Na}_2\text{Si}_3\text{O}_7$<br>solution | NaOH | Si/Al | Na/Al | Thermal<br>treatment          |
|-----------------------------------|----|------------------------|------------------------------------------------|------|-------|-------|-------------------------------|
| MKGP                              | 12 | 0                      | 18.0                                           | 2.8  | 2     | 1.2   | 1 day 60 °C +<br>1 week 25 °C |
| 0.5% $\text{H}_2\text{O}_2$ -MKGP | 12 | 0.16                   | 18.0                                           | 2.8  | 2     | 1.2   | 1 day 60 °C +<br>1 week 25 °C |
| 1% $\text{H}_2\text{O}_2$ -MKGP   | 12 | 0.33                   | 18.0                                           | 2.8  | 2     | 1.2   | 1 day 60 °C +<br>1 week 25 °C |

Table C.4. BET surface area, average pore size, and pore volume of raw materials.

| Sample       | Surface area<br>( $\text{m}^2/\text{g}$ ) | Pore volume<br>( $\text{cm}^3/\text{g}$ ) | Pore size<br>(Å) |
|--------------|-------------------------------------------|-------------------------------------------|------------------|
| Calcined Sep | 101.8                                     | 0.5                                       | 273.8            |
| MK           | 14.4                                      | 0.09                                      | 312.5            |

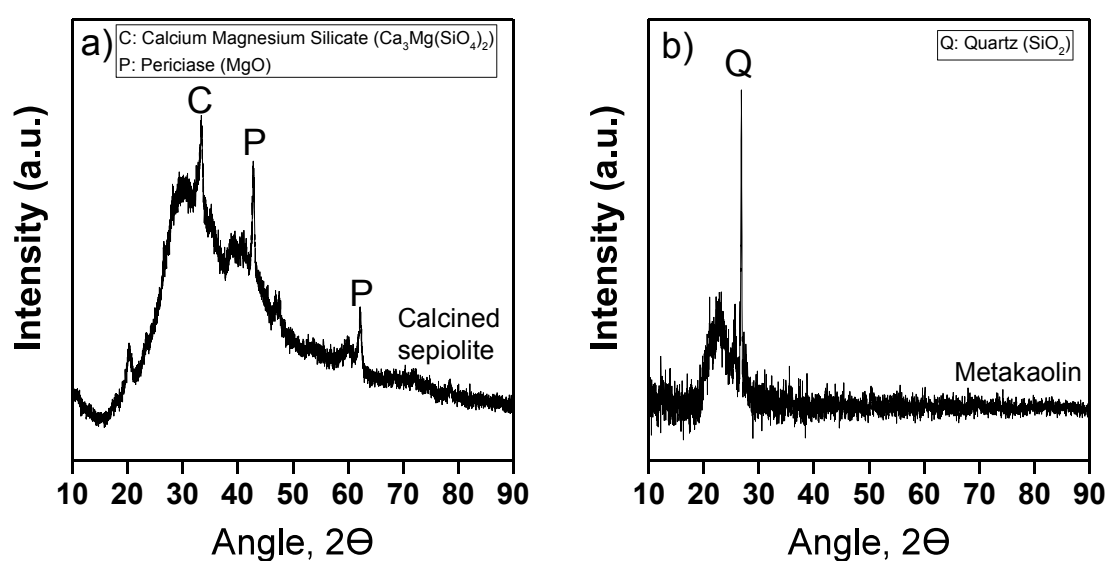


Figure C.1. XRD patterns of a) Calcined Sep and b) MK.

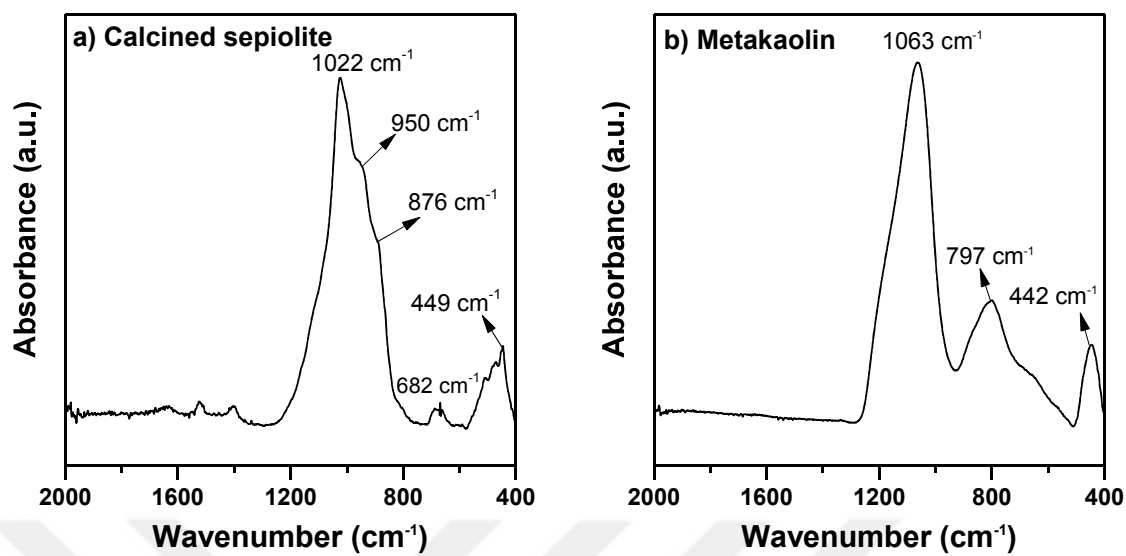


Figure C.2. FTIR patterns of a) Calcined Sep and b) MK.

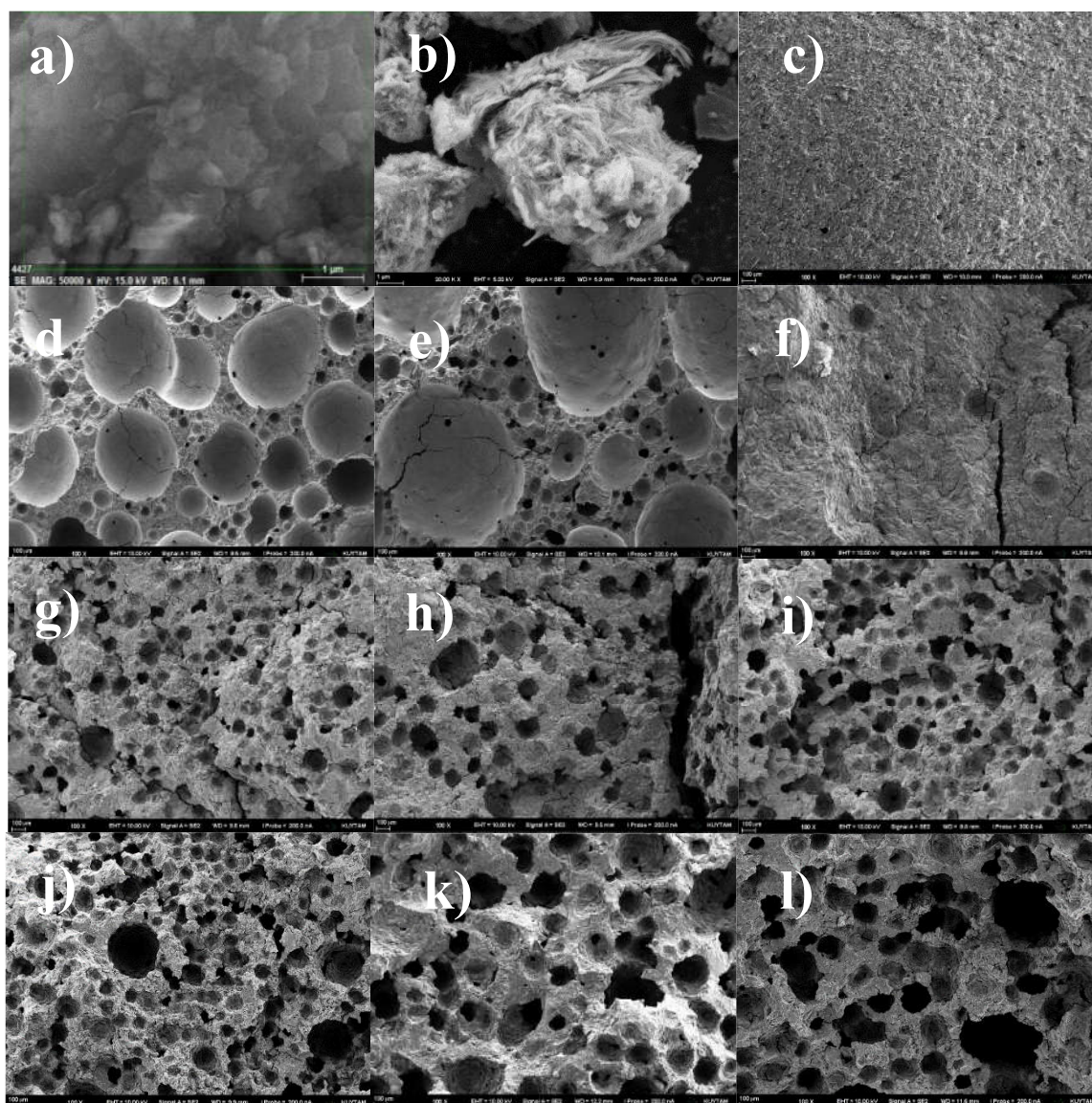


Figure C.3. SEM images of materials: a) MK- at a magnification of 50 k $\times$ , b) Calcined Sep- at a magnification of 20 k $\times$ , synthesized materials at a magnification of 100 $\times$ : c) MKGP, d) 0.5% $\text{H}_2\text{O}_2$ -MKGP, e) 1% $\text{H}_2\text{O}_2$ -MKGP, f) Sep-AAM, g) 0.5% $\text{H}_2\text{O}_2$ -Sep-AAM, h) 1% $\text{H}_2\text{O}_2$ -Sep-AAM, i) 2% $\text{H}_2\text{O}_2$ -Sep-AAM, j) 3% $\text{H}_2\text{O}_2$ -Sep-AAM, k) 6% $\text{H}_2\text{O}_2$ -Sep-AAM, and l) 8% $\text{H}_2\text{O}_2$ -Sep-AAM.

Table C.5. Compressive strength values of the synthesized samples.

| Sample                               | Compressive strength (MPa) |
|--------------------------------------|----------------------------|
| Sep-AAM                              | 37                         |
| 0.5% $\text{H}_2\text{O}_2$ -Sep-AAM | 15.8                       |
| 1% $\text{H}_2\text{O}_2$ -Sep-AAM   | 16.3                       |
| 2% $\text{H}_2\text{O}_2$ -Sep-AAM   | 11.7                       |
| 3% $\text{H}_2\text{O}_2$ -Sep-AAM   | 9.2                        |
| 6% $\text{H}_2\text{O}_2$ -Sep-AAM   | 6.9                        |
| 8% $\text{H}_2\text{O}_2$ -Sep-AAM   | 6.5                        |
| MKGP                                 | 28                         |
| 0.5% $\text{H}_2\text{O}_2$ -MKGP    | 4.2                        |
| 1% $\text{H}_2\text{O}_2$ -MKGP      | 2.1                        |

For 8% $\text{H}_2\text{O}_2$ -Sep-AAM, zeta potential had decreased from -6.2 to -26.4eV when pH is increased from 2 to 12. In a similar manner, zeta potential of 1% $\text{H}_2\text{O}_2$ -MKGP was -54.9 eV when pH is equal to 12. Even though zeta potential measurements imply a more negatively charged surface for 8% $\text{H}_2\text{O}_2$ -Sep-AAM than it is for 1% $\text{H}_2\text{O}_2$ -MKGP, 8% $\text{H}_2\text{O}_2$ -Sep-AAM displayed comparatively higher adsorption capacity towards cationic MB dye. Due to heterogeneous nature of clay minerals, electrostatic interactions and adsorptive properties of these minerals is a complex phenomenon [1]. Cation exchange capacity (CEC) is a measure demonstrating the ability of clay minerals ability for adsorbing cations from the solution medium [2]. For layered minerals (i.e. MK and Sep) that are swelled in the water, the amount of adsorbed adsorbate may be greater than corresponding clay mineral's cation exchange capacity [1]. When this occurs, the value and even the sign of the zeta potential of the clay mineral may alter owing to the formation of micelles [1, 3]. CEC of kaolinite mineral was reported to be mostly in the region between 0.028 - 0.058 mol/kg [4]. Sep mineral's CEC, on the other hand was reported to be in the range of 0.1 to 0.15 mol/kg [5]. Therefore,

higher CEC of Sep-based AAM possessed higher adsorption performance towards cationic MB dye.

