

REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**SYNERGETIC EFFECT OF RECYCLED COARSE AGGREGATE AND
STEEL FIBER ON THE MECHANICAL AND DURABILITY
ASPECTS OF FLY ASH/SLAG BASED GEOPOLYMER CONCRETE**

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MASTER OF SCIENCE THESIS

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Signature



*Dedicated to my father Mekonnen LAKEW
and my mother Tarekech ABULA.*



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LIST OF SYMBOLS

σ	Compressive Strength
CO_2	Carbon dioxide
D	Diameter of the Cylindrical Specimen
L	Length of the Specimen
M2	Mass of the Specimen After the Test
M1	Mass of the Specimen Before the Test
Na_2SiO_3	Sodium silicate
NaOH	Sodium Hydroxide
A	Surface Area of the Specimen
F _s	Splitting Tensile Strength (MPa)
b	The Width of the Tested Specimen
t	Thickness Loss due to Abrasion
d	The Thickness of the Prismatic Specimen
P	Maximum Load Read From the Testing Machine
V	Volume of the Specimen

LIST OF ABBREVIATIONS

ACAA	American Coal Ash Association
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standards
CDW	Construction and Demolition Waste
CS	Crushed Sand
EW	Extra-water
FA	Fly Ash
GGBFS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Concrete
NCA	Natural Coarse Aggregates
OPC	Ordinary Portland Cement
RCA	Recycled Coarse Aggregates
RS	River Sand
SF	Steel Fiber
SFRGC	Steel Fiber-Reinforced Geopolymer Concrete
SP	Superplasticizer
UPV	Ultrasonic Pulse Velocity

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Synergetic Effect of Recycled Coarse Aggregate and Steel Fiber on the Mechanical and Durability Aspects of Fly Ash/Slag Based Geopolymer Concrete

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Department of Civil Engineering

Master of Science Thesis

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Nowadays, concrete becomes among the most widely consumed substances in the world. Conventional concrete production releases a significant amount of GHG and consumes a valuable size of virgin materials such as aggregates. For instance, among the core ingredients of concrete, manufacturing one ton of cement emits approximately an equal amount of carbon dioxide, and 1.7 tons of raw materials are used in one ton of cement production.

Scholars have conducted several studies to discover sustainable options that can be feasible in terms of mechanical properties, durability characteristics, and ecological acceptance to conventional concrete. As a result, industrial and geological outputs exhibiting pozzolanic characteristics are being used instead of ordinary portland cement. These materials have excellent potential to overcome the drawbacks of

ordinary cement. Also, reusing construction and demolition wastes to prepare concrete conserves virgin aggregates, minimizes disposal costs, and overcomes unnecessary use of landfills.

In this study, fly ash/slag-based geopolymers were used instead of conventional cement because of their excellent engineering properties. Unlike low calcium-based geopolymer binders, which require the elevated temperature to harden fly ash/slag-based geopolymers attain an intended strength at room temperature due to CSH that happens in conjunction with geopolymeric gel. Also, the recycled coarse aggregate is utilized as a partial substitution of natural coarse aggregate. In the study, experimental examinations are performed to assess the effect of the various proportion of recycled coarse aggregate and steel fiber on the fly ash/slag-based geopolymer concrete, cured at ambient temperature. Several mix variations were also employed to investigate the compressive strength, splitting tensile strength, flexural strength, sulfate resistance, elevated temperature resistance, freezing and thawing resistance, abrasion resistance, and energy absorption capacity. Additionally, an ultrasonic pulse velocity test was carried out to check the overall quality of the concrete. In conclusion, the results indicated that the partial replacement of recycled coarse aggregate up to 30% and 0.6% steel fiber proportion resulted in an ideal overall performance compared to that of fly ash/slag-based geopolymer concrete produced with 100% natural coarse aggregate.

Keywords: Recycled aggregate, steel fiber, geopolymer concrete, mechanical properties, durability properties

Geri Dönüşümlü İri Agrega ve Çelik Lifin Uçucu Kül/Cüruf Esaslı Jeopolimer Betonun Mekanik ve Dayanıklılık Özelliklerine Sinerjik Etkisi

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Günümüzde, beton dünyada en çok tüketilen ürün haline gelmiştir. Geleneksel beton üretimi, önemli miktarda sera gazı açığa çıkarır ve agregalar gibi çok büyük miktarda işlenmemiş doğal kaynaklar kullanılmaktadır. Örneğin betonun temel bileşenlerinden olan bir ton çimento üretiminde yaklaşık olarak aynı miktarda karbondioksit açığa çıkarır ve 1.7 ton ham madde kullanılır.

Araştırmacılar, dayanım, dayanıklılık, ekolojik uygulanabilirlik ve ekonomik fayda açısından uygulanabilir olan sürdürülebilir seçenekleri keşfetmenin bir yolunu bulmak için çaba harcamaktadırlar. Puzolanik özellikler gösteren bazı endüstriyel atıklar ve jeolojik maddeler, yukarıda belirtilen hedeflere ulaşılmasına katkıda bulunmaktadır. Puzolanik reaktivite, kabul edilebilir niteliklere ve önemli ölçüde uygulanabilirlik kolaylığına sahip bir bağlayıcı elde etmeye yardımcı olur. Yeni beton hazırlamak için inşaat ve yıkıntı atıklarının yeniden kullanılması ile

işlenmemiş doğal agrega rezervleri korunur, bertaraf maliyetini en aza indirir ve atık dolgu alanlarının gereksiz kullanımının önüne geçilecektir.

Bu çalışmada kullanılan bağlayıcı maddeler, çok iyi mühendislik özelliklerinden dolayı geleneksel çimento yerine uçucu kül/cüruf bazlı jeopolimerler kullanılmıştır. Betonun sertleşmesi için yüksek sıcaklık gerektiren düşük kalsiyum jeopolimer bağlayıcıların aksine uçucu kül/cüruf bazlı jeopolimerler kullanıldı. Jeopolimerik jel ile birlikte meydana gelen CSH sayesinde oda sıcaklığında istenen bir mukavemete ulaşırlar. Ayrıca bu çalışmada geri dönüşüm agregası ile doğal agrega belli oranda ikame edilerek kullanılmıştır. Çelik lif katkılı ve çeşitli oranlarda doğal agregaya ile ikame edilen geri dönüşüm agregası ile hazırlanan ve oda sıcaklığında kürlenmiş uçucu kül/cüruf bazlı jeopolimer beton numunelerinin üzerindeki etkisini araştırmak için deneysel çalışmalar yapılmıştır. Basınç mukavemeti, yarmada çekme mukavemeti, eğilmede çekme mukavemeti, sülfat direnci, yüksek sıcaklık direnci dayanımı, donma ve çözülme dayanıklılık direnci, aşınma direnci ve tokluğu araştırmak için çeşitli karışım varyasyonları da kullanılmıştır. Ek olarak, betonun genel kalitesini kontrol etmek için ultrases geçiş hızı testi yapıldı. Sonuç olarak, %0,6 oranında çelik lif içeren %30 'a kadar geri dönüşüm agregasının doğal agregaya ile ikame edilerek üretilen jeopolimer beton, %100 doğal agrega ile üretilen uçucu kül/cüruf esaslı jeopolimer betona kıyasla ideal bir performans göstermiştir.

Anahtar Kelimeler: Geri-dönüştürülmüş agrega, çelik lif, jeopolimer beton, mekanik özellikler, dayanıklılık özellikleri

1.1 Background

Concrete can be mentioned among the most consumed substances in recent day developmental activities. The construction sector is the leading consumer of this good. The cement and its products such as concrete and mortar, which are known to be the framework of the recent construction sector utilize virgin natural resources as the core ingredient. Also, it is the largest releaser of CO₂ headed by only transportation and energy, consecutively. According to the studies, around 5% of the total world, hazardous gas emissaries are contributed during the Ordinary Portland cement production process [1]. Moreover, a report released by Schneider et al. [2] in 2011, indicated global yearly cement production of approximately 2.8 billion tones that is increased to 4 billion tones yearly in 2018 [3].

Due to the profound impact of Portland cement on the natural ecosystem, several studies have addressed various possible measurements, mainly focusing on reducing emissions of clinker production and limiting the content of clinker hired, through new technologies [1]. Utilization of the high volume cementitious elements as the partial replacement of the OPC was also considered as a possible alternative to overcome the listed limitations of conventional cement [4].

Recently, hiring completely non-cement binders known as geopolymers is gaining momentum [2], and it is thought to be an excellent shift to reduce world clinker production level. Previous studies demonstrated that employing geopolymer products in the concrete industry may reduce global carbon dioxide emission by an average of 85% [5]. Geopolymer, which is becoming a primary focus of recent green technology, is a product of base materials owing to the high content of alumina and silica. The precursor elements are obtained from either industrial wastes primarily fly ash and slag or geologic products such as metakaolin.

Geopolymers usually obtain strength through the geopolymerization process. Fly ash-slag-based geopolymer exhibits a complex reaction that encompasses hydration of calcium oxide [6, 7] and therefore it gives a calcium silicate hydrate modified with aluminum (CASH), as a primary binding phase. In the geo-polymerization process, alkalination of the alumina and silica enriched elements entails the dissolution of silica and alumina followed by coagulation and then a highly exothermic condensation reaction followed by crystallization leading to the creation of a three-dimensional network of the amorphous alumina-silicate hydrate binder [6, 8], which possess different reaction mechanism from that of OPC.

Also, geopolymers have various benefits in terms of maintaining a binder owing to a low embodied energy and less CO₂ release [9]. Fly ash/slag-based GPC hardens at room temperature. Furthermore, the majority of geopolymer products are not hostile to handle and store. And also, it doesn't need a special mixing procedure; therefore, it can be easily hired for a potential replacement of OPC. Geopolymer-based concrete possesses outstanding mechanical and durability characteristics. This was demonstrated in studies [9, 10].

These days, the amount of CDWs is significantly raising around the world. For instance, in the European Union countries, the annual CDW is estimated to be over 450 million tonnes, out of which only 25% is recycled [11]. In the case of China, this value turns more than 1.5 billion tonnes according to the study taken in 2016 [12]. However, the rate of utilization holds only 10% of the total production. CDW are foes to the natural ecosystem if they cannot be appropriately managed because conventional disposal of these wastes requires storage place and contribute to carbon emissions, heading to critical environmental problems [13]. Furthermore, the deterioration of raw materials is abruptly increasing, which prospects the inclusion of RCA in the synthesis of concrete to be a promising alternative for both utilization of CDW and conservation of environmental and natural resources.

Therefore, one of the best solutions to mitigate the drawbacks of the CDW is re-employing Construction and demolition wastes as a recycled construction input like recycled aggregates [14].

In this thesis, the geopolymer binder obtained by combining ground granulated blast furnace slag and fly ash was used. Also, the part of natural crushed limestone coarse aggregate was substituted by RCA. This work examines various mechanical and durability characteristics of steel fiber reinforced geopolymer concrete prepared with recycled aggregate, which is rarely addressed in previous studies.

1.2 The Objective of the Thesis

The focus of this study is to explore the influence of recycled aggregates on the performance of fly ash-slag-based Geopolymer concrete with the inclusion of different ingredients.

The main objectives of the study include:

- Studying the influence of partial replacement of recycled coarse aggregates on the mechanical and durability performance of fly ash/slag-based Geopolymer concrete.
- Inspecting the effect of utilizing a different percentage of steel fibers on the mechanical performance and durability properties of the geopolymer concrete matrix.