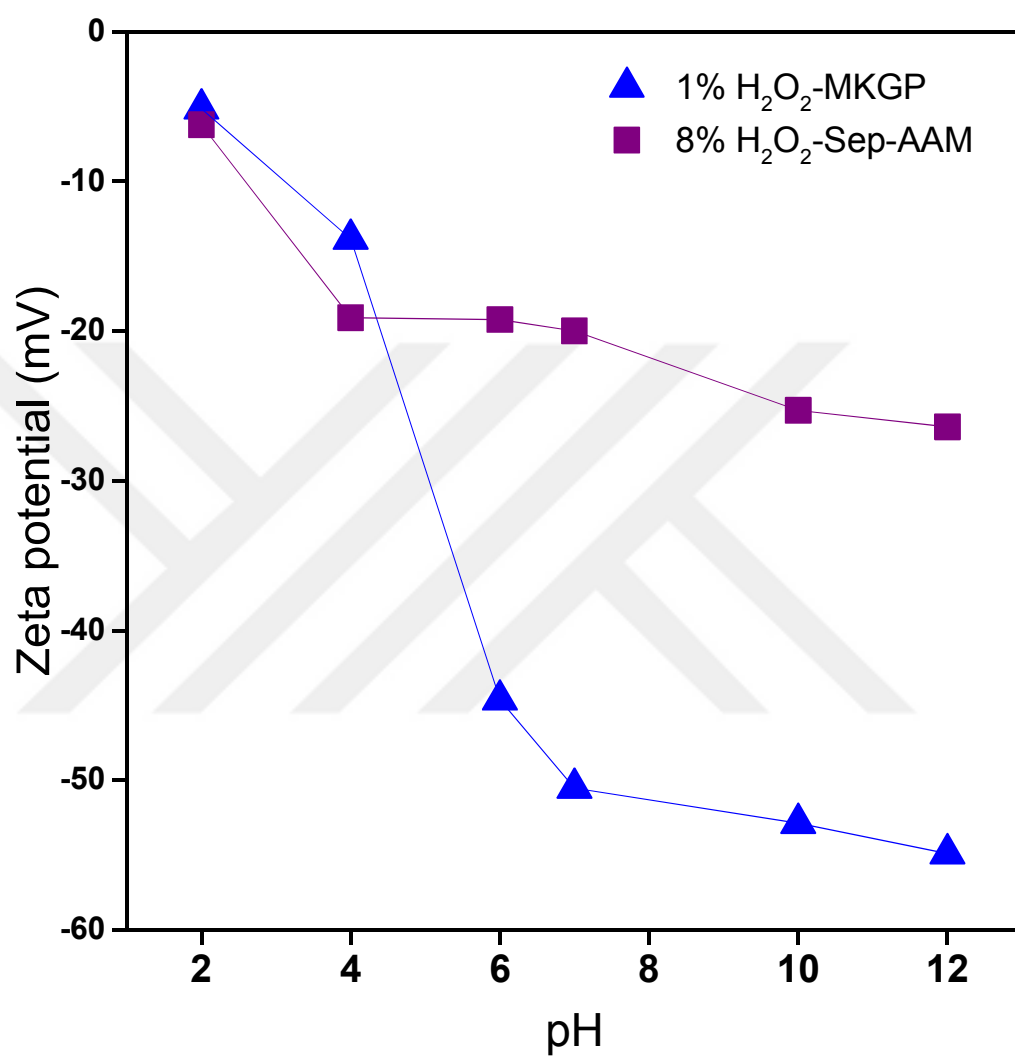


Figure C.4. The change of zeta potential with pH for 1%H<sub>2</sub>O<sub>2</sub>-MKGP and 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM.

Table C.6. The effect of initial MB concentration on uptake and removal efficiency for synthesized AAMs..

| Adsorbent              | $C_0$ (mg L <sup>-1</sup> ) | $q_{e,exp}$ (mg g <sup>-1</sup> ) | Removal efficiency (%) |
|------------------------|-----------------------------|-----------------------------------|------------------------|
| Sep-AAM                | 30                          | 2.35                              | 96.35                  |
|                        | 40                          | 3.48                              | 94.10                  |
|                        | 50                          | 3.93                              | 90.32                  |
|                        | 60                          | 4.44                              | 88.92                  |
|                        | 70                          | 4.59                              | 79.8                   |
|                        | 90                          | 6.37                              | 75.70                  |
|                        | 110                         | 6.64                              | 66.87                  |
| 0.5% $H_2O_2$ -Sep-AAM | 30                          | 3.50                              | 96.07                  |
|                        | 40                          | 3.85                              | 86.23                  |
|                        | 50                          | 4.68                              | 84.29                  |
|                        | 60                          | 5.47                              | 85.28                  |
|                        | 70                          | 5.70                              | 76.98                  |
|                        | 90                          | 6.60                              | 76.22                  |
|                        | 110                         | 6.54                              | 64.65                  |
| 1% $H_2O_2$ -Sep-AAM   | 30                          | 2.62                              | 81.71                  |
|                        | 40                          | 4.30                              | 87.55                  |
|                        | 50                          | 4.55                              | 83.43                  |
|                        | 60                          | 5.29                              | 84.74                  |
|                        | 70                          | 4.77                              | 65.74                  |
|                        | 90                          | 6.33                              | 63.42                  |
|                        | 110                         | 7.08                              | 61.98                  |
| 2% $H_2O_2$ -Sep-AAM   | 30                          | 3.53                              | 96.35                  |
|                        | 40                          | 4.71                              | 93.44                  |
|                        | 50                          | 5.83                              | 90.39                  |
|                        | 60                          | 6.36                              | 84.52                  |
|                        | 70                          | 7.26                              | 82.75                  |

Table C.6. The effect of initial MB concentration on uptake performances and removal efficiency for synthesized AAMs. (cont.)

| Adsorbent            | $C_0$ (mg L <sup>-1</sup> ) | $q_{e,exp}$ (mg g <sup>-1</sup> ) | Removal efficiency (%) |
|----------------------|-----------------------------|-----------------------------------|------------------------|
| 2% $H_2O_2$ -Sep-AAM | 90                          | 9.08                              | 72.12                  |
|                      | 110                         | 10.15                             | 69.98                  |
| 3% $H_2O_2$ -Sep-AAM | 30                          | 3.89                              | 91.16                  |
|                      | 40                          | 4.89                              | 85.93                  |
|                      | 50                          | 6.06                              | 83.22                  |
|                      | 60                          | 7.06                              | 82.56                  |
|                      | 70                          | 7.41                              | 73.67                  |
|                      | 90                          | 8.88                              | 66.49                  |
|                      | 110                         | 9.36                              | 61.98                  |
| 6% $H_2O_2$ -Sep-AAM | 30                          | 4.45                              | 95.46                  |
|                      | 40                          | 6.27                              | 85.43                  |
|                      | 50                          | 6.95                              | 84.82                  |
|                      | 60                          | 7.80                              | 84.61                  |
|                      | 70                          | 8.28                              | 77.45                  |
|                      | 90                          | 8.83                              | 63.43                  |
|                      | 110                         | 9.79                              | 56.42                  |
| 8% $H_2O_2$ -Sep-AAM | 30                          | 4.38                              | 93.78                  |
|                      | 40                          | 7.27                              | 97.13                  |
|                      | 50                          | 8.08                              | 89.15                  |
|                      | 60                          | 9.99                              | 82.54                  |
|                      | 70                          | 9.02                              | 72.26                  |
|                      | 90                          | 11.30                             | 70.59                  |
|                      | 110                         | 10.26                             | 58.42                  |
| MKGP                 | 30                          | 1.34                              | 73.0                   |
|                      | 40                          | 2.17                              | 72.93                  |

Table C.6. The effect of initial MB concentration on uptake performances and removal efficiency for synthesized AAMs. (cont.)

| Adsorbent           | $C_0$ (mg L <sup>-1</sup> ) | $q_{e,exp}$ (mg g <sup>-1</sup> ) | Removal efficiency (%) |
|---------------------|-----------------------------|-----------------------------------|------------------------|
| MKGP                | 50                          | 2.47                              | 69.99                  |
|                     | 60                          | 2.73                              | 66.03                  |
|                     | 70                          | 2.78                              | 57.62                  |
|                     | 90                          | 3.53                              | 53.71                  |
|                     | 110                         | 4.35                              | 58.87                  |
| 0.5% $H_2O_2$ -MKGP | 30                          | 2.54                              | 62.98                  |
|                     | 40                          | 4.73                              | 74.41                  |
|                     | 50                          | 4.56                              | 62.93                  |
|                     | 60                          | 4.98                              | 59.43                  |
|                     | 70                          | 5.69                              | 58.56                  |
|                     | 90                          | 6.09                              | 45.52                  |
|                     | 110                         | 7.19                              | 46.42                  |
| 1% $H_2O_2$ -MKGP   | 30                          | 5.00                              | 92.66                  |
|                     | 40                          | 6.30                              | 73.67                  |
|                     | 50                          | 5.97                              | 60.36                  |
|                     | 60                          | 7.85                              | 67.13                  |
|                     | 70                          | 7.95                              | 59.51                  |
|                     | 90                          | 8.06                              | 42.97                  |
|                     | 110                         | 7.81                              | 37.08                  |

Table C.7. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto synthesized AAMs for different initial MB concentrations (*Contact time* = 24 h).