1.3 Significance of the Study

This experimental work flourishes an increasing effort in terms of substituting natural coarse aggregates with CDWs known as recycled coarse aggregates, in a geopolymer concrete production. Numerous studies have investigated various attributes of geopolymer concrete manufactured with natural aggregates; however, only a limited number of researchers have addressed different properties of geopolymer concrete in combination with steel fiber reinforcement and partial replacement of recycled coarse aggregates simultaneously. Thus, this experimental work discloses information on the performance of fly ash-slag-based recycled aggregate geopolymer concrete in terms of mechanical and durability characteristics.

1.4 Hypothesis

Hiring the recycled coarse aggregate and geopolymer binder in the concrete minimizes the possible environmental hazards and virgin material consumption. Nevertheless, the recycled coarse aggregate might cause a reduction in the mechanical properties and durability characteristics of the resulting concrete matrix. Unlike, natural coarse aggregates because of their nature and attached old mortar recycled aggregates may possess some structural defects that in turn will cause a fall in concrete performance. In this study, the mechanical performance and durability properties of the recycled coarse aggregate geopolymer concrete containing steel fiber will be examined. The possible outcome will reveal that the strength properties and durability aspects of the fly ash/slag-based geopolymer concrete will drop with the rise of the recycled coarse aggregate content. In contrast, increasing the steel fiber ratio may improve the overall properties of the resulting concrete; and therefore, steel fiber inclusion would compensate for the possible reduction that might happen due to the recycled coarse aggregate utilization. So the combined effect of partial replacement of recycled coarse aggregate and steel fiber will result in competitive properties both in terms of engineering applications and environmental sustainability.

1.5 General Structure of the Thesis

This section of the study included the general structure of the study. The thesis is structured into five sections. The first chapter of the research addresses the overall introduction, objectives, and significance of the study. The second chapter illustrates a literature review of the previous studies in line with the investigated dimensions of the thesis. Past studies conducted on geopolymer concrete prepared with the inclusion of recycled aggregate were discussed in this chapter. The third chapter gives detailed information about the materials used, the experiments performed and their respective procedures followed to attain an intended outcome. The fourth chapter explains and discusses the results collected from the tests. Finally, the summary and conclusion of the study including the recommendation for future investigation are given in the fifth section.

2.1 Introduction

The concrete industry, believed to be the driving force of modern construction, has numerous drawbacks in terms of environmental issues and sustainability. Conventional construction technologies release a large amount of GHG to the atmosphere due to its crucial ingredients such as clinker. According to the studies, a tone of Portland cement production loads approximately one-tonne CO₂ to the environment [15]. Geopolymer paste was believed to be able to substitute conventional ones and offer comparable mechanical properties [16]. Primarily, the term geopolymers were invented in 1978 in an attempt to introduce a fire-resistant binding substance due to the terrible fire that happened in France. Later days the study extended to the material being employed in marine ships and wooden structures for fire and thermal protection [17]. Currently, the main target is moved to the construction sector because of its ability to manufacture high strength and reliable concrete [17]. Also, it possesses excellent resistance to an acidic environment and physical characteristics [15, 16]. Geopolymer binders like fly ash and slag, in line with their wide availability, reduce hazardous gas production by 80 to 90% compared to OPC [18]. Therefore, Geopolymer technology is termed as a greener alternative to OPC concrete, for use in construction and infrastructure development. Production of concrete matrix, with the merging of geopolymer binders and CDW as a recycled aggregate, plays a crucial role in terms of improving sustainability in concrete production. The following part of this section presents some of the current understandings about geopolymers and concrete manufactured from geopolymeric products.

2.2 Geopolymers and their Formation

Geopolymers are inorganic polymers with a stable three-dimensional network of silicon and aluminum ions interconnected with an oxygen bond. Apart from the

main constituents such as SO^{4-} and AlO^{4-} , geopolymers contain the alkali cations like sodium or potassium ions, which are sandwiched inside the network of the Ca-anorthite, Na-albite, or K-orthoclase. The alkali cations balance the negative charge associated with the tetrahedral aluminate units that react with silicate units to form a three-dimensional structure. Davidovits [19] in his study explained the stable nature of geopolymers in comparison with alkali-activated substances. For example, he explained the reaction of alkali-activated slag and Slag/metakaolin-based geopolymer composites. The slag is obtained from the glassy substance known as melilite and akermanite (Mg-silicate). The alkalination of these minerals causes depolymerization of the slag components into hydrate and hydroxide precipitates. Figure 2.1 illustrates the chemical reaction of alkali-activated slag. The two small molecules melilite and akermanite will react and form a more complicated framework containing (K, Ca)-cyclo-ortho (sialate - disiloxo), Ca-disiloxonate - hydrate, and precipitation of $\text{Al}(\text{OH})_3$, $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$.

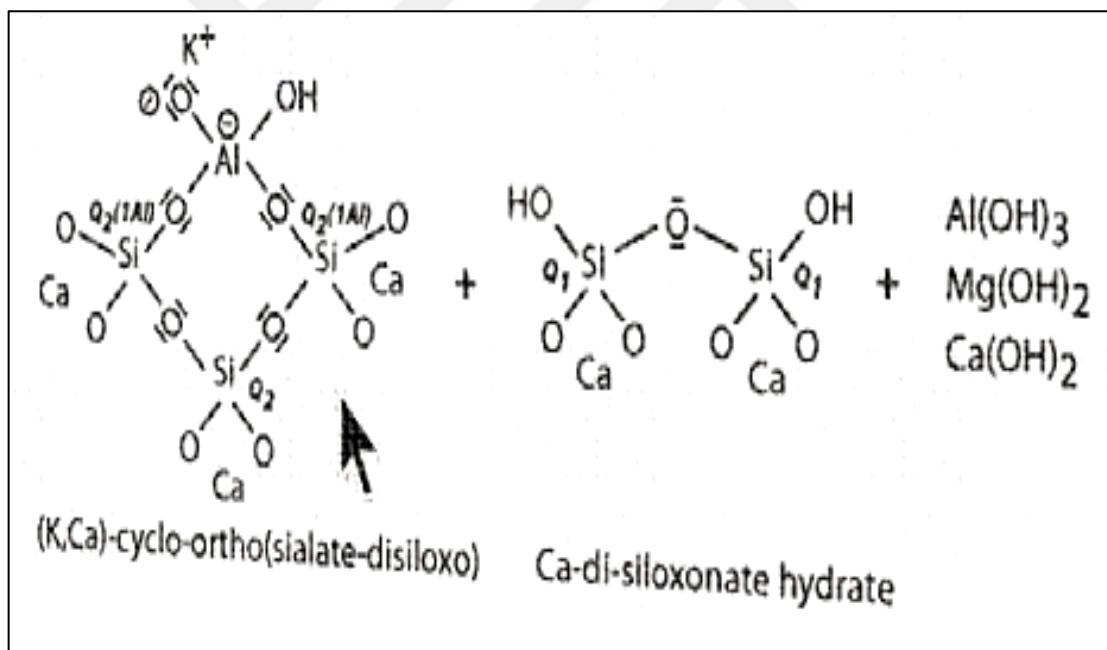


Figure 2. 1 Chemical makeup of alkali-activated slag [19]

The shortcoming of this reaction is the existence of an unbounded alkali cation that is potassium or sodium ion. The free alkali cation is extremely vulnerable to migrate in contact with the water molecule. This realizes an unstable nature of alkali-activated slag which leads to leaching out effect and harms the long-term properties

of alkali-activated products. Unlike alkali-activated slag, geopolymers do not allow the alkali cations to migrate in contact with the wet environment due to their three-dimensional networking structure. These in return enhances the durability of the geopolymer products by avoiding its leaching out effect. The addition of a networking molecule of metakaolin in the above reaction results in a stable and three-dimensional geopolymer network. The interaction between networking elements and free cations provides long-term stability with good physicochemical properties because in the chemical structure of geopolymers the Na^+ or K^+ cations are located inside the structure of the cycle. As a result, the Na^+ or K^+ cations cannot easily penetrate the network of the geopolymer to migrate in contact with the water molecule. The 3D structural model for geo-polymers is shown in Figures 2.2 and 2.3.

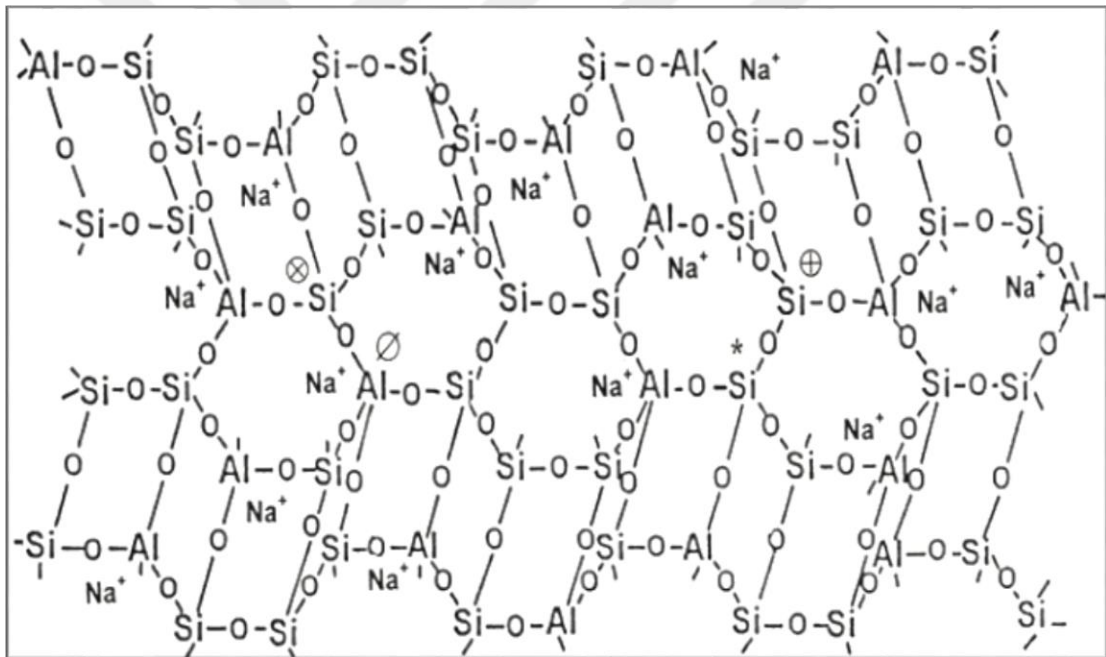


Figure 2. 2 Geopolymer structure model for K-Poly (Sialate-Siloxo) [20]