| Adsorbent                                       | $q_{e,exp}$<br>(mg g <sup>-1</sup> ) | $C_0$<br>(mg L <sup>-1</sup> ) | Pseudo-first-order<br>adsorption kinetics |                                      |       | Pseudo-second-order adsorption<br>kinetics                 |                                      |       | Removal<br>(%) |
|-------------------------------------------------|--------------------------------------|--------------------------------|-------------------------------------------|--------------------------------------|-------|------------------------------------------------------------|--------------------------------------|-------|----------------|
|                                                 |                                      |                                | $k_{1,ads,app}$<br>(min <sup>-1</sup> )   | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{2,ads,app}$<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ |                |
| Sep-AAM                                         | 2.35                                 | 30                             | 6×10 <sup>-4</sup>                        | 2.44                                 | 0.89  | 3.5×10 <sup>-3</sup>                                       | 2.51                                 | 0.99  | 96.35          |
|                                                 | 3.48                                 | 40                             | 3.8×10 <sup>-3</sup>                      | 3.36                                 | 0.97  | 1.9×10 <sup>-3</sup>                                       | 3.77                                 | 0.99  | 94.10          |
|                                                 | 3.93                                 | 50                             | 3.1×10 <sup>-3</sup>                      | 4.22                                 | 0.96  | 8.7×10 <sup>-4</sup>                                       | 4.47                                 | 0.95  | 90.32          |
|                                                 | 4.44                                 | 60                             | 1×10 <sup>-3</sup>                        | 3.06                                 | 0.79  | 7.7×10 <sup>-4</sup>                                       | 5.15                                 | 0.95  | 88.92          |
|                                                 | 4.59                                 | 70                             | 2.5×10 <sup>-3</sup>                      | 4.44                                 | 0.93  | 6.8×10 <sup>-4</sup>                                       | 5.22                                 | 0.93  | 79.8           |
|                                                 | 6.37                                 | 90                             | 1.3×10 <sup>-3</sup>                      | 6.06                                 | 0.96  | 1.6×10 <sup>-4</sup>                                       | 9.22                                 | 0.78  | 75.70          |
|                                                 | 6.64                                 | 110                            | 2.1×10 <sup>-3</sup>                      | 6.93                                 | 0.95  | 2.2×10 <sup>-4</sup>                                       | 8.64                                 | 0.79  | 66.87          |
| 0.5% H <sub>2</sub> O <sub>2</sub> -<br>Sep-AAM | 3.50                                 | 30                             | 2.9×10 <sup>-3</sup>                      | 3.204                                | 0.97  | 1.2×10 <sup>-3</sup>                                       | 3.93                                 | 0.98  | 96.07          |
|                                                 | 3.85                                 | 40                             | 3.1×10 <sup>-3</sup>                      | 4.40                                 | 0.98  | 7.3×10 <sup>-4</sup>                                       | 4.57                                 | 0.96  | 86.23          |
|                                                 | 4.68                                 | 50                             | 2.7×10 <sup>-3</sup>                      | 4.71                                 | 0.97  | 4.1×10 <sup>-4</sup>                                       | 6.07                                 | 0.99  | 84.29          |
|                                                 | 5.47                                 | 60                             | 2.1×10 <sup>-3</sup>                      | 5.06                                 | 0.96  | 5.2×10 <sup>-4</sup>                                       | 6.54                                 | 0.95  | 85.28          |
|                                                 | 5.70                                 | 70                             | 1.7×10 <sup>-3</sup>                      | 4.86                                 | 0.87  | 4.3×10 <sup>-4</sup>                                       | 6.90                                 | 0.93  | 76.98          |
|                                                 | 6.60                                 | 90                             | 2.3×10 <sup>-3</sup>                      | 6.51                                 | 0.96  | 8.2×10 <sup>-5</sup>                                       | 11.24                                | 0.60  | 76.22          |
|                                                 | 6.54                                 | 110                            | 2.5×10 <sup>-3</sup>                      | 8.43                                 | 0.95  | 9.7×10 <sup>-5</sup>                                       | 10.29                                | 0.58  | 64.65          |
| 1% H <sub>2</sub> O <sub>2</sub> -Sep-<br>AAM   | 2.62                                 | 30                             | 3×10 <sup>-3</sup>                        | 2.70                                 | 0.99  | 9.4×10 <sup>-4</sup>                                       | 3.22                                 | 0.93  | 81.71          |
|                                                 | 4.30                                 | 40                             | 4.2×10 <sup>-3</sup>                      | 4.62                                 | 0.97  | 9.1×10 <sup>-4</sup>                                       | 5.13                                 | 0.97  | 87.55          |
|                                                 | 4.55                                 | 50                             | 3.2×10 <sup>-3</sup>                      | 5.86                                 | 0.96  | 3.5×10 <sup>-4</sup>                                       | 5.93                                 | 0.89  | 83.43          |
|                                                 | 5.29                                 | 60                             | 1.7×10 <sup>-3</sup>                      | 4.80                                 | 0.93  | 3.9×10 <sup>-4</sup>                                       | 6.64                                 | 0.92  | 84.74          |
|                                                 | 4.77                                 | 70                             | 2.8×10 <sup>-3</sup>                      | 5.24                                 | 0.96  | 5.6×10 <sup>-4</sup>                                       | 5.67                                 | 0.93  | 65.74          |
|                                                 | 6.33                                 | 90                             | 2.4×10 <sup>-3</sup>                      | 6.00                                 | 0.95  | 3.7×10 <sup>-4</sup>                                       | 7.97                                 | 0.94  | 63.42          |
|                                                 | 7.08                                 | 110                            | 2.2×10 <sup>-3</sup>                      | 7.20                                 | 0.94  | 3.4×10 <sup>-4</sup>                                       | 8.27                                 | 0.90  | 61.98          |
| 2% H <sub>2</sub> O <sub>2</sub> -Sep-<br>AAM   | 3.53                                 | 30                             | 5.7×10 <sup>-3</sup>                      | 3.73                                 | 0.82  | 2.2×10 <sup>-3</sup>                                       | 3.85                                 | 0.97  | 96.35          |
|                                                 | 4.71                                 | 40                             | 2.8×10 <sup>-3</sup>                      | 3.66                                 | 0.98  | 1.3×10 <sup>-3</sup>                                       | 5.13                                 | 0.99  | 93.44          |
|                                                 | 5.83                                 | 50                             | 2.5×10 <sup>-3</sup>                      | 3.73                                 | 0.83  | 1.3×10 <sup>-3</sup>                                       | 6.21                                 | 0.99  | 90.39          |
|                                                 | 6.36                                 | 60                             | 2.7×10 <sup>-3</sup>                      | 5.16                                 | 0.74  | 7.8×10 <sup>-4</sup>                                       | 7.03                                 | 0.97  | 84.52          |
|                                                 | 7.26                                 | 70                             | 1.7×10 <sup>-3</sup>                      | 5.98                                 | 0.87  | 4.2×10 <sup>-4</sup>                                       | 8.31                                 | 0.93  | 82.75          |

Table C.7. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto synthesized AAMs for different initial MB concentrations (*Contact time* = 24 h). (cont.)

| Adsorbent            | $q_{e,exp}$<br>(mg g <sup>-1</sup> ) | $C_0$<br>(mg L <sup>-1</sup> ) | Pseudo-first-order<br>adsorption kinetics |                                      |       | Pseudo-second-order adsorption<br>kinetics                 |                                      |       | Removal<br>(%) |
|----------------------|--------------------------------------|--------------------------------|-------------------------------------------|--------------------------------------|-------|------------------------------------------------------------|--------------------------------------|-------|----------------|
|                      |                                      |                                | $k_{1,ads,app}$<br>(min <sup>-1</sup> )   | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{2,ads,app}$<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ |                |
| 2% $H_2O_2$ -Sep-AAM | 9.08                                 | 90                             | 3.3×10 <sup>-3</sup>                      | 14.11                                | 0.95  | 1.2×10 <sup>-5</sup>                                       | 28.90                                | 0.15  | 72.12          |
|                      | 10.15                                | 110                            | 1.8×10 <sup>-3</sup>                      | 9.51                                 | 0.96  | 1.9×10 <sup>-4</sup>                                       | 12.64                                | 0.89  | 69.98          |
| 3% $H_2O_2$ -Sep-AAM | 3.89                                 | 30                             | 4.3 ×10 <sup>-3</sup>                     | 4.37                                 | 0.97  | 1.5×10 <sup>-3</sup>                                       | 4.28                                 | 0.99  | 91.16          |
|                      | 4.89                                 | 40                             | 3.1×10 <sup>-3</sup>                      | 5.93                                 | 0.99  | 3.9×10 <sup>-4</sup>                                       | 6.15                                 | 0.93  | 85.93          |
|                      | 6.06                                 | 50                             | 2.2×10 <sup>-3</sup>                      | 5.75                                 | 0.98  | 3.8×10 <sup>-4</sup>                                       | 7.45                                 | 0.95  | 83.22          |
|                      | 7.06                                 | 60                             | 2.2×10 <sup>-3</sup>                      | 6.49                                 | 0.98  | 4.8×10 <sup>-4</sup>                                       | 7.90                                 | 0.93  | 82.56          |
|                      | 7.41                                 | 70                             | 1.9×10 <sup>-3</sup>                      | 8.85                                 | 0.98  | 2.7×10 <sup>-4</sup>                                       | 9.49                                 | 0.92  | 73.67          |
|                      | 8.88                                 | 90                             | 2.6×10 <sup>-3</sup>                      | 8.50                                 | 0.99  | 3.4×10 <sup>-4</sup>                                       | 10.47                                | 0.96  | 66.49          |
|                      | 9.36                                 | 110                            | 2.5×10 <sup>-3</sup>                      | 8.12                                 | 0.93  | 3.3×10 <sup>-4</sup>                                       | 11.56                                | 0.95  | 61.98          |
| 6% $H_2O_2$ -Sep-AAM | 4.45                                 | 30                             | 2.6×10 <sup>-3</sup>                      | 3.70                                 | 0.99  | 1×10 <sup>-3</sup>                                         | 4.99                                 | 0.98  | 95.46          |
|                      | 6.27                                 | 40                             | 2.8×10 <sup>-3</sup>                      | 4.99                                 | 0.92  | 9.6×10 <sup>-4</sup>                                       | 6.78                                 | 0.99  | 85.43          |
|                      | 6.95                                 | 50                             | 2.7×10 <sup>-3</sup>                      | 6.80                                 | 0.99  | 4.6×10 <sup>-4</sup>                                       | 8.04                                 | 0.97  | 84.82          |
|                      | 7.80                                 | 60                             | 3×10 <sup>-3</sup>                        | 7.35                                 | 0.99  | 5.7×10 <sup>-4</sup>                                       | 8.77                                 | 0.98  | 84.61          |
|                      | 8.28                                 | 70                             | 2.3×10 <sup>-3</sup>                      | 6.24                                 | 0.96  | 7×10 <sup>-4</sup>                                         | 9.06                                 | 0.99  | 77.45          |
|                      | 8.83                                 | 90                             | 2.6×10 <sup>-3</sup>                      | 8.83                                 | 0.86  | 4.1×10 <sup>-4</sup>                                       | 11.01                                | 0.95  | 63.43          |
|                      | 9.79                                 | 110                            | 1.3×10 <sup>-3</sup>                      | 11.39                                | 0.80  | 1.5×10 <sup>-4</sup>                                       | 15.03                                | 0.81  | 56.42          |
| 8% $H_2O_2$ -Sep-AAM | 4.38                                 | 30                             | 2.9×10 <sup>-3</sup>                      | 5.420                                | 0.99  | 3.6×10 <sup>-4</sup>                                       | 5.70                                 | 0.89  | 93.78          |
|                      | 7.27                                 | 40                             | 3.3×10 <sup>-3</sup>                      | 7.91                                 | 0.99  | 4.5×10 <sup>-4</sup>                                       | 8.47                                 | 0.97  | 97.13          |

Table C.7. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto synthesized AAMs for different initial MB concentrations (*Contact time* = 24 h). (cont.)