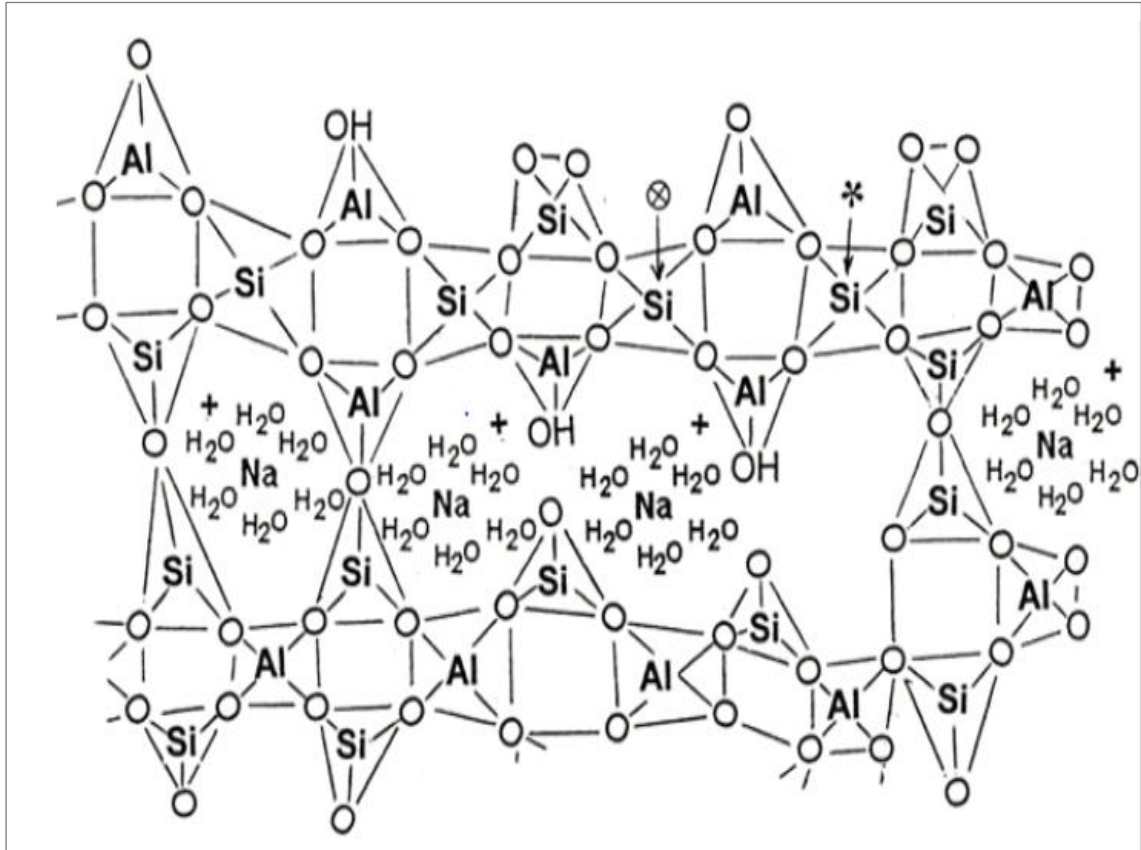


Figure 2. 3 Geopolymer model by Barbosa et al. [21]

2.2.1 Geopolymerization Process

Geopolymers are yielded from the polycondensation of the base materials enriched with aluminum (Al) and silicon (Si) and the alkaline-liquids, resulting in a 3-D polymeric structure. The base precursors could be obtained from either natural minerals or by-products as well. Mainly, either Sodium or Potassium based activator liquids are the most widely utilized chemical solutions in the geopolymer sector.

Firstly, the chemical makeup of the geopolymers was proposed by a French scholar known as Davidovits. He introduced the name “Geopolymer” to represent these materials whose structure is derived from a poly (sialate) Si-O-Al-O framework structure. He has postulated the following empirical formula “ $M_n \{-(Si - O_2)_z - Al\} - O$ ” to describe geopolymers [20].

Where:

- M indicates alkaline elements such as potassium, calcium, or sodium.

- n refers to the degree of polymerization
- the symbol (–) indicates the presence of a bond;
- z is 1, 2, 3

Based on the Si and Al ratio, three monomeric units of Geopolymers are proposed [20]: This is indicated in figure 2.4 below.

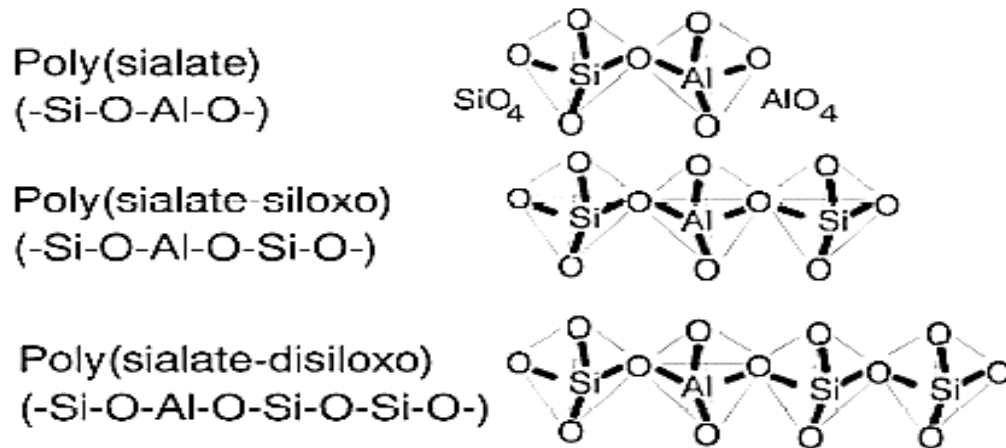


Figure 2. 4 Chemical framework of poly-sialates [20]

Geopolymerization is for the creation of geopolymers. Geo-polymerization involves mainly three stages. Primarily dissolution of aluminum and silicon enriched materials in the alkali solution possessing alkali activators or amalgamation of the components. An alkali attack on precursor material causes the dissolution of Si and Al and, reduces the size of large particles. Secondly, the Aluminium and Silicon complex diffuse from the particle surfaces to the inter-particle spaces. Lastly, a gel phase is produced from the polymerization and stabilization takes place [20, 21, and 22]. These processes can be affected by the curing environment, the degree and size of the reactive phase in the main precursors, main ingredients particle size, the level of alkalinity, and the proportion of liquefied silicate [22]. The simplified form of the geopolymer formation cycle is given in figure 2.5.

Provis et al. [23] have revealed a clear representation of the geopolymeriation of fly ash and Metakaolin. The representation consists of an in-depth figure concerning the silicate oligomers that might be included in the alkali solution. Based on the Si/Al ratio, the oligomers have been classified into amorphous and non-crystalline phases.

Apart from the zeolite phase, an alternative reaction line was kicked off for the direct formation of Al-Si gel as indicated in figure 2.6.

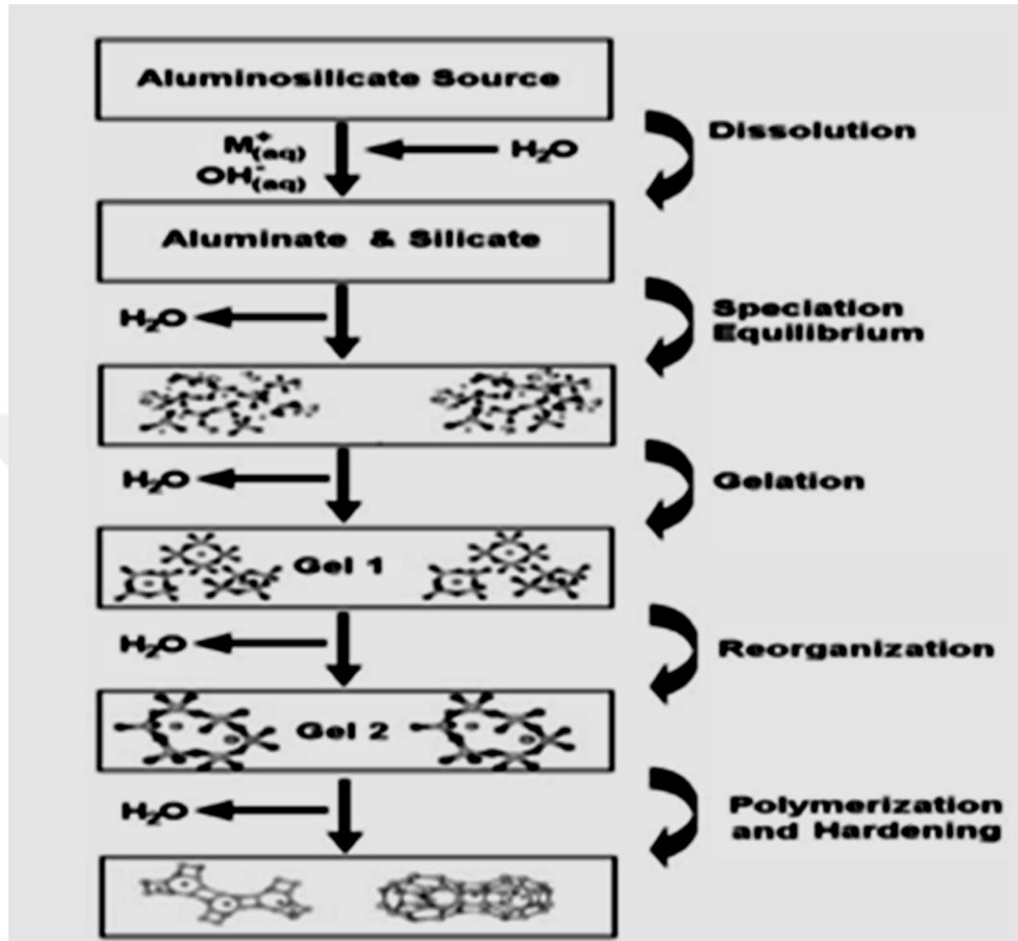


Figure 2. 5 The reaction process of geopolymers [24]

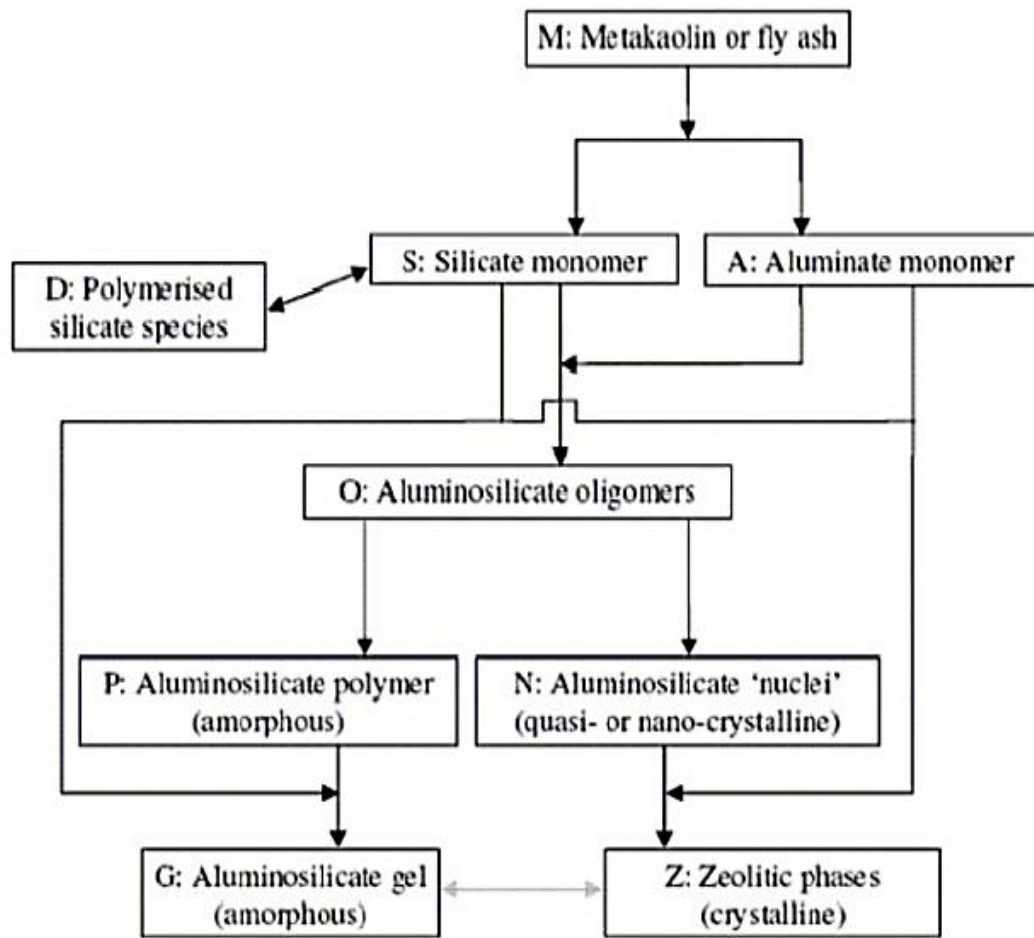


Figure 2. 6 Geopolymer reaction model [23]

2.3 Constituents of Fly ash/Slag based Geopolymers

2.3.1 Fly Ash

Fly ash is a fine particulate residue obtained from the combustion of pulverized coal which might cause anthropogenic deterioration of the environment. It is a widely available substance around the globe. According to Malhotra [15], the yearly production of fly ash throughout the world was estimated to be 780million tons by the year 2010. The report by Sirri Uyanik et al. [25] revealed the amount of fly ash produced in Turkey approximately 24million tons from which more than 50% is calcareous (appropriate for concrete production) and it was expected to be doubled by 2023. According to Gorhan et al. [26], less than 10% of the total production is

utilized in the relevant sectors in Turkey. ACAA [27] reported the hiring of fly ash in construction industries would have valuable environmental and technical benefits in terms of concrete durability, energy-saving, GHG emissions lowering, and conserving virgin materials and resources. There are distinct categorizations for fly ash in different international codes. In Turkey, mainly, the EN is employed to differentiate Fly ash types. TS EN 197-1 [28] classifies fly ashes into siliceous fly ashes (V) where reactive Silica and Alumina are important elements and Calcareous Fly ashes (W) where reactive Ca is a core element.

ASTM C 618 [29] marks fly ash as *“the finely divided residue that results from the combustion of ground or powdered coal and that is transported by flue gasses.”* It is collected from the combustion gases either mechanically and utilizing electrostatic precipitators. The kinds and contents of incombustible substances affect the chemical makeup of fly ash. In ACI, [30] the major and minor ingredients of fly ashes are indicated. The four dominant constituents are listed as silica, alumina, calcium oxide, and iron oxide. Also, sulfur, magnesium, sodium, and potassium have occurred in lesser quantities. Benschmidt et al., [31] have shown that the ingredients in the coal determine the chemical and mineral phase structure of fly ash. Apart from chemical structure loss of ignition that measures the degree of unburnt carbon, uniformity and fineness are among the peculiar attributes of fly ash. Fly ash contains spherical and finely graded particles that make it a less water consuming substance in comparison to its corresponding Portland cement [32].

2.3.2 Ground Granulated Blast Furnace Slag

The ground granulated blast furnace is a by-product obtained by melting iron ore, flux, and coke combined in a blast furnace. The compounds such as CaO, SiO₂, Al₂O₃, and MgO are the major constituents of a blast furnace slag. According to Alwis et al. [33], CaO is considered as the main contributor to compressive strength development and determining the basicity of the slag output. The particle size of slag determines the reactivity of the slag with alkali activators in the binder production process. The particles having less than 2micro-meters (μm) react fully in a day while large size particles react slowly compared to small size particles [17]. Provis et al. [17] also disclosed that while employing slag in geopolymer production, the

proportion of various sizes of particles should be assured to regulate the quality of the geopolymer cement.

Blast furnace slag has a long history in the construction sector, and also slag is a sufficiently available material in the world today. As EUROSLAG Association [34] reported the manufacturing of blast furnace slag in Europe recorded 25M tonnes in 2018. The major part of blast furnace production is utilized in concrete production.

2.3.3 Fly ash/ Slag based Geopolymers

Slag and fly ash combination is a widely used ingredient in geopolymer concrete production. It has numerous advantages in terms of developing a binder having minimum embodied energy, and physical similarity with conventional cement. Fly ash/slag-based geopolymers are capable of setting and hardening at ambient temperature. Furthermore, these types of geo-polymers are safe to handle and store. The mixing procedure can be achieved in the same procedure as Portland cement concrete, therefore, can be easily employed for a potential substitution of ordinary Portland cement.

Low calcium-based geo-polymeric products such as low calcium fly ash and metakaolin require an extremely long time to set and to harden at room temperature. As a result, abundantly previous studies were focused on a geopolymer concrete and mortar cured at an elevated temperature that limits their applicability in real-world construction projects. [16, 35, 36, 37].

Studies showed that the combination of slag with fly ash or vice versa can significantly improve the setting and hardening time of the geopolymer matrix at normal conditions. Apart from this, it has a valuable impact on the short and long-term strength parameters of the GPC and mortar. Susan et al. [38] stated that the availability of calcium compounds speeds up the geo-polymerization process. On the other hand, the disintegration of the silicate and aluminum monomers controls the geo-polymerization process. According to Yip et al. [39], the existence of silicate and aluminum monomers in an alkaline solution determines the formulation of the framework of the resulting matrix. And also, the level of dissolution of the monomers from source materials affects the formulation of the geopolymeric

structure. As stated in section 2.2 the combination of Slag and Metakaolin results in a three-dimensional and stable network of geopolymer products. According to Davidovits [20], Fly ash plays a significant role as a Metakaolin does, in terms of chemical structure stabilization, durability, and strength. Fly ash – slag based geopolymer binder encompasses both the geo-polymeric gel and calcium-silicate-hydrate simultaneously, where the calcium-silicate-hydrate gel is accountable for establishing early age strength.

2.3.4 Alkaline Activators

Geo-polymers are obtained from the alkalination of alumina-silicate substances by alkaline liquids. Alkaline-activator, mainly the combination of sodium or potassium hydroxide and sodium silicate solutions, reacts with the alumina-silicate substances to give the geopolymer binder that contributes to manufacturing the geopolymer mortar or concrete matrix in combination with other ingredients.

According to Lindgard et al. [40] alkaline solution, which would be active at the time of silica and alumina dissolution, has a significant contribution during the condensation process. Alkaline solution selection bases on the availability, price of the solution, and an intended reactivity rate.

The kind of alkaline solution has an important role in governing geopolymer matrix behavior. In this study, the combination of NaOH and Na₂SiO₃ solution was used. Palomo et al., [41] revealed that the mixture of NaOH and Na₂SiO₃ solution resulted in better compressive strength than its corresponding potassium solution. However, Xu and Van [42] revealed that the KOH gave advanced compressive strength than sodium hydroxide provided that both of them are mixed with sodium silicate solution. On the other hand, the rate of dissolution of NaOH was higher than KOH.

Iftekhair et al. [43] reported the impact of the chemical concentration on the Palm Oil Fuel Ash – sand matrix, and they obtained improved strength performance with the increase of concentration. According to Guo. et al. [44] high concentration of alkaline solution facilitates greater dissolution and enhances the geo-polymerization reaction.

2.4 Factors Affecting the Characteristics of Geopolymer

Concrete

Unlike Ordinary Portland cement, whose performance mainly bases on the water – binder ratio, several factors can affect the performance of geopolymer binders. Plenty of previous studies have already addressed various factors that may alter different properties of the geo-polymer matrix.

Xiaobin et al. [45] investigated the effect of water content on fly ash/Slag-based cement-sand matrix cured at a negative temperature. The early age mechanical and microstructural characteristics of the matrix have shown significant improvement while using lower water content. However, long-term performance has been slightly affected by water content variation. In the geopolymer concrete, excess water can interrupt the condensation process that in turn affects its setting time. Lloyd et al. [46] have shown an inverse relationship of the water content and the compressive performance of fly ash-based geo-polymer concrete matrix although higher water content has enhanced the workability of the fresh concrete matrix. In this study, the water content implies the sum of water used in NaOH solution, Na_2SiO_3 solution, and extra water included in the mix. Aliabdo et al. [47] disclosed that adding extra water has enhanced the workability although decreased other characteristics of geopolymer concrete. They suggested an ideal extra water amount to be 30 kg/m³, which has little effect on the mechanical characteristics of a resulting matrix.

Pradip and Prabir [48] conducted the effect of slag on various attributes of fly ash GPC matrix cured at normal temperature. They concluded that the addition of slag improved early age compressive strength and setting time, but decreased workability and handling time of the concrete matrix exposed to ambient temperature, with the increase of slag proportion. Furthermore, the compactness of the binder was improved with the rise of the slag amount. In their study, with no extra water and superplasticizer, the combination of 10% slag, 40% alkaline solution, and Na_2SiO_3 to NaOH ratio 1.5 to 2.5 were recommended as an ideal combination of geopolymer mixture. A study by Apriany et al. [49] demonstrated a

constructive role of slag on the mechanical and microstructural characteristics of fly ash GPC. According to their investigation, increasing the slag content has significantly improved the initial compressive performance of unheated specimens. It has also helped with the formation of denser structures in unheated specimens because of its CSH gel. Davidovits [50] demonstrated that the addition of slag quicken setting time and improves the compressive performance of fly ash/Metakaolin GPC cured in a normal environment. Temuujin et al., [51] proved that the addition of CaO significantly improves setting times of fly ash-based geopolymers. Also, in the study by Yip et al. [39] fly ash to slag ratio is considered among the significant factors that interfere geo-polymerization process despite its positive effect on the compressive strength development. Hardjito and Rangan [16] have shown the effect of curing temperature and curing time on GPC. The compressive strength of the low calcium fly ash-based geopolymers increased with the increase of curing time. However, the rate of change after 24hrs was not as significant as it was in the first 24 hrs. On top of these, elevated temperature enhances the polymerization process, producing a higher dissolution rate. Khale et al. [52], and Hardjito and Rangan [16] suggested a maximum curing temperature of 75°C and 60°C, respectively. However, Davidovits [53], and Nath and Sarker [54] experimented with room temperature curing can be attained with the incorporation of slag in the low- calcium-based geopolymer matrix. The proportion of aluminum and silicon has a significant impact on the mechanical and durability characteristics of the geopolymer concrete matrix. In geopolymer production silica can be obtained from the silicate solution and the solid ingredients. However, base substances are the only contributors to the availability of aluminum in the geopolymer matrix. In the study by Provis et al. [17], it was revealed that the content of aluminum and its rate of release throughout the reaction influenced various properties of the resulting matrix. These include setting time, internal structure framework, resilience to an acidic environment, and concrete performance development.

2.5 Properties of the Geopolymer Concrete

Several studies have declared geopolymer concrete owns excellent physical and mechanical characteristics to substitute conventional concrete. Some of the peculiar properties of geopolymer concrete are reviewed in the following section.

Wallah et al. [55] carried out creep and drying shrinkage characteristics of GPC in comparison to that of conventional concrete, and they revealed that OPC concrete exhibits higher creep than its corresponding geopolymer concrete. However, geopolymer concrete cured at ambient temperature experiences similar drying shrinkage with conventional concrete. An elevated temperature curing results in minimum drying shrinkage.

The study performed by Ahmet et al. [56], indicated that slag-based GPC specimens cured at room temperature, undergo higher compressive and tensile strength than concrete produced from ordinary Portland cement and fly ash only. Chi et al. [57] confirmed the better compressive performance of fly ash/slag-based geopolymer matrix in comparison to both conventional concrete and low calcium-based geopolymer matrix. Hardjito et.al. [58] Obtained significantly higher compressive performance for low calcium fly ash-based geopolymer concrete cured at elevated temperature. Therefore, it is possible to attain higher compressive strength low calcium geopolymer products by introducing heat activation that facilitates the geopolymerization process.