| Adsorbent                                | $q_{e,exp}$<br>(mg g <sup>-1</sup> ) | $C_0$<br>(mg L <sup>-1</sup> ) | Pseudo-first-order<br>adsorption kinetics |                                      |       | Pseudo-second-order adsorption<br>kinetics                 |                                      |       | Removal<br>(%) |
|------------------------------------------|--------------------------------------|--------------------------------|-------------------------------------------|--------------------------------------|-------|------------------------------------------------------------|--------------------------------------|-------|----------------|
|                                          |                                      |                                | $k_{1,ads,app}$<br>(min <sup>-1</sup> )   | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{2,ads,app}$<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ |                |
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 8.08                                 | 50                             | 3.2×10 <sup>-3</sup>                      | 9.46                                 | 0.97  | 2.5×10 <sup>-4</sup>                                       | 10.15                                | 0.91  | 89.15          |
|                                          | 9.99                                 | 60                             | 2.4×10 <sup>-3</sup>                      | 9.57                                 | 0.99  | 2.1×10 <sup>-4</sup>                                       | 11.36                                | 0.92  | 82.54          |
|                                          | 9.02                                 | 70                             | 3.3×10 <sup>-3</sup>                      | 11.94                                | 0.95  | 2.2×10 <sup>-4</sup>                                       | 11.17                                | 0.88  | 72.26          |
|                                          | 11.30                                | 90                             | 2.6×10 <sup>-3</sup>                      | 10.25                                | 0.98  | 3.4×10 <sup>-4</sup>                                       | 12.97                                | 0.97  | 70.59          |
|                                          | 10.26                                | 110                            | 2.6×10 <sup>-3</sup>                      | 9.25                                 | 0.99  | 4.3×10 <sup>-4</sup>                                       | 11.37                                | 0.97  | 58.42          |
| MKGP                                     | 1.34                                 | 30                             | 2.5×10 <sup>-3</sup>                      | 1.24                                 | 0.96  | 1.4×10 <sup>-3</sup>                                       | 1.67                                 | 0.92  | 73.0           |
|                                          | 2.17                                 | 40                             | 3.3×10 <sup>-3</sup>                      | 2.53                                 | 0.97  | 1.5×10 <sup>-3</sup>                                       | 2.48                                 | 0.95  | 72.93          |
|                                          | 2.47                                 | 50                             | 3.2×10 <sup>-3</sup>                      | 3.12                                 | 0.96  | 8.2×10 <sup>-4</sup>                                       | 3.06                                 | 0.93  | 69.99          |
|                                          | 2.73                                 | 60                             | 2.2×10 <sup>-3</sup>                      | 2.538                                | 0.93  | 6.8×10 <sup>-4</sup>                                       | 3.47                                 | 0.89  | 66.03          |
|                                          | 2.78                                 | 70                             | 1.6×10 <sup>-3</sup>                      | 2.49                                 | 0.91  | 6.2×10 <sup>-4</sup>                                       | 3.64                                 | 0.88  | 57.62          |
|                                          | 3.53                                 | 90                             | 2.2×10 <sup>-3</sup>                      | 4.63                                 | 0.95  | 1.2×10 <sup>-4</sup>                                       | 6.12                                 | 0.22  | 53.71          |
|                                          | 4.35                                 | 110                            | 9×10 <sup>-4</sup>                        | 4.14                                 | 0.95  | 1.8×10 <sup>-4</sup>                                       | 6.55                                 | 0.61  | 58.87          |
| 0.5%H <sub>2</sub> O <sub>2</sub> -MKGP  | 2.54                                 | 30                             | 1.1×10 <sup>-3</sup>                      | 2.37                                 | 0.95  | 4.2×10 <sup>-4</sup>                                       | 3.53                                 | 0.71  | 62.98          |
|                                          | 4.73                                 | 40                             | 1.9×10 <sup>-3</sup>                      | 4.86                                 | 0.99  | 3.4×10 <sup>-4</sup>                                       | 5.87                                 | 0.85  | 74.41          |
|                                          | 4.56                                 | 50                             | 1.1×10 <sup>-3</sup>                      | 4.16                                 | 0.92  | 2.4×10 <sup>-4</sup>                                       | 6.44                                 | 0.75  | 62.93          |
|                                          | 4.98                                 | 60                             | 1.5×10 <sup>-3</sup>                      | 4.65                                 | 0.96  | 2.9×10 <sup>-4</sup>                                       | 6.77                                 | 0.86  | 59.43          |
|                                          | 5.69                                 | 70                             | 1.8×10 <sup>-3</sup>                      | 5.56                                 | 0.99  | 3.4×10 <sup>-4</sup>                                       | 6.82                                 | 0.89  | 58.56          |

Table C.7. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto synthesized AAMs for different initial MB concentrations (*Contact time* = 24 h). (cont.)

| Adsorbent                                   | $q_{e,exp}$<br>(mg g <sup>-1</sup> ) | $C_0$<br>(mg L <sup>-1</sup> ) | Pseudo-first-order<br>adsorption kinetics |       |      | Pseudo-second-order<br>adsorption kinetics |       |      | Removal<br>(%) |
|---------------------------------------------|--------------------------------------|--------------------------------|-------------------------------------------|-------|------|--------------------------------------------|-------|------|----------------|
| 0.5%H <sub>2</sub> O <sub>2</sub> -<br>MKGP | 6.09                                 | 90                             | 2.1×10-3                                  | 7.12  | 0.95 | 3.9×10-4                                   | 7.07  | 0.85 | 45.52          |
|                                             | 7.19                                 | 110                            | 2×10-2                                    | 7.90  | 0.73 | 6.5×10-5                                   | 13.11 | 0.56 | 46.42          |
| 1%H <sub>2</sub> O <sub>2</sub> -<br>MKGP   | 5.00                                 | 30                             | 2.7×10 <sup>-3</sup>                      | 8.12  | 0.90 | 1.8×10 <sup>-5</sup>                       | 15.58 | 0.09 | 92.66          |
|                                             | 6.30                                 | 40                             | 2×10 <sup>-3</sup>                        | 7.47  | 0.96 | 1.3×10 <sup>-4</sup>                       | 9.66  | 0.65 | 73.67          |
|                                             | 5.97                                 | 50                             | 2.3×10 <sup>-3</sup>                      | 8.40  | 0.93 | 2.7×10 <sup>-5</sup>                       | 14.56 | 0.13 | 60.36          |
|                                             | 7.85                                 | 60                             | 3×10 <sup>-3</sup>                        | 11.95 | 0.92 | 5.2×10 <sup>-5</sup>                       | 14.51 | 0.51 | 67.13          |
|                                             | 7.95                                 | 70                             | 3×10 <sup>-3</sup>                        | 11.52 | 0.92 | 1×10 <sup>-4</sup>                         | 11.52 | 0.63 | 59.51          |
|                                             | 8.06                                 | 90                             | 2.1×10 <sup>-3</sup>                      | 5.92  | 0.94 | 6.4×10 <sup>-4</sup>                       | 8.73  | 0.97 | 42.97          |
|                                             | 7.81                                 | 110                            | 3.3×10 <sup>-3</sup>                      | 6.71  | 0.91 | 6.2×10 <sup>-4</sup>                       | 9.25  | 0.97 | 37.08          |

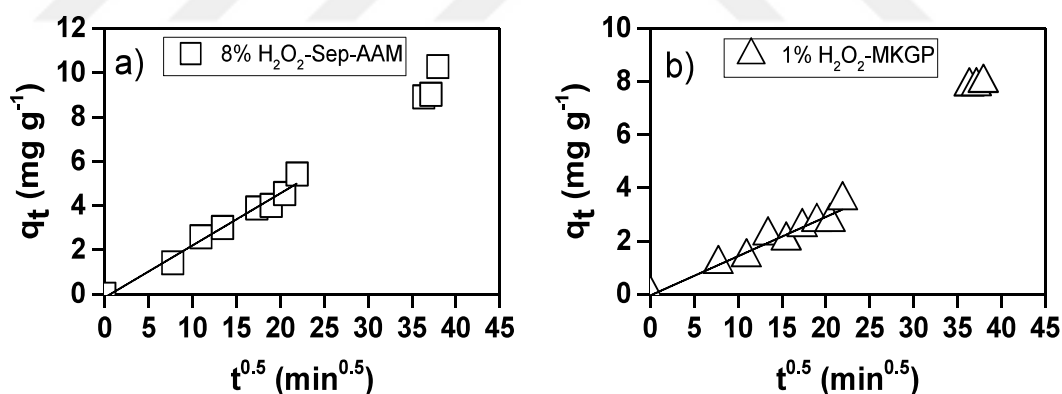


Figure C.5. Intraparticle diffusion model for the adsorption of MB onto a) 8% H<sub>2</sub>O<sub>2</sub>-Sep-AAM and b) 1% H<sub>2</sub>O<sub>2</sub>-MKGP (*Contact time* = 24 h,  $C_0$  = 70 mg L<sup>-1</sup>).

Table C.8. Parameters of intraparticle diffusion model for the synthesized AAMs (*Contact time* = 24h,  $C_0 = 70 \text{ mg L}^{-1}$ ).

| Sample                                      | $k_p$<br>( $\text{mg g}^{-1} \text{ min}^{-0.5}$ ) | $C$<br>( $\text{mg g}^{-1}$ ) | $R^2$ |
|---------------------------------------------|----------------------------------------------------|-------------------------------|-------|
| Sep-AAM                                     | 0.13                                               | -0.01                         | 0.99  |
| 0.5% H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 0.16                                               | 0.045                         | 0.99  |
| 1% H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.13                                               | 0.05                          | 0.99  |
| 2% H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.19                                               | 0.35                          | 0.97  |
| 3% H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.21                                               | 0.06                          | 0.99  |
| 6% H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.30                                               | 0.10                          | 0.97  |
| 8% H <sub>2</sub> O <sub>2</sub> -Sep-AAM   | 0.24                                               | -0.14                         | 0.98  |
| MKGP                                        | 0.07                                               | -0.03                         | 0.97  |
| 0.5% H <sub>2</sub> O <sub>2</sub> -MKGP    | 0.13                                               | -0.04                         | 0.97  |
| 1% H <sub>2</sub> O <sub>2</sub> -MKGP      | 0.15                                               | -0.05                         | 0.96  |

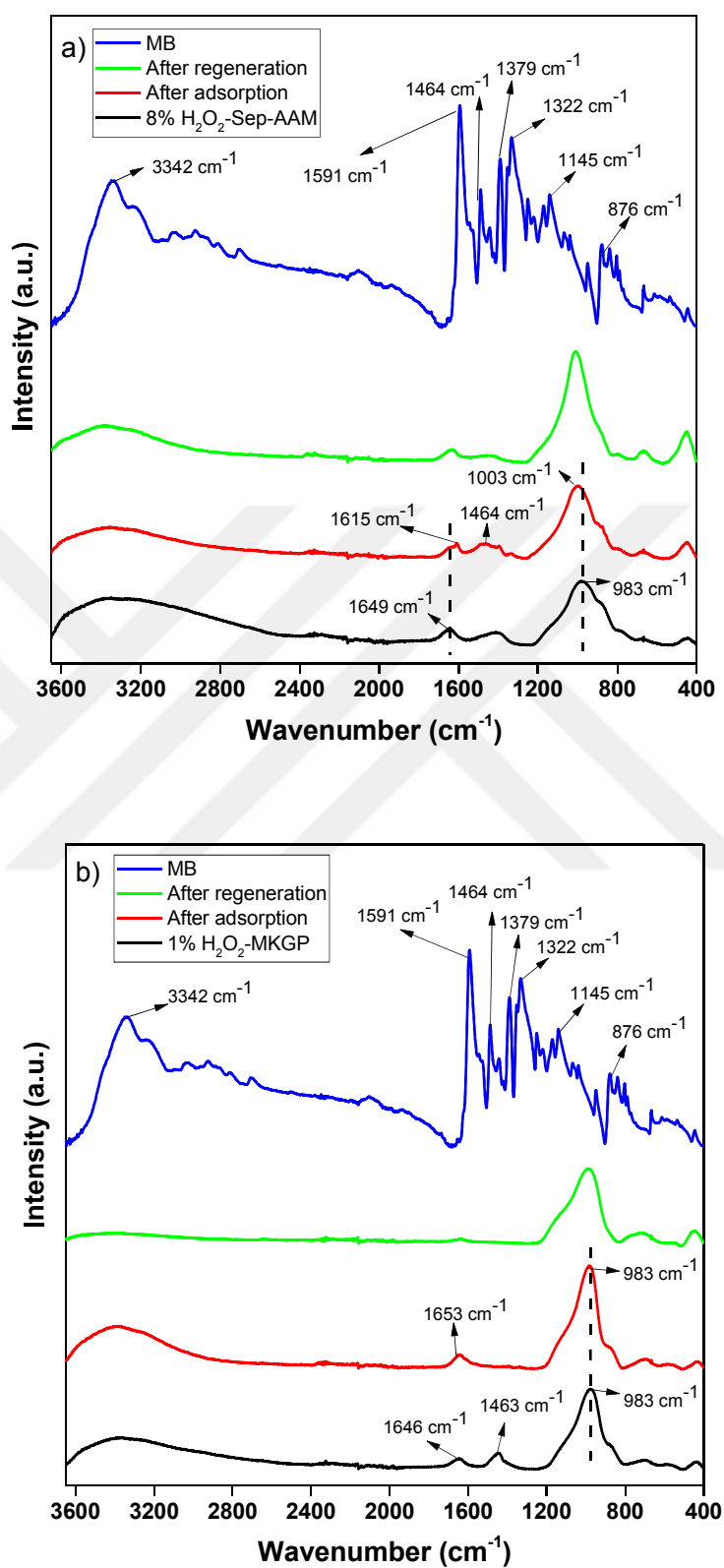


Figure C.6. FTIR spectra of MB and a) 8% $\text{H}_2\text{O}_2$ -Sep-AAM and b) 1% $\text{H}_2\text{O}_2$ -MKGP sample before and after adsorption, and after 4 cycles of regeneration (*Contact time* = 24 h).