Ahmet et al. [56] studied the impact of chemical aggression on the durability characteristics of GPC and OPC concrete. They used both visual inspection and weight loss measurements to determine the effect of an acidic, sulfate, and marine environment on test specimens. According to their study, conventional concrete experienced the greatest surface deterioration; in contrast, slag and fly ash-based geopolymers experienced moderate and slight surface deterioration after exposure to chemical attacks, respectively. Sulfuric acid aggression is perceived to be the most serious attack. Also, the rate of mechanical performance decline in OPC concrete has been slightly higher than the drop in the case of the geopolymer concrete matrix. Chen Huiguo et al. [59] investigated the response of fly ash/slag-based geopolymer concrete exposed to various degrees of high temperature. According to the study,

GPC specimens have shown fewer surface changes such as color change, mass loss, cracks, and corner breakage in comparison to conventional cement concrete specimens. Some strength parameters of OPC concrete samples exposed to elevated temperature have significantly declined in comparison to specimens at room temperature. In contrast, GPC specimens subjected to high temperature possessed the greatest compressive strength at 400°C; however, it has shown considerable reduction after 400°C. After catastrophic fire damage in France, Davidovits [53] conducted intensive research to find materials possessing higher thermal stability and introduced mineral materials known as geopolymers. Finally, he revealed that the Geopolymer concrete matrix exhibits better thermal stability than OPC concrete. This is because mainly geopolymer concrete results from a polycondensation process, unlike OPC concrete which yields from a hydration process. In the study by Kumar et al. [60], a fly ash/slag-based geopolymer matrix is anticipated to result in better thermal characteristics than its OPC encounter. This might be due to the lesser concentration of CaOH in geopolymeric products.

2.6 The Effect of Recycled Aggregates on the Properties of Geopolymer Concrete

Several researchers have addressed the pros and cons of utilizing recycled aggregates instead of natural aggregates to produce geopolymer concrete. Arenas [61] presented the better environmental and technical characteristics of recycled aggregate used in geo-polymeric concrete than crushed-granite aggregates. The following section discusses the effect of using CDWs as a coarse aggregate to produce geopolymer concrete in comparison with NCA.

According to the study by Jianhe et al. [62], the recycled aggregate GPC with the liquid-binder ratio of 0.5 has shown a slightly higher slump than natural aggregate concrete with the same water-binder proportion. The recycled aggregate utilized was pre-wetted based on its moisture absorption capacity. Also, its slump increased with increasing water-binder ratio but declined when GGBS content was increased in the mixture. The fly ash/GGBS based GPC possesses a higher slump than OPC concrete provided that natural aggregate is fully replaced by recycled aggregate. Nevertheless, the initial and final setting time of the RCA geopolymer concrete

reduces with the increase of GGBS content. An optimum setting time and slump can be achieved by fixing the appropriate water-binder ratio, calcium content, and managing water-reducer in the concrete production process.

Nuaklong et al. [63] presented that geo-polymer concrete with recycled aggregate resulted in lower compressive strength than conventional concrete with raw aggregate. Nevertheless, the flexural and splitting tensile strength of the recycled aggregate geopolymer concrete was slightly higher than the normal aggregate concrete provided that sodium hydroxide concentration was fixed to 12M. In contrast, the density and abrasion resistance of recycled aggregate geopolymer concrete appeared lower than that of natural aggregate geopolymer concrete. In the study done by Naga et al. [64], the mechanical performance of geopolymer concrete with the recycled aggregate proportion of up to 40% has shown only a slight reduction with the increase of re-used aggregate ratio. Whereas the decrement rate after 40% replacement was adverse that might limit the concrete's usability for the structural applications. Mesgari et al. [65] found that the partial replacement of coarse natural aggregate with recycled geopolymer concrete aggregate ratio of up to 20% has caused an insignificant change in the modulus of elasticity, flexural strength, and volume of permeable voids of OPC concrete. However, its effect on the compressive performance was moderate. On the other hand, the 50% and 100% replacement ratio has resulted in a significant strength reduction in the case of both conventional and geopolymer concrete matrix, although geopolymer concrete appeared more resilient in comparison with OPC concrete.

Mahdieh et al. [66] explored the interfacial performance between fly ash paste and recycled aggregate concrete with the aid of a laser scanning microscope (LSM) and Energy dispersive spectroscopy (EDS). The observation indicated that both new and old interfaces in fly ash-based GPC with recycled aggregate were found dense. The prior incomplete interphase of re-used aggregate particles inside the recycled aggregates geopolymer concrete was not porous, which was not seen in the case of conventional concrete with the same aggregate. The mixture of fly ash-based geopolymer with recycled aggregate is considered as a suitable combination with improved engineering properties that can head to environmentally friendly

construction input. Liu et al. [67] carried out the microstructural characterization of the new interfacial transition zone in geopolymer concrete blends with re-used aggregates and observed that feeble transitional interphase doesn't create.

Jianhe et al. [62] revealed that the ultimate stress of the stress-strain diagram of the re-used aggregate concrete was reduced, and the top and bottom sections of the curve became gentle in the case of natural aggregate concrete. When the conventional cement was fully substituted by fly ash/slag-based geopolymer paste, the ultimate stress-strain was increased, with the increase of slag content.

According to the study by Nuaklong et al. [63], the geopolymer concrete containing recycled concrete aggregate possessed higher water absorption and sorptivity than its corresponding natural crushed limestone aggregate. Also, the volume of permeable voids amplified with the increase of recycled aggregate. Hwang et al. [68] revealed that recycled aggregate concrete exhibits lower durability characteristics such as chloride resistance, sulfate attack, and frost action than reference natural aggregate specimens. Ammar and Jasem [69] found that the chloride invasion increased with increasing of recycled aggregate replacement level after 28 days of exposure to marine water with 3% chloride concentration. However, after 14 days of saturation, concrete specimens with a 30% recycled aggregates replacement ratio revealed the lowest chloride diffusion than plain OPC concrete. Geopolymer concrete shown better durability performance than ordinary Portland cement in a sulfuric acid solution was revealed by Ariffin et al. [70].

Several researchers investigated the effect of recycled aggregates, on the creep and shrinkage behavior of the recycled aggregates concrete. The authors agreed that the creep and shrinkage of concrete raised, with an increase in recycled aggregates amount. Hoai and Quoc [71] in their review indicated that the recycled aggregates substitution of up to 30%, has shown only a slight increase in the shrinkage behavior of the concrete, mostly lower than 10%. Nevertheless, the replacement ratio of 50% and more, resulted in a significant change, in the shrinkage of the resulting concrete matrix. Gomez Soberon [72] revealed that the creep increased with increasing recycled aggregate content; however, until 30% of recycled aggregate substitution, only a limited creep happened.

2.7 Fiber-Reinforced Geopolymer Concrete

Concrete is a crucial material of infrastructure development, principally because it may set and hardens at ambient temperature, even when immersed in liquid. Nevertheless, as a construction input, particularly as a structural application, there are some shortcomings and constraints. Concrete possess very low tensile strength and highly brittle material in nature. Although concrete exhibits excellent compressive strength, its tensile performance is comparatively ten to fifteen times lower, than its corresponding compressive performance. Likewise, huge concrete structures can encounter impressive extension and shrink with temperature variances. Moreover, water infiltrates into pores that may create serious cracking in the chilly climate as a result of freeze-thaw cycles. The vast majority of these deficiencies might be dispensed with or possibly improved by reinforcement and inclusion of the fiber additives. The following section addresses the influence of fiber inclusion in geopolymer concrete.

Kumaravel and Ilango [73] tested the impact of crimped-ended steel fiber on GPC. The authors used an aspect ratio and a volume fraction of steel fibers 50 and 1%, respectively. The workability and setting time of fresh GPC was similar and even better than that of OPC concrete. Moreover, the fiber maintained an excellent bond with the fly ash/slag-based GPC matrix.

The comparative study on durability parameters of OPC and geopolymer concrete containing fiber and plain concrete was performed by Ganesan et al. [74]. The durability dimensions tested were appeared to be enhanced with the incorporation of fibers in the case of both concrete types. In general, fiber-reinforced geopolymer concrete specimens possessed better durability characteristics than its encounter plain GPC and OPC concrete as well. Al-Mashhadani et al. [75] examined the mechanical performance and internal characteristics of fly ash-based geopolymer mortar with steel, polypropylene, and polyvinyl alcohol fiber additives. The authors revealed that the mechanical strength of the composites was improved with the increase of fiber content. Moreover, the flexural strength of polyvinyl alcohol-reinforced mortar specimens exhibited the highest deviation to the control

specimen. Likewise, abrasion resistance and drying shrinkage were found to be enhanced when fibers were employed. Also, an acceptable interfacial bonding was formed between fibers and fly ash binder mortar matrix. However, polypropylene fibers have developed comparatively weaker bond strength than steel and polyvinyl alcohol fiber additives. Xiaolu and Xuejiao [76] analyzed the impact of polypropylene, basalt, and steel fiber on the microstructural and mechanical properties of geopolymer composites. The report indicated that the late age mechanical performance of the fly ash and slag-based geopolymer matrix was improved with the addition of polypropylene and basalt fiber additives. Whereas, the toughness and reinforcement impact was significantly enhanced when steel fiber was used. Also, limited crack propagation and lower pore development were demonstrated due to the inclusion of fibers. In general, steel fiber has recorded an outstanding performance in comparison to its encounter polypropylene and basalt fibers. In the study by Genesa et al. [77], the engineering characteristics of geopolymer composite reinforced with steel fiber were investigated. In the study, a steel fiber volume proportion of 0.25, 0.5, 0.75, and 1%, and a concrete grade of 40MPa was used. The authors demonstrated a significant increase in modulus of elasticity and splitting tensile strength of nearly 64.92% and 61.63%, respectively, at a 1% volume fraction of fibers. Likewise, compressive performance and modulus of rupture of the reinforced composite increased by 8% and 24%, respectively, at the same amount of fiber content. According to the study done by Sukontasukkul et al. [78], the synergetic effect of the fibers has shown better performance in terms of toughness, flexural, and residual strengths than sole polypropylene addition. The toughness and residual strength appeared to be proportional to the steel fiber content. The impact of polypropylene fibers on the metakaolin-based geopolymer concrete produced, with the partial replacement of recycled aggregates, was evaluated by Behforouz et al. [79]. The polypropylene fibers were appeared to be worthwhile in flexural strength, split tensile strength, and drying shrinkage of the geopolymer matrix. Moreover, the load-deflection curve improvement was observed, with the increase of the polypropylene fiber ratio. This, in turn, resulted in higher fracture toughness and better maximum load potential. Furthermore, the microstructural assessment showed that the polypropylene fiber plays a significant

role in restricting possible crack distribution due to bounding maintained between fibers and geopolymer binder.



3.1 Introduction

In this section of the thesis, the materials hired in the research work will be discussed. And also, the peculiar attributes of the materials are given in the form of a table, and figure. Furthermore, the working methodology of each experiment is explained in detail.

3.2 Materials

3.2.1 Slag

GGBFS was used as a base material to make the paste for producing the GPC specimens. It was obtained from the cement factory, known as Bolu, based in Turkey. The specific weight of the slag is 2.91g/cm^3 . The properties of GGBFS employed in this thesis are appeared in Table 3.1 and Figure 3.1, respectively.

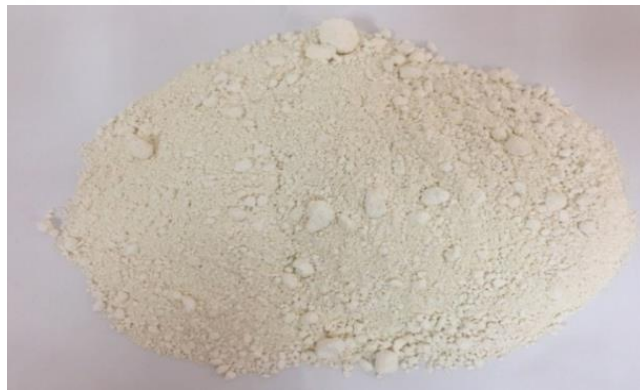


Figure 3. 1 Sample slag used

3.2.2 Fly Ash

In the experimental study, low calcium fly ash (ASTM class F) in combination with slag was used as the main precursor. The fly ash was supplied by a company based in Turkey. The class F fly ash used in this experimental work confirms the standard specifications stipulated in ASTM C618 [80]. X-Ray Fluorescence analysis was

conducted to determine the chemical up of the fly ash and its composition is displayed in Table 3.1. The specific weight of the fly ash was recorded as 2.32g/cm^3 . The sample fly ash used in this experimental work is also given in figure 3.2.



Figure 3. 2 Sample fly ash used

Table 3. 1 Chemical composition of fly ash and slag

NO.	Oxides	Content (%)	
		Fly ash	Slag
1	SiO ₂	58.75	40.55
2	Al ₂ O ₃	25.24	12.83
3	Fe ₂ O ₃	5.76	1.1
4	CaO	1.46	35.58
5	MgO	2.22	5.87
6	SO ₃	0.008	0.18
7	Na ₂ O	0.60	0.79

8	Free CaO	0.11	-
9	Cl ⁻	0.015	0.014
10	K ₂ O	4.05	-
11	LOI	1.12	0.03
12	TiO ₂	-	0.75

3.2.3 Aggregates

Recycled and natural coarse aggregates were supplied from the local sources. Coarse aggregates with a size of 12-20mm and 5-12mm were identified as NO. II and NO. I, respectively. Fine aggregates with Dmax 4 mm were also prepared from crushed limestone and river sand, given that both types contribute equal proportion. The aggregates classification is summarized in figure 3.3.

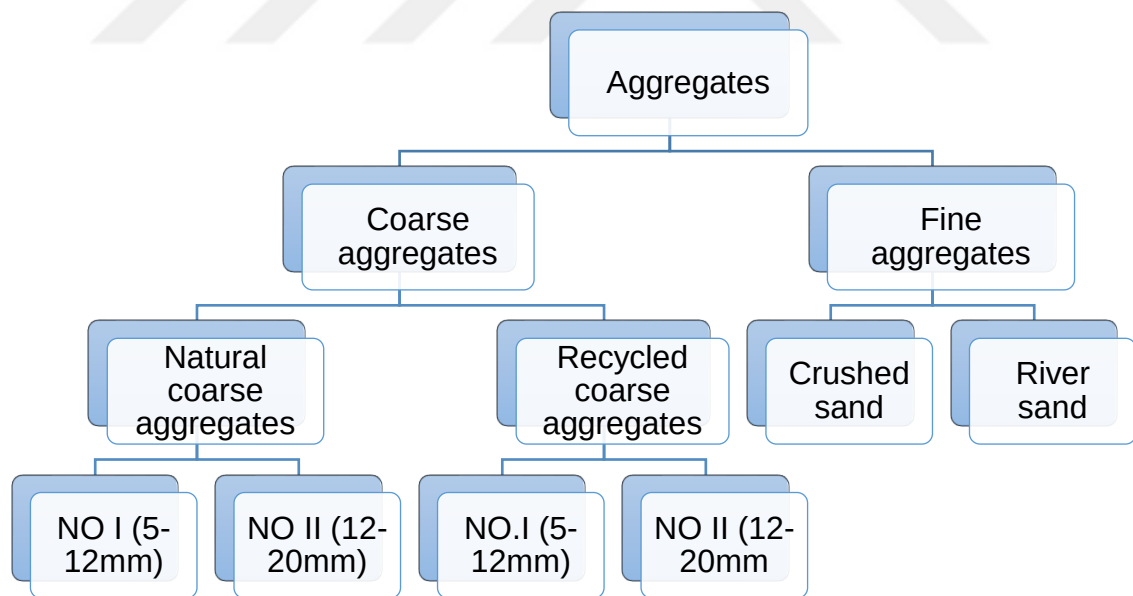


Figure 3. 3 Classification of aggregates utilized

In this experimental work, NCA and RCA possessing the following physical properties were employed. Table 3.2 contains some characteristics of the aggregates. Figure 3.4 and figure 3.5 show the gradation of NO II and NO I.

Table 3. 2 Physical characteristics of aggregates

Measured characteristics		Nominal size (mm)	Water absorption (%)	Specific gravity
Fine aggregate	Crushed Sand	4	1.11	2.67
	Riverbed Sand	4	-	2.69
Coarse aggregate	Natural coarse aggregate	20	0.9	2.71
	Recycled coarse aggregate	20	6.6	2.45

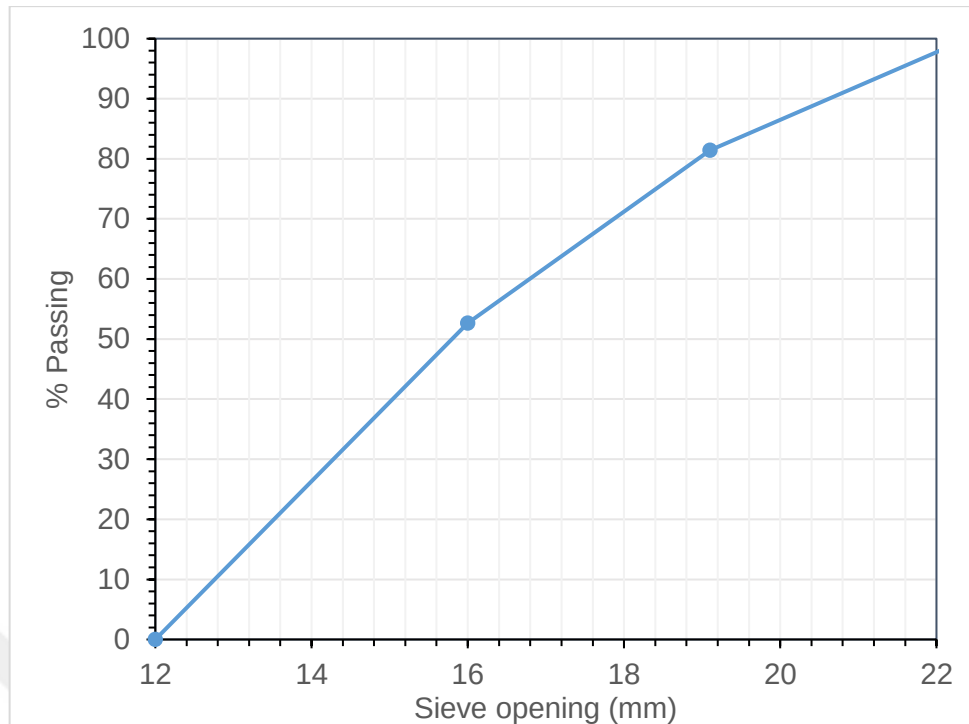


Figure 3.4 Gradation of NO II coarse aggregate used

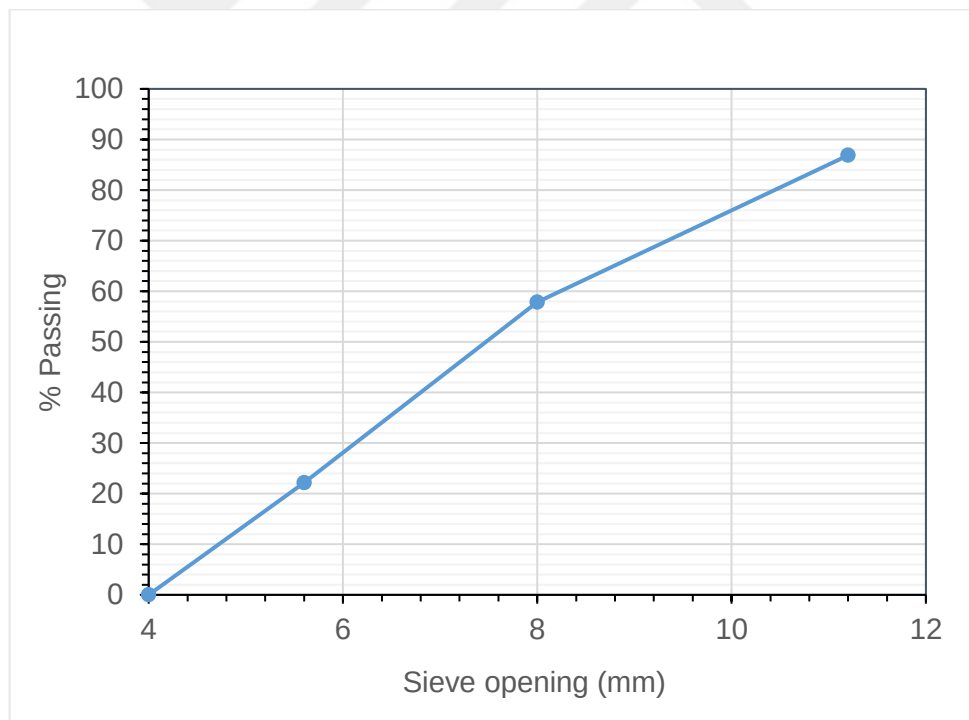


Figure 3.5 Gradation of NO I coarse aggregate used

3.2.4 Superplasticizer

To enhance the workability of the fresh concrete mix, a carboxylic ether polymer with long side chains in liquid form, under the brand name MasterGlenium 51, supplied by BASF Türk Kimya San. ve Tic. Ltd. Şti. based in Turkey, was used throughout the study. All the application and safety procedures stated in the product specification and standard regulation manuals were strictly enforced. The product specifications appeared in Table 3.3.

Table 3. 3 Characteristics of the superplasticizer used

Chemical Description	Modified Polycarboxylic Ether Based
Name	Master Glenium 51
Color	Dark brown
State	Liquid
PH Value	6-7
Specific gravity (kg/l) @ 20°C	1.082 - 1.142
Chloride content (%)	=< 0.1 (by mass)
Alkali content (%)	=< 3 (by mass)
Recommended dosage	1-2% (% binder content)

3.2.5 Alkaline activators

In this thesis, a mixture of NaOH and Na₂SiO₃ solution was chosen as a chemical activator to react with solid substances to produce slag/fly ash-based fiber reinforced geopolymer concrete. Sodium silicate was utilized because it is less expensive than its Potassium encounter. The technical details of the commercially available sodium silicate and sodium hydroxide are indicated in Table 3.4 and Table 3.5, respectively. It was supplied by Chemicals Company based in Turkey. Sodium

hydroxide solid was dissolved in pure water to prepare a NaOH solution of 13M concentration. The molarity of sodium hydroxide was adjusted by considering the workability, strength, and durability properties of the resulting concrete.

Table 3. 4 Properties of sodium silicate

Grade	GDF-48
Na ₂ O (%)	11 – 12
SiO ₂ (%)	22 – 23
Wt. ratio SiO ₂ /Na ₂ O	2
Specific gravity (g/ml @ 20°C)	1.458
Appearance	Light Yellow or Colorless
Density (g/ml)	1,38 ± 0,010
Fe (ppm)	100 Max.