Table C.9. Langmuir separation factor  $R_L$  for synthesized AAMs at different temperatures, at all the initial MB concentrations used.

| Adsorbent              | $C_0$ (mg L <sup>-1</sup> ) | $R_L$ |
|------------------------|-----------------------------|-------|
| Sep-AAM                | 30                          | 0.034 |
|                        | 40                          | 0.026 |
|                        | 50                          | 0.021 |
|                        | 60                          | 0.017 |
|                        | 70                          | 0.015 |
|                        | 90                          | 0.012 |
|                        | 110                         | 0.009 |
| 0.5% $H_2O_2$ -Sep-AAM | 30                          | 0.089 |
|                        | 40                          | 0.068 |
|                        | 50                          | 0.055 |
|                        | 60                          | 0.047 |
|                        | 70                          | 0.040 |
|                        | 90                          | 0.031 |
|                        | 110                         | 0.026 |
| 1% $H_2O_2$ -Sep-AAM   | 30                          | 0.185 |
|                        | 40                          | 0.145 |
|                        | 50                          | 0.120 |
|                        | 60                          | 0.102 |
|                        | 70                          | 0.089 |
|                        | 90                          | 0.070 |
|                        | 110                         | 0.058 |
| 2% $H_2O_2$ -Sep-AAM   | 30                          | 0.120 |

Table C.9. Langmuir separation factor  $R_L$  for synthesized AAMs at different temperatures, at all the initial MB concentrations used. (cont.)

| Adsorbent                                | $C_0$ (mg L <sup>-1</sup> ) | $R_L$ |
|------------------------------------------|-----------------------------|-------|
| 2%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 40                          | 0.093 |
|                                          | 50                          | 0.076 |
|                                          | 60                          | 0.064 |
|                                          | 70                          | 0.055 |
|                                          | 90                          | 0.044 |
|                                          | 110                         | 0.036 |
| 3%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 30                          | 0.160 |
|                                          | 40                          | 0.125 |
|                                          | 50                          | 0.102 |
|                                          | 60                          | 0.087 |
|                                          | 70                          | 0.075 |
|                                          | 90                          | 0.059 |
|                                          | 110                         | 0.049 |
| 6%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 30                          | 0.098 |
|                                          | 40                          | 0.075 |
|                                          | 50                          | 0.061 |
|                                          | 60                          | 0.051 |
|                                          | 70                          | 0.044 |
|                                          | 90                          | 0.035 |
|                                          | 110                         | 0.029 |
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 30                          | 0.029 |
|                                          | 40                          | 0.035 |

Table C.9. Langmuir separation factor  $R_L$  for synthesized AAMs at different temperatures, at all the initial MB concentrations used. (cont.)

| Adsorbent                                | $C_0$ (mg L <sup>-1</sup> ) | $R_L$ |
|------------------------------------------|-----------------------------|-------|
| 8%H <sub>2</sub> O <sub>2</sub> -Sep-AAM | 50                          | 0.029 |
|                                          | 60                          | 0.024 |
|                                          | 70                          | 0.021 |
|                                          | 90                          | 0.016 |
|                                          | 110                         | 0.013 |
| MKGP                                     | 30                          | 0.421 |
|                                          | 40                          | 0.353 |
|                                          | 50                          | 0.304 |
|                                          | 60                          | 0.267 |
|                                          | 70                          | 0.238 |
|                                          | 90                          | 0.195 |
|                                          | 110                         | 0.166 |
| 0.5%H <sub>2</sub> O <sub>2</sub> -MKGP  | 30                          | 0.366 |
|                                          | 40                          | 0.302 |
|                                          | 50                          | 0.257 |
|                                          | 60                          | 0.224 |
|                                          | 70                          | 0.198 |
|                                          | 90                          | 0.161 |
|                                          | 110                         | 0.136 |
| 1%H <sub>2</sub> O <sub>2</sub> -MKGP    | 30                          | 0.082 |
|                                          | 40                          | 0.063 |
|                                          | 50                          | 0.051 |

Table C.9. Langmuir separation factor  $R_L$  for synthesized AAMs at different temperatures, at all the initial MB concentrations used. (cont.)

| Adsorbent                             | $C_0$ (mg L <sup>-1</sup> ) | $R_L$ |
|---------------------------------------|-----------------------------|-------|
| 1%H <sub>2</sub> O <sub>2</sub> -MKGP | 60                          | 0.043 |
|                                       | 70                          | 0.037 |
|                                       | 90                          | 0.029 |
|                                       | 110                         | 0.024 |

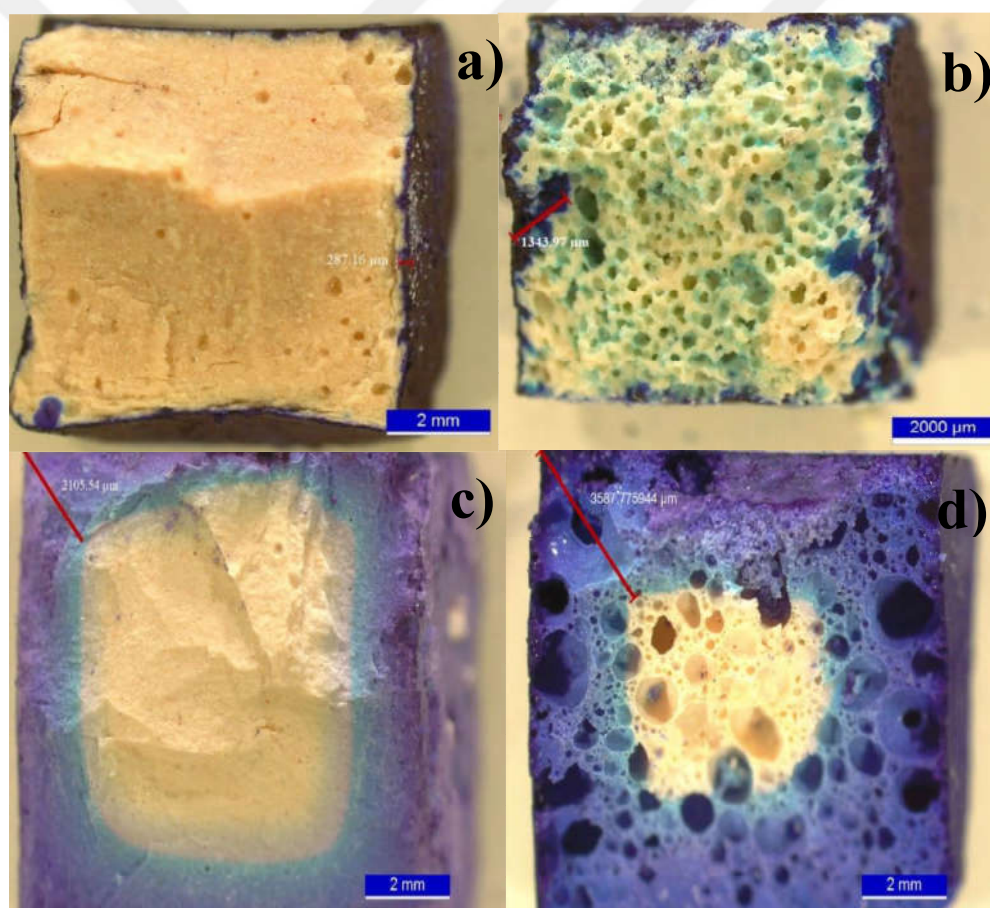


Figure C.7. Stereo microscopy micrographs of the distinct MB diffusion throughout a) Sep-AAM, b) 8%H<sub>2</sub>O<sub>2</sub>-Sep-AAM, c) MKGP, and d) 1%H<sub>2</sub>O<sub>2</sub>-MKGP, after adsorption (Contact time = 24 h,  $C_0$  = 110 mg L<sup>-1</sup>).

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- C5. Rytwo G., S. Nir, L. Margulies, B. Casal, J. Merino, E. Ruiz-Hitzky, and J. M. Serratos, “Adsorption of Monovalent Organic Cations on Sepiolite: Experimental Results and Model Calculations”, *Clays and Clay Minerals*, Vol. 46, No. 3, pp. 340–348, 1998.

## APPENDIX D: SUPPLEMENTARY INFORMATION 4

Table D.1. Chemical compositions (wt%) of MK, raw RM, and calcined RM used in this study.

| Material    | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | CaO  | MgO  | Na <sub>2</sub> O |
|-------------|------------------|--------------------------------|------------------|--------------------------------|------------------|------|------|-------------------|
| MK          | 56.21            | 41.04                          | 1.15             | 0.36                           | 0.46             | 0.09 | 0.07 | -                 |
| RM          | 11.67            | 14.02                          | 5.78             | 37.1                           | 0.31             | 1.1  | 0.23 | 9.39              |
| Calcined RM | 12.59            | 16.85                          | 5.94             | 37.45                          | 0.31             | 1.44 | 0.2  | 10.55             |

Table D.2. The amounts of raw materials (in g) used in geopolymer synthesis, corresponding molar Si/Al and Al/Na ratios, and synthesis conditions used in RMGP synthesis in this study.

| Sample | RM | MK | Na <sub>2</sub> Si <sub>3</sub> O <sub>7</sub> solution | NaOH | Si/Al | Al/Na | Thermal treatment              |
|--------|----|----|---------------------------------------------------------|------|-------|-------|--------------------------------|
| RMGP   | 2  | 8  | 14.01                                                   | 1.69 | 2     | 0.83  | 1 day 60 °C<br>+ 4 weeks 25 °C |

Table D.3. BET surface area, average pore size, and pore volume of RMGP and calcined RMGP.

| Sample        | Surface area (m <sup>2</sup> /g) | Pore volume (cm <sup>3</sup> /g) | Pore size (Å) |
|---------------|----------------------------------|----------------------------------|---------------|
| RMGP          | 27.14                            | 0.159                            | 324.13        |
| Calcined RMGP | 21.14                            | 0.135                            | 404.25        |