Table 3. 5 Properties of sodium hydroxide

Characteristics	Description
Color (Solid)	White
Molar mass (g/mol)	40
Density (g/cm ³)	2.13
Specific gravity (g/ml @ 20°C)	2.13
Boiling point	1390 °C
Freezing point	14 °C

PH	13-14
NaOH (%)	99
Na ₂ CO ₃ (%)	0.3
SO ₄ (%)	≤ 0.01
Cl (%)	≤ 0.01
Al (%)	≤ 0.002
Fe (%)	≤ 0.002

3.2.6 Steel Fiber

In this investigation, crimped steel fibers obtained from the local suppliers named KrampeHarex İnşaat Mühendislik Yapı Ürünleri Sanayi ve Ticaret Ltd. was used. The technical specifications of the fibers obtained from the provider are given in Table 3.6 and it is shown in Figures 3.6 and 3.7.

Table 3. 6 Properties of crimped steel fiber utilized in the study

Characteristics	Value
Fiber type	Crimpled steel
Width (d) (mm)	2.30 / 2.95
Length (l) (mm)	50±10%
Cross-section	Straight
Tensile strength (MPa)	800±15%

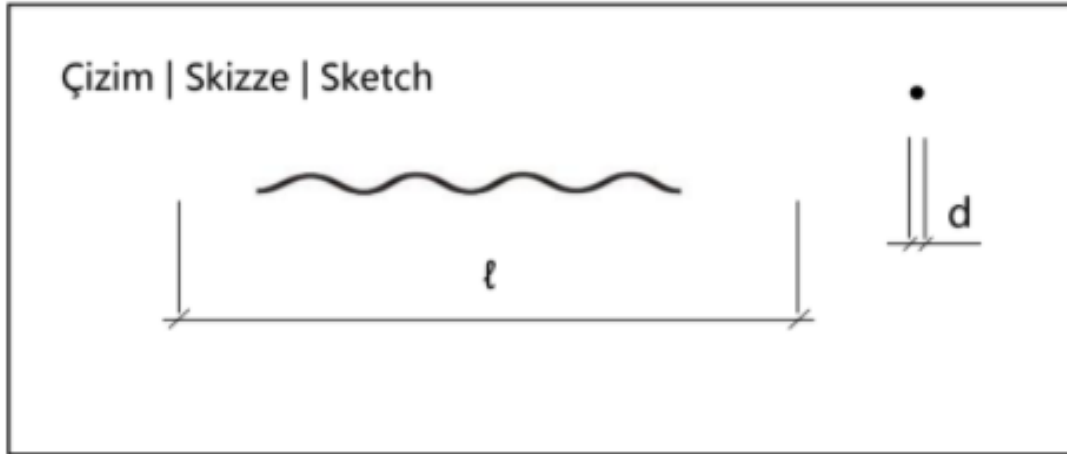


Figure 3. 6 Details of steel fiber used



Figure 3. 7 Crimped Steel Fiber used in the study

3.3 Preliminary Investigation

The trial mixes were carried out in the study to understand the characteristics of the concrete mixtures and to determine the mixture that will possess acceptable physical, chemical, and mechanical properties. As indicated in the previous section, no code and standard guide the fabrication and the curing of the geopolymer concrete. This preliminary investigation targeted to monitor the effect of some

factors in the performance of the geopolymer concrete samples and assessed in terms of compressive performance. Also, the workability and homogeneity of the mix were visually inspected. The factors such as chemical to binder ratio and additional water-based on the water-absorbing capacity of recycled aggregates were taken into consideration. The specimens of the trial experiment were cubical shaped with 100×100×100mm. Table 3.7 contains details of some trial mixes.

Table 3. 7 Mix proportions and strength results of some trial mixes

Parameters	Trial 1	Trial 2
Binder percentage	75% Slag and 25% Fly ash	75% Slag and 25% Fly ash
Chemical to binder ratio	0.45:1	0.5:1
Molarity of NaOH	13	13
Na ₂ SiO ₃ /NaOH	2.5:1	2.5:1
Coarse aggregates / Binder	3:1	3:1
Fine aggregates / Binder	2:1	2:1
28 days compressive strength (MPa)	22.15	34.25
90 days Compressive strength (MPa)	25.83	37.86

According to table 3.7, the compressive strength increased with the increase of a chemical to binder ratio. The compressive strength results of trial 1 appeared in figure 3.8. The concrete mixtures produced with a chemical to binder ratio of 0.45 resulted in a lower homogeneity of fresh concrete; therefore, the concrete casting was laborious, and the vibration was intensive. This might be due to the insufficient liquid content used to saturate solid ingredients in concrete. In this study, a chemical

to binder proportion of 0.5 issued a homogeneous fresh concrete. RCA was saturated to maintain the surface saturated dry condition. The mixtures manufactured with an activator to solid ratio of 0.5, confirmed to be investigated in this study.

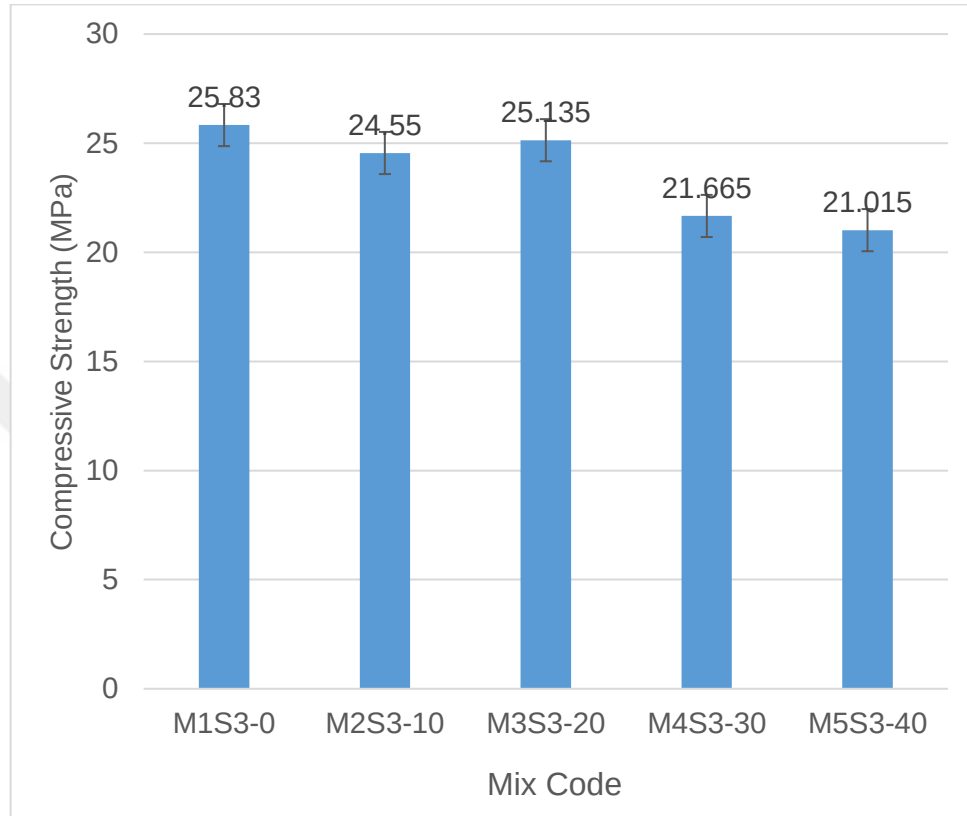


Figure 3.8 90 days compressive strength of slag-fly ash-based geopolymer concrete

3.4 Mix Proportion

In this study, the precursor materials possessing the chemical composition indicated in Table 3.1 were used to form a geopolymer binder. An equal share of crushed gravel sand and river sand having a nominal size of 4mm was hired as a fine aggregate. The NCA and RCA having properties given in Table 3.2 were also used in different proportions. The outputs of sieve analysis for aggregates have appeared in Figures 3.4 and 3.5. The chemical solutions containing sodium hydroxide and sodium silicate were used as an activator. The Na_2SiO_3 to NaOH ratio of 2.5 was employed. The same ratio of sodium silicate to sodium hydroxide was used in the study by Mustafa et al [81]. The proportion of activator solution to base material

was chosen as 0.5. To produce concrete having appropriate workability, strength, and durability properties the molarity of sodium hydroxide was adjusted to 13M. Moreover, to enhance the workability of geopolymer concrete a modified polycarboxylic ether-based superplasticizer was hired during the mixing process. And also, to keep an appropriate level of concrete flowability extra water was added to the mix. Steel fibers (fig. 3.7) having properties shown in Table 3.6 were also used in the study. A similar mix proportion was kept with the rise in the proportion of recycled aggregate and fibers. However, to maintain the surface saturated state of the coarse aggregates, recycled aggregates were dry surface saturated before mixing operation. The ingredients used during the geopolymer concrete preparation are displayed in figure 3.9. Table 3.9 revealed in-depth information about the mixture proportions used in the experimental work.