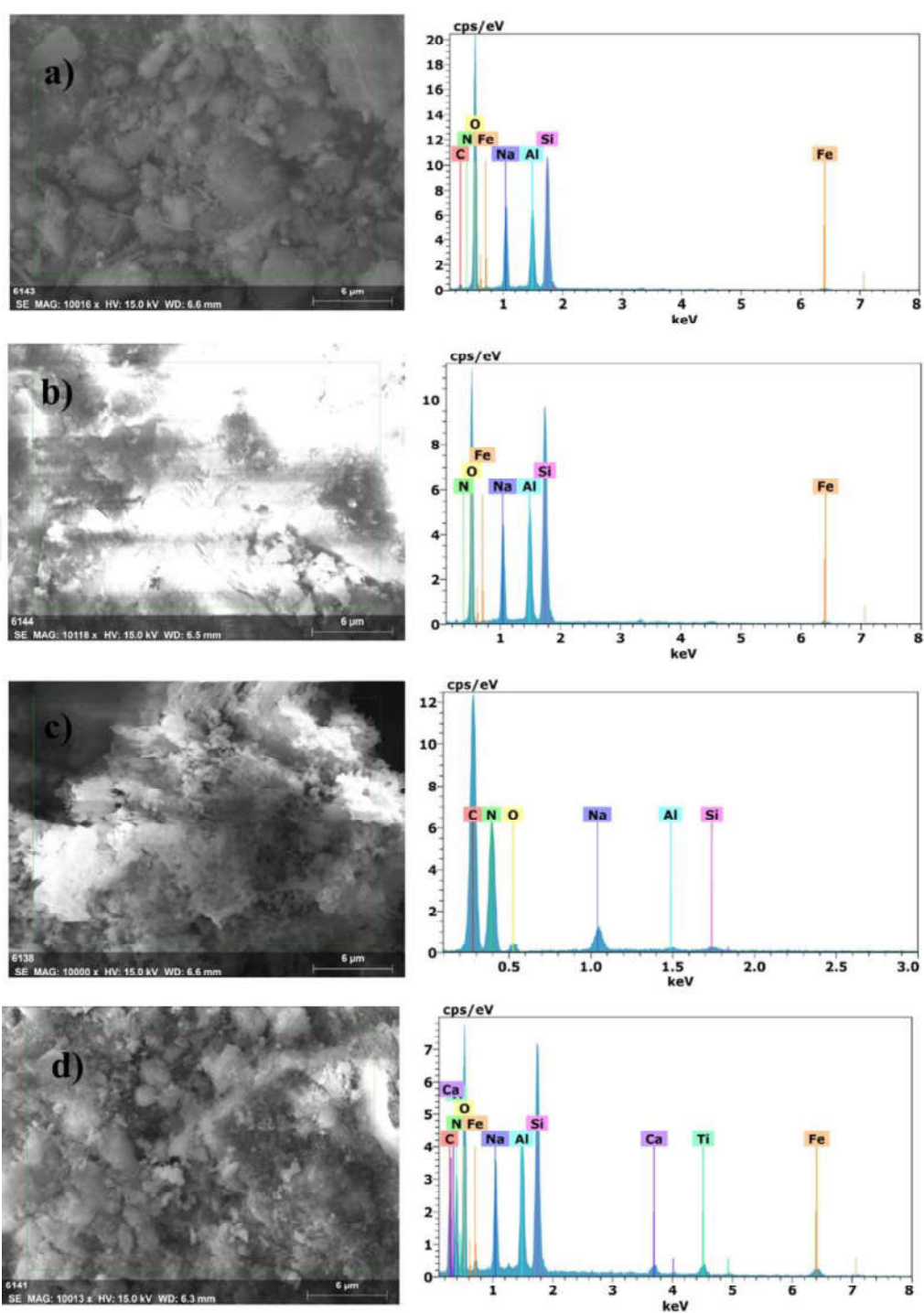


Figure D.1. SEM image, corresponding elemental analysis of a) RMGP, b) Calcined RMGP, c) g-C<sub>3</sub>N<sub>4</sub>, and d) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

Table D.4. Atomic % of C, N, O, Si, Al, Na, and Fe in samples which are calculated from EDS spectra.

| Sample                                | Atomic % |      |      |      |     |     |     |
|---------------------------------------|----------|------|------|------|-----|-----|-----|
|                                       | C        | N    | O    | Si   | Al  | Na  | Fe  |
| RMGP                                  | 6.5      | 0.4  | 62.3 | 13.9 | 6.3 | 8.6 | 1.1 |
| Calcined RMGP                         | -        | 1.2  | 59.8 | 20.6 | 8.2 | 9.6 | 0.6 |
| g-C <sub>3</sub> N <sub>4</sub>       | 36.9     | 57.9 | 3.9  | 0.1  | 0.1 | 1.1 | -   |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 20.2     | 24.1 | 38.9 | 6.9  | 3.7 | 3.6 | 1.2 |

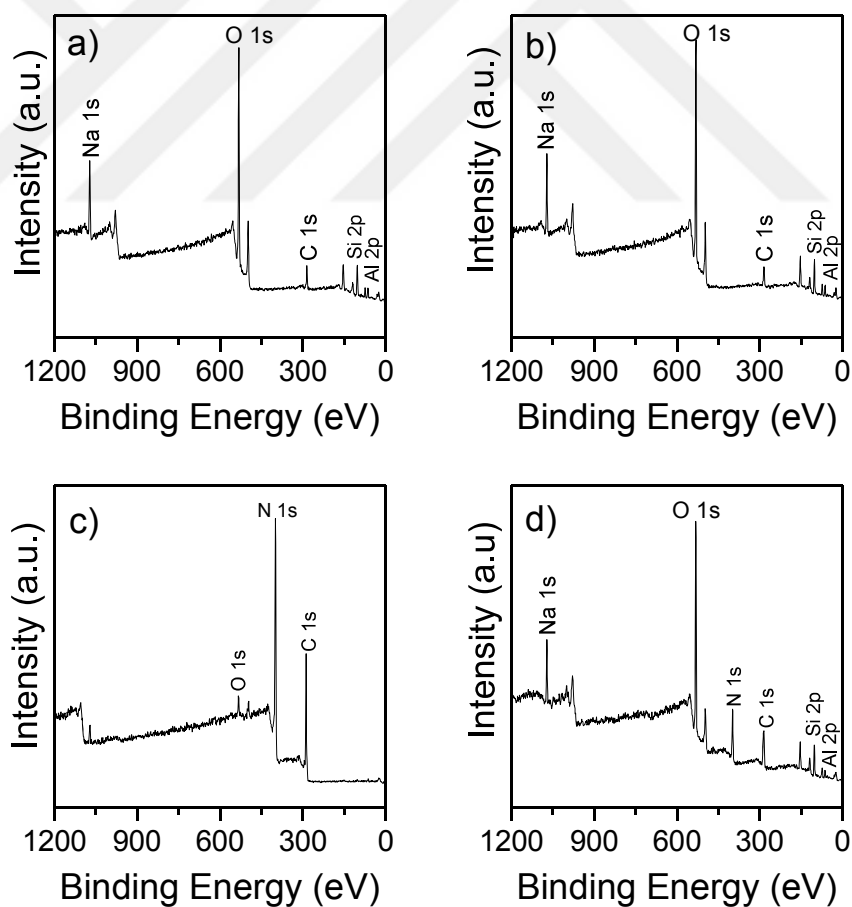


Figure D.2. XP survey spectrum of a) RMGP, b) Calcined RMGP, c) g-C<sub>3</sub>N<sub>4</sub>, and d) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

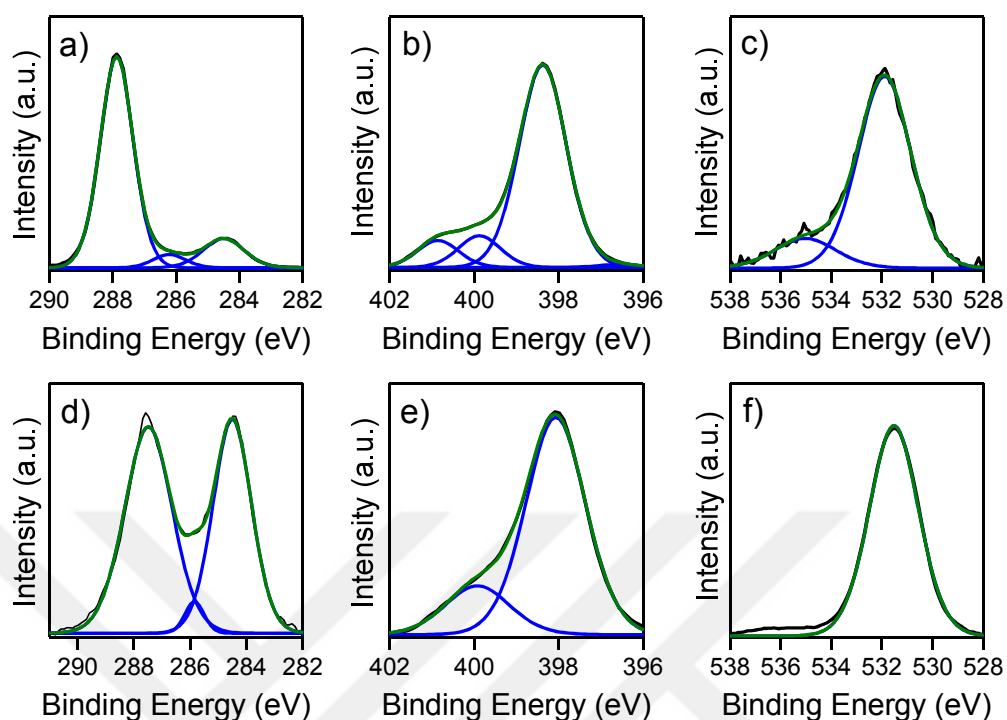


Figure D.3. XPS patterns of a) C 1s, b) N 1s, c) O 1s of g-C<sub>3</sub>N<sub>4</sub>, d) C 1s, e) N 1s, and f) O 1s of g-C<sub>3</sub>N<sub>4</sub>/RMGP (Blue lines: fitted individual peaks, green lines: envelope of all fitted peaks).

Table D.5. Atomic % of different elements obtained from fitted peak information of C 1s, O 1s, N 1s, Si 2p, Al 2p, Fe 2p, and Na 1s XP spectra.

| Sample                                | C<br>(at%) | N<br>(at%) | O<br>(at%) | Si<br>(at%) | Al<br>(at%) | Na<br>(at%) | Fe<br>(at%) |
|---------------------------------------|------------|------------|------------|-------------|-------------|-------------|-------------|
| RMGP                                  | -          | -          | 60.9       | 19.6        | 8.5         | 10.8        | 0.2         |
| Calcined RMGP                         | -          | -          | 59.4       | 19.6        | 9.0         | 11.7        | 0.2         |
| g-C <sub>3</sub> N <sub>4</sub>       | 43.2       | 53.4       | 3.4        | -           | -           | -           | -           |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 22.3       | 15.2       | 38.6       | 12.2        | 5.5         | 5.6         | 0.6         |

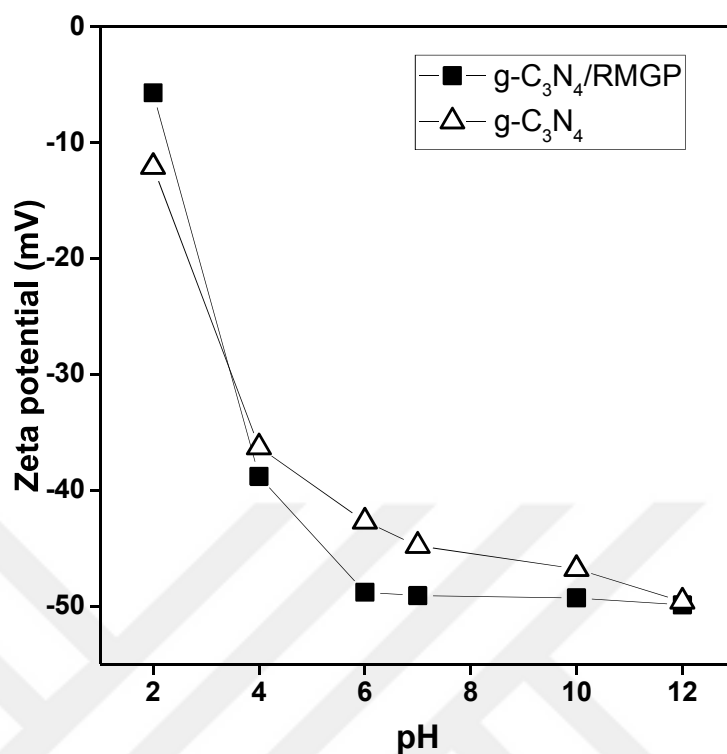


Figure D.4. The change of zeta potential with pH for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP.

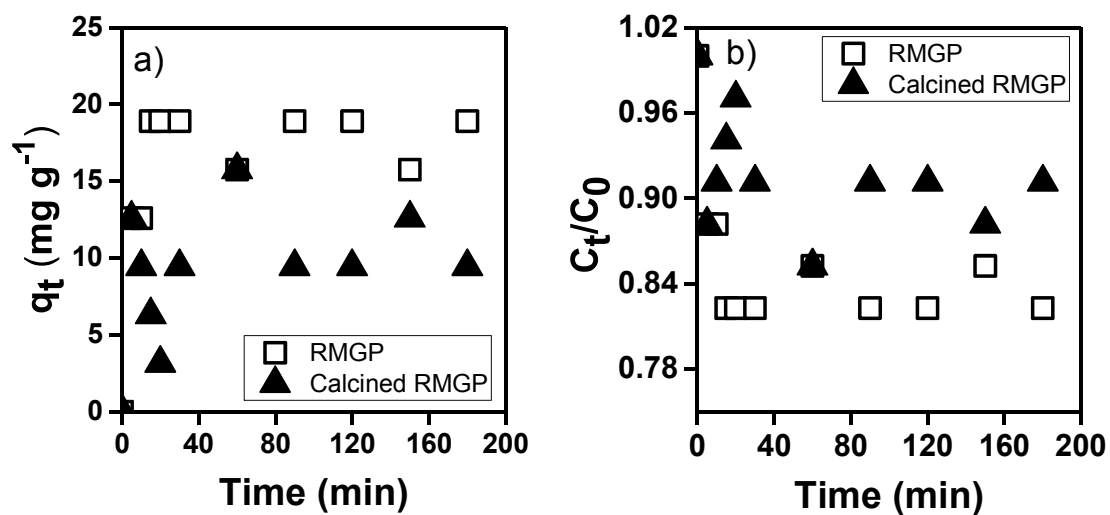


Figure D.5. The influence of contact time on a) Uptake and b)  $C_t/C_0$  of RMGP and Calcined RMGP.

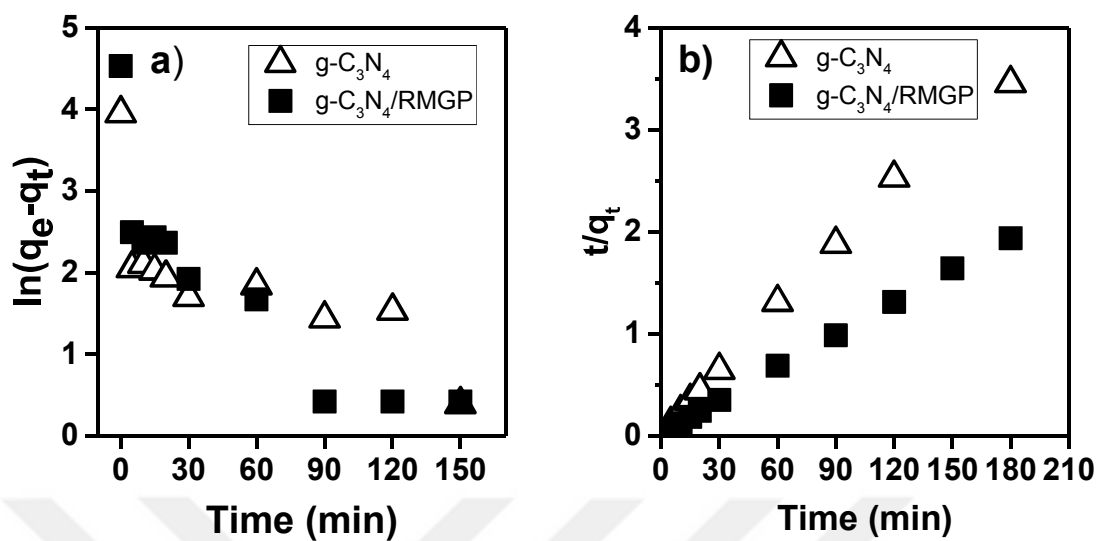


Figure D.6. Pseudo-first and pseudo-second-order kinetic models for the adsorption of MB onto a) g-C<sub>3</sub>N<sub>4</sub> and b) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

Table D.6. Pseudo-first and pseudo-second-order kinetic model parameters and removal efficiency (%) for adsorption of MB onto RMGP and calcined RMGP.

| Adsorbent        | $q_{e,exp}$<br>(mg g <sup>-1</sup> ) | Pseudo-first-order<br>adsorption kinetics |                                      |       | Pseudo-second-order<br>adsorption kinetics                 |                                      |       | Removal<br>(%) |
|------------------|--------------------------------------|-------------------------------------------|--------------------------------------|-------|------------------------------------------------------------|--------------------------------------|-------|----------------|
|                  |                                      | $k_{1,ads,app}$<br>(min <sup>-1</sup> )   | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{2,ads,app}$<br>(g mg <sup>-1</sup> min <sup>-1</sup> ) | $q_{e,cal}$<br>(mg g <sup>-1</sup> ) | $R^2$ |                |
| RMGP             | 18.89                                | $8.2 \times 10^{-3}$                      | 8.61                                 | 0.51  | $5 \times 10^{-2}$                                         | 17.9                                 | 0.98  | 17.72          |
| Calcined<br>RMGP | 12.60                                | $6.1 \times 10^{-3}$                      | 6.53                                 | 0.37  | $3 \times 10^{-2}$                                         | 10.9                                 | 0.95  | 11.81          |

Table D.7. The influence of adsorbent amount on the apparent pseudo-second-order adsorption kinetic rate constant and adsorption parameters for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP.

| Sample                                | Adsorbent amount (g) | $k_{2,ads,app}$ (g mg <sup>-1</sup> min <sup>-1</sup> ) | $q_{e,exp}$ (mg g <sup>-1</sup> ) | Removal (%) | $R^2$ |
|---------------------------------------|----------------------|---------------------------------------------------------|-----------------------------------|-------------|-------|
| g-C <sub>3</sub> N <sub>4</sub>       | 0.006                | $5.4 \times 10^{-3}$                                    | 70.8                              | 42.5        | 1     |
|                                       | 0.008                | $7.08 \times 10^{-3}$                                   | 60.2                              | 48.1        | 0.99  |
|                                       | 0.01                 | $1.10 \times 10^{-2}$                                   | 52.07                             | 48.82       | 0.99  |
|                                       | 0.012                | $3.0 \times 10^{-2}$                                    | 46.41                             | 55.7        | 1     |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 0.006                | $1.65 \times 10^{-3}$                                   | 143.6                             | 80.8        | 1     |
|                                       | 0.008                | $2.30 \times 10^{-3}$                                   | 115.2                             | 86.4        | 1     |
|                                       | 0.01                 | $5.0 \times 10^{-3}$                                    | 92.9                              | 87.1        | 1     |
|                                       | 0.012                | $6.38 \times 10^{-3}$                                   | 72.7                              | 81.8        | 1     |

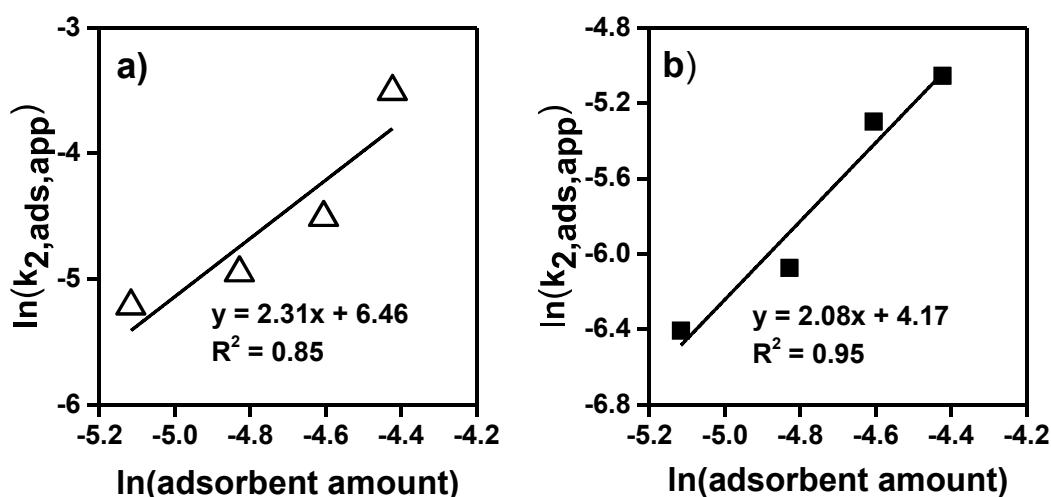


Figure D.7. Influence of adsorbent amount on the apparent pseudo-second-order adsorption rate constant for a) g-C<sub>3</sub>N<sub>4</sub> and b) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

To identify the diffusion mechanism, intraparticle diffusion model should be applied to the experimental data, as corresponding diffusion-related mechanisms cannot be understood from pseudo-first- and pseudo-second-order adsorption kinetic models. The

intraparticle diffusion model was applied on g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP samples and shown in Figure D.7. This figure displays that there are two main different characteristics of the diffusion process within this time period (3 h). For both of these two different adsorbents, first steep portion of the figure implies the presence of boundary layer diffusion. Second portion provides information on the intraparticle diffusion and as it is seen from this figure, this portion does not pass through the origin. This situation shows that for the adsorption of MB molecules on both g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP, intraparticle diffusion is not the only rate controlling step [1, 2]. As it is deduced from Figure D.7, very rapid adsorption takes place initially within the first 5 minutes, and at the later stages intraparticle diffusion becomes determinant in the whole adsorption process. Results extracted from fitting the experimental data to intraparticle diffusion model is summarized in Table D.8. As stated previously, first sharper portion of Figure D.7 within the first 5 minutes of adsorption signifies that MB dye molecules are diffused through the solution to reach the external surface of the adsorbents. Results presented in Table D.8, implies that the value of  $k_{p,1}$  is higher for g-C<sub>3</sub>N<sub>4</sub>/RMGP than it is for g-C<sub>3</sub>N<sub>4</sub>, showing that a more rapid adsorption occurs. The intercept of the second portion provides information on the boundary layer thickness and the existence of viscous drag between MB molecules and corresponding adsorbent. In this regard,  $C_2$  value being greater for g-C<sub>3</sub>N<sub>4</sub>/RMGP (Table D.8) shows that adsorption intensity is higher for g-C<sub>3</sub>N<sub>4</sub>/RMGP than it is for g-C<sub>3</sub>N<sub>4</sub>. Second step also denotes to the step where intraparticle diffusion occurs and MB molecules being transported via intraparticle diffusion. Consequently, after the first 5 minutes of adsorption, intraparticle diffusion is the rate determining step. Similar trends in adsorption behaviour were also observed by Li et al. for biochar/g-C<sub>3</sub>N<sub>4</sub> composites for MB adsorption where results pointed out that adsorption was affected by both external and internal diffusion mechanisms [3].

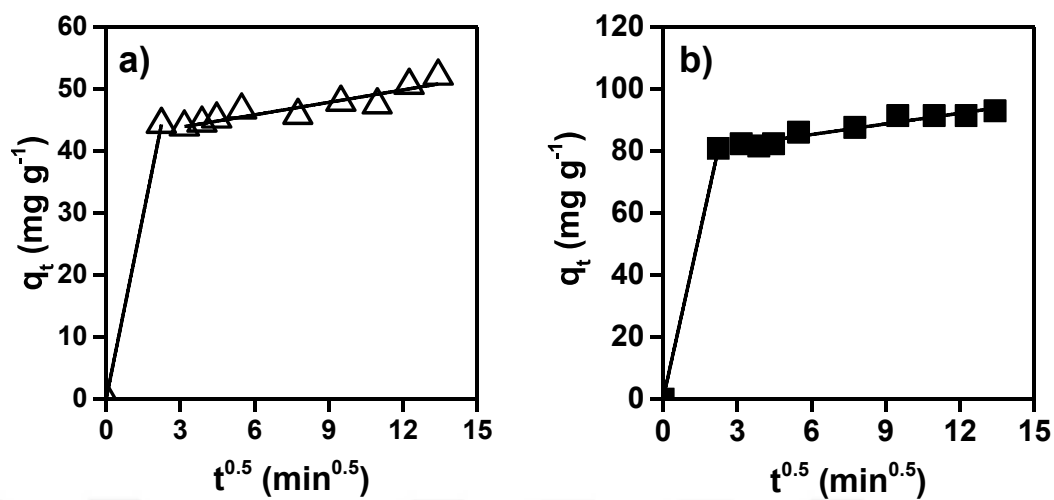


Figure D.8. Intraparticle diffusion model for the adsorption of MB onto a) g-C<sub>3</sub>N<sub>4</sub> and b) g-C<sub>3</sub>N<sub>4</sub>/RMGP.