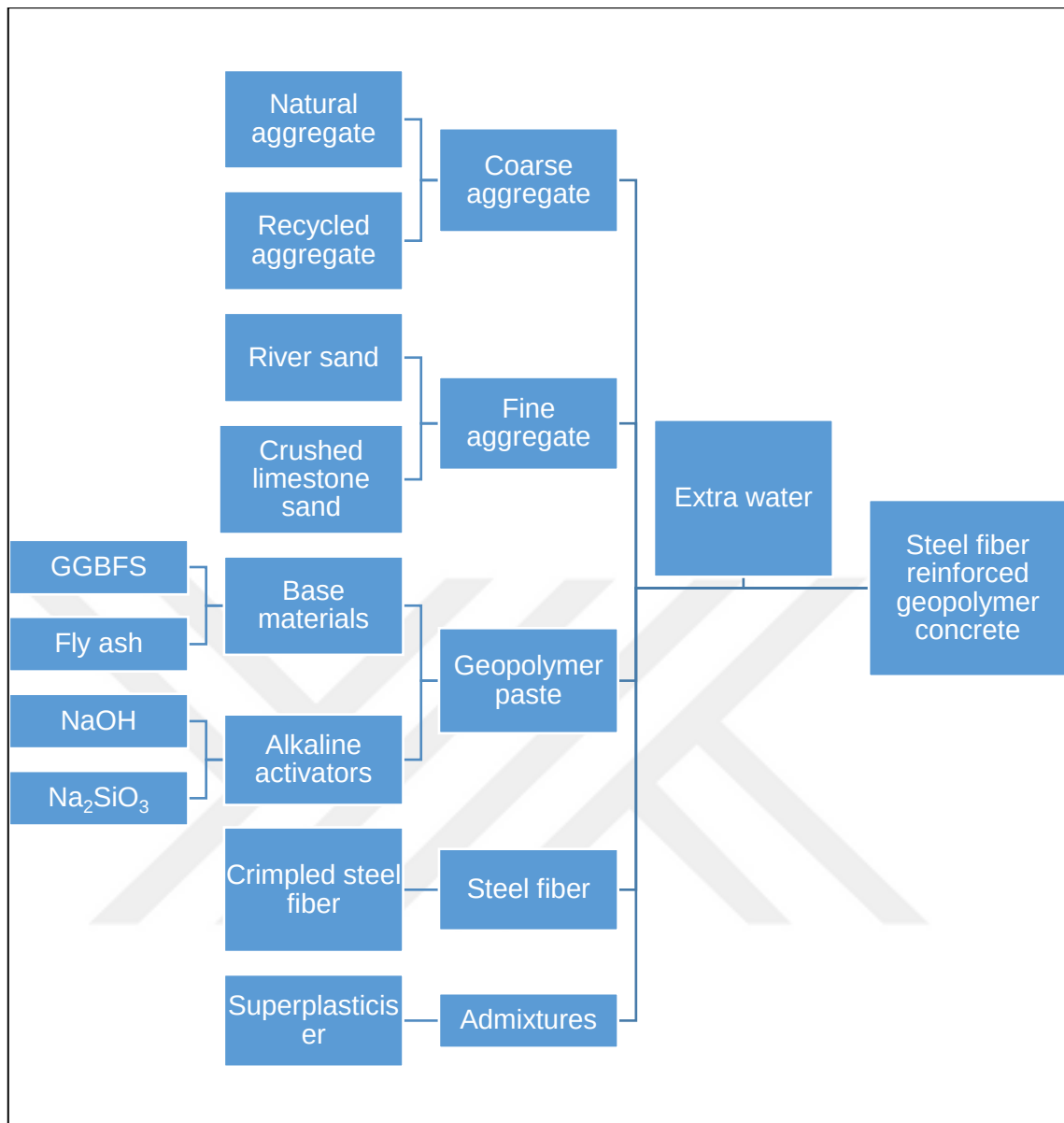


Figure 3. 9 Steel fiber reinforced geopolymer concrete production process

Table 3. 8 Explanations for the mix codes used in the study

Mix code	Explanation
M1S3-0	0.3% steel fiber ratio and no recycled aggregate
M2S3-10	0.3% steel fiber ratio and 10% recycled aggregate
M3S3-20	0.3% steel fiber ratio and 20% recycled aggregate
M4S3-30	0.3% steel fiber ratio and 30% recycled aggregate
M5S3-40	0.3% steel fiber ratio and 40% recycled aggregate
M6S6-0	0.6% steel fiber ratio and no recycled aggregate
M7S6-10	0.6% steel fiber ratio and 10% recycled aggregate
M8S6-20	0.6% steel fiber ratio and 20% recycled aggregate
M9S6-30	0.6% steel fiber ratio and 30% recycled aggregate
M10S6-40	0.6% steel fiber ratio and 40% recycled aggregate

Table 3. 9 The details of the mix proportion (kg/m³)

Mix code	FA	Slag	NCA	RCA	RS	CS	NaOH	Na ₂ SiO ₃	SP	EW	Steel fiber (By volume)
M1S3-0	89.54	268.63	1114.32	0	371.23	371.23	51.18	127.92	15.22	30.4	0.3%
M2S3-10	89.54	268.63	1002.8	111.44	371.23	371.23	51.18	127.92	15.22	30.4	0.3%
M3S3-20	89.54	268.63	891.44	222.88	371.23	371.23	51.18	127.92	15.22	30.4	0.3%
M4S3-30	89.54	268.63	780.02	334.30	371.23	371.23	51.18	127.92	15.22	30.4	0.3%
M5S3-40	89.54	268.63	668.58	445.76	371.23	371.23	51.18	127.92	15.22	30.4	0.3%
M6S6-0	89.54	268.63	1114.32	0	371.23	371.23	51.18	127.92	15.22	30.4	0.6%
M7S6-10	89.54	268.63	1002.8	111.44	371.23	371.23	51.18	127.92	15.22	30.4	0.6%
M8S6-20	89.54	268.63	891.44	222.88	371.23	371.23	51.18	127.92	15.22	30.4	0.6%
M9S6-30	89.54	268.63	780.02	334.30	371.23	371.23	51.18	127.92	15.22	30.4	0.6%
M10S6-40	89.54	268.63	668.58	445.76	371.23	371.23	51.18	127.92	15.22	30.4	0.6%

3.5 Production of Test Specimens

3.5.1 Mixing and Casting

Mixing is an essential part of the concrete production process. In this study, all the necessary steps have been taken into consideration to produce the steel fibers reinforced geopolymer concrete, according to the normal mixing standard. The activating chemicals liquids were mixed at least 24 hours before merging the alkaline solutions and solid ingredients. In the previous studies [82] it is recommended to combine the NaOH and Na₂SiO₃ solution at least 24 hours before mixing liquid chemicals and solid substances. The author also emphasized that the pre-mixing of the liquid solutions enhances the polymerization process by disintegrating the dimeric and trimeric form of the sodium silicate solution into monomer because the commercially obtained sodium silicate solution appears either in the form of dimer or trimer. Also, the superplasticizer was added to the chemical mixtures 2-3hrs before adding alkaline liquids to the solid ingredients. In the same way, on the day of mixing the extra water and superplasticizer were mixed. Finally, the general procedures followed in this experimental work are explained as shown below.

Primarily, dry mixing of the base materials and aggregates was performed in a fixed pan mixer of 240 liter capacity with rotating blades existing in a construction materials laboratory was continued for about 1 minute. All the coarse aggregates were pre-wetted based on their water absorption capacity to maintain the saturated surface dry condition.

Secondly, the activator liquids and superplasticizers mixed were poured into the dry mix and mixed for 2 minutes. After 2 minutes of mixing the solid constituents and liquid activators combined with superplasticizers in a pan mixer, steel fiber was manually distributed throughout the wet mix. Then, extra-water mixed with superplasticizer was added to the mix immediately after the fiber inclusion, and mixing continued for 1 minute until we obtain a homogeneous mix.

The workability capacity of the series was assured by performing a slump test of the fresh geopolymer concrete. The slump magnitude was slightly decreased with the increase of the steel fiber ratio. Generally, the slump height was recorded in the range of 16-20cm.

Subsequently, the fresh geopolymer concrete was cast into the oiled cubical, cylindrical, and prismatic molds immediately after mixing. Then, it was vibrated on a vibration table for about 20s to rid of air voids and leveled using a smooth trowel. Then after the specimens were covered, to restrict alkali liquid vaporization, and kept at room temperature for 24 hours before demolding.

3.5.2 Curing of the Test Specimens

The curing mechanisms for the geopolymer concrete matrix are majorly based on the types of base materials included. Elevated temperature curing is usually needed when a low calcium-based substance is utilized. Whereas high calcium geopolymer products like slag do not require a heat curing procedure. In this experimental work, slag constitutes the major part of the binding materials and thus a room temperature curing was considered. Immediately after molding, the specimens were covered, to restrict alkali liquid vaporization, and kept at room temperature for 24 hrs. Then after the test samples were demolded and moved into the controlled curing room; the room's temperature was adjusted to 23°C and relative humidity of 55±10%. After the required age was attained the specimens were taken from the curing room to wipe clean and then the test was conducted.

3.6 Test Procedures

3.6.1 Compressive Strength

It is a crucial parameter to determine the concrete's hardness. Also, this property of concrete helps to estimate other characteristics of the concrete matrix, qualitatively. Compressive strength is a prominent dimension to be considered while performing a concrete structural design. In this study, the compressive tests were performed following EN 12390-3 [83]. For each mix series, three 10x10x10 cm cubes were tested for 28 days and 90 days after casting. The test was taken on the 3000 kN contest compression testing machine that was hired to determine the maximum

load-carrying capacity of the test specimens. The compression testing machine was fixed to a constant loading rate of 0.6 MPa/S. The non-casting part of the specimen was exposed to constant loading until failure. The compressive strength testing specimen and the testing machine are shown in figure 3.10. Finally, the compressive strength of the cubes was calculated from the maximum force reading on the testing machine using equation 3.1. The compressive strength was determined using the average compressive strength of the two cubes from the same mix design.

$$\sigma = \frac{P}{A} \quad (3.1)$$

Where

σ : Compressive strength (MPa)

P: Maximum load read from the testing machine (N)

A : Surface area of the specimen (mm²)

3.6.2 Splitting Tensile Strength

This test is an indirect and easiest way to obtain the tensile characteristics of concrete. According to Nevili [84], the measured splitting tensile performance of concrete is believed to represent tensile strength obtained using the direct tensile strength test method. The author mentioned the possible positive deviation of the Split Tensile test result from 5 to 12%. In the study, the cylindrical samples at age 28 and 90 days were subjected to splitting tensile strength test machine until the failure and the maximum applied force was read from the testing machine. The test was taken on the 3000 kN testing machine and the constant loading rate was fixed to 1.6 kN/Sec. The test is carried out according to ASTM C496 -11 [85] standard procedure. An average of three cylindrical specimens was used to determine the splitting tensile strength of each concrete mixture and Equation 3.2 was used to evaluate the tensile strength of the test sample.

$$f_s = \frac{2P}{\pi LD} \quad (3.2)$$

Where,

f_s : Splitting tensile strength (MPa)

P: Maximum applied load read from the testing machine (N)

L: Length of the cylindrical specimen (mm)

D: Diameter of the cylindrical specimen (mm)



Figure 3. 10 Compressive strength testing machine and specimen used in the study

3.6.3 Flexural Strength Test

Flexural strength is among the peculiar properties of fiber-reinforced geopolymer concrete matrix. It gives information about the indirect tensile behavior of the resulting matrix. In this study, a three-point bending test was conducted according to ASTM C1609 [86] standard procedure. A total of four 100×100×500mm prismatic samples were cast per mix design and cured for 90 days. The test installation is displayed in figure 3.11. The casting side of the beam was subjected to the central loading using a compressive and tensile strength Testing Machine found in Yildiz Technical University at a loading rate of 1mm/min. The beam was simply supported on both edges with an effective span length of 450mm. This test was conducted to determine the flexural strength and energy absorption capacity of the geopolymer concrete samples using the load-deflection obtained from the three points flexural strength test result. The displacement result was used from the load-deflection

curve displayed in the computer without installing an extra displacement measuring instrument like LVDT.

Primarily, the energy absorption capacity of the resulting concrete matrix will be evaluated from the load-deflection diagram usually it is equal to the area under the load-deflection curve until recorded deflection suits $1/150$ of span length. The flexural toughness (T_b) is shown in equation (3.3) below and also the evaluation method based on the Japanese Standard (JSCE-SF4) is utilized to determine the flexural toughness as given in the equation.

$$\sigma_b = \frac{T_b}{\delta_{tb}} * \frac{l}{bd^2} \quad (3.3)$$

Where:

σ_b : flexural toughness factor $\left(\frac{N}{mm^2}\right)$

T_b : flexural toughness (J)

δ_{tb} : the deflection at $\frac{1}{150}$ of the span length l (mm)

l, b, d (mm) are the sample length, breadth, and depth, respectively.

Since the matrix is fiber reinforced, energy absorption of both the plain concrete and the post crack energy absorption capacity due to the presence of fiber will be discussed.

During the test, load and deflection data were recorded and then the flexural strength of the specimens are evaluated using the following formula:

$$\sigma_f = \frac{F \times l}{b \times d^2} \quad (3.4)$$

Where F is the maximum force applied (N), l is the span length between two supports (mm), b is the width of the tested specimen (mm), and d is the thickness (mm).



Figure 3.11 Three-point bending test installation

3.6.4 Abrasion Resistance Test

In this experimental work, the concrete specimen of $71 \times 71 \times 71$ mm was subjected to abrasion using a rotating disc abrasion machine that appeared in figure 3.12. The specimen was centrally loaded with a 294 ± 3 N load. Each specimen was tested for 16 cycles, each consisting of 22 revolutions. The grinding path of the disc, evenly strewn with 20 g of the standard abrasive powder, rotates at a speed of 30rpm. The thickness of the sample was measured using a thickness measuring instrument from six points at the end of each cycle. Also, the resulting loss in mass of the specimen was evaluated, to determine the abrasion loss of the concrete