Table D.8. Parameters of intraparticle diffusion model for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP.

| Sample                                | $k_{p,1}$<br>(mg g <sup>-1</sup> min <sup>-0.5</sup> ) | $C_1$<br>(mg g <sup>-1</sup> ) | $R^2$ | $k_{p,2}$<br>(mg g <sup>-1</sup> min <sup>-0.5</sup> ) | $C_2$<br>(mg g <sup>-1</sup> ) | $R^2$ |
|---------------------------------------|--------------------------------------------------------|--------------------------------|-------|--------------------------------------------------------|--------------------------------|-------|
| g-C <sub>3</sub> N <sub>4</sub>       | 19.81                                                  | 0                              | 1     | 0.67                                                   | 41.83                          | 0.85  |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 36.15                                                  | 0                              | 1     | 1.15                                                   | 78.46                          | 0.92  |

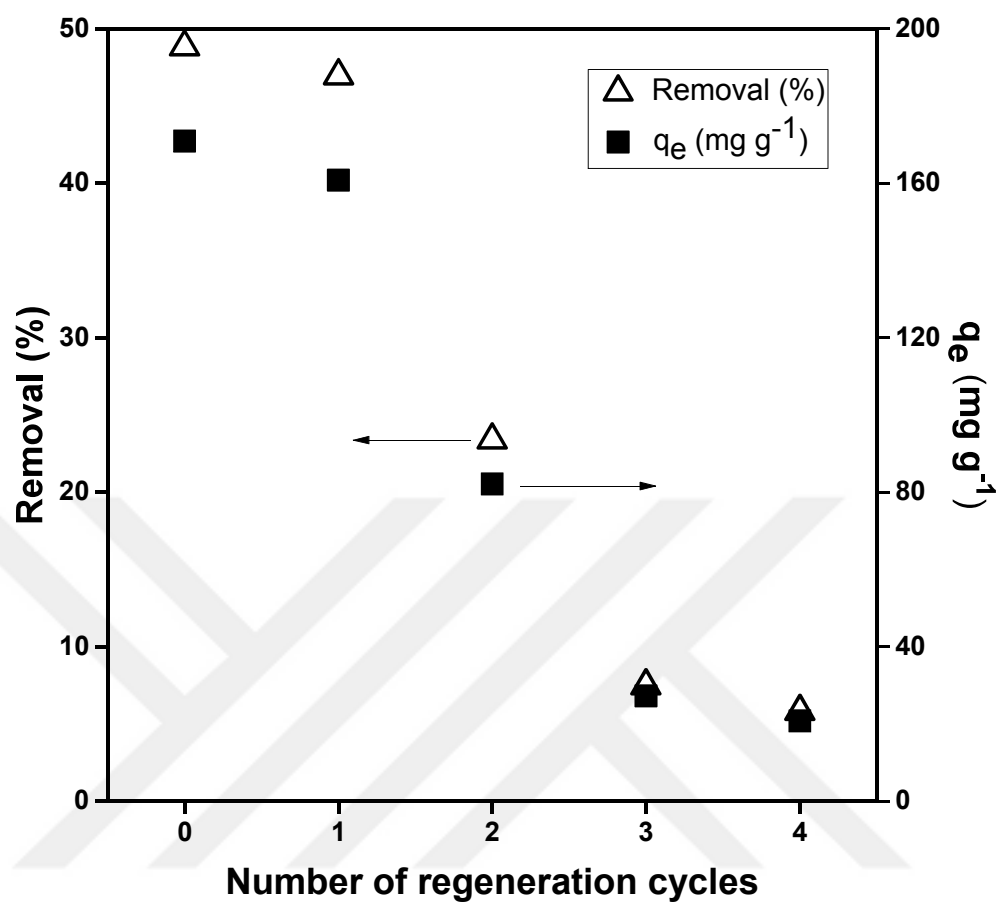


Figure D.9. MB removal (%) and uptake values for g-C<sub>3</sub>N<sub>4</sub>/RMGP after regeneration cycles.

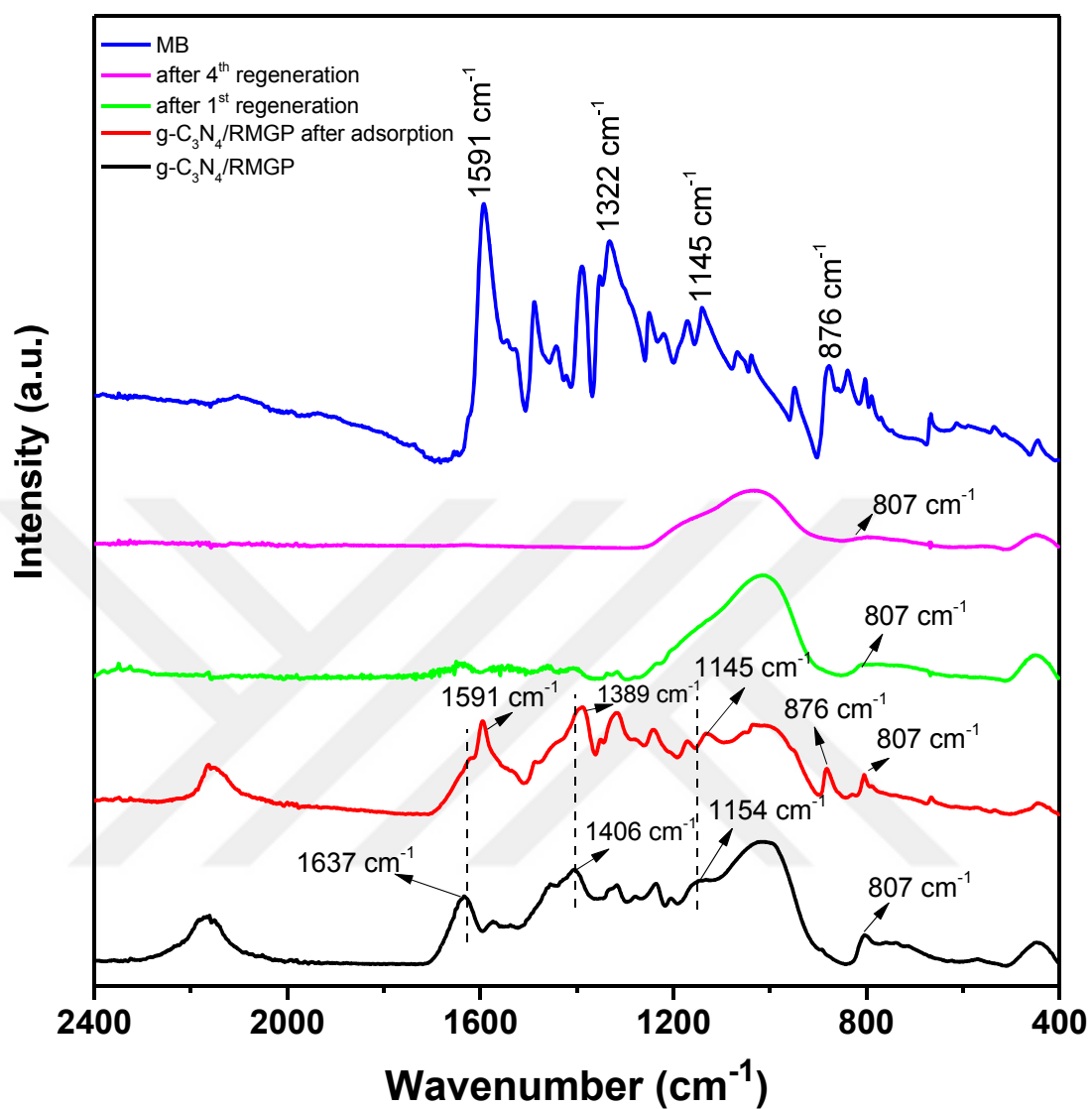


Figure D.10. FTIR spectra of MB and g-C<sub>3</sub>N<sub>4</sub>/RMGP sample before and after adsorption, and after 4 cycles of regeneration (*Contact time* = 3 h).

Table D.9. Langmuir separation factor  $R_L$  for g-C<sub>3</sub>N<sub>4</sub> and g-C<sub>3</sub>N<sub>4</sub>/RMGP for all the initial MB concentrations used.

| Sample                                | Initial MB concentration (mg L <sup>-1</sup> ) | $R_L$ |
|---------------------------------------|------------------------------------------------|-------|
| g-C <sub>3</sub> N <sub>4</sub>       | 10                                             | 0.044 |
|                                       | 20                                             | 0.022 |
|                                       | 30                                             | 0.015 |
|                                       | 40                                             | 0.011 |
|                                       | 50                                             | 0.009 |
|                                       | 60                                             | 0.007 |
|                                       | 70                                             | 0.006 |
| g-C <sub>3</sub> N <sub>4</sub> /RMGP | 10                                             | 0.218 |
|                                       | 20                                             | 0.122 |
|                                       | 30                                             | 0.085 |
|                                       | 40                                             | 0.065 |
|                                       | 50                                             | 0.053 |
|                                       | 60                                             | 0.044 |
|                                       | 70                                             | 0.038 |

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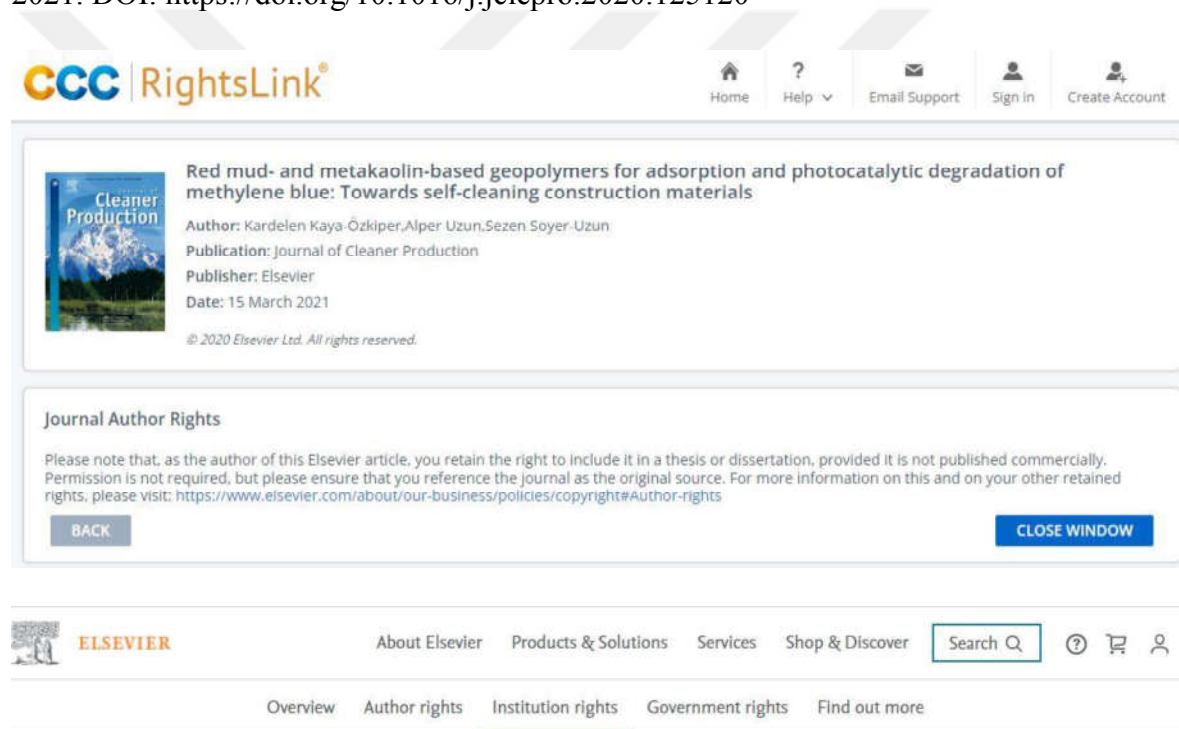
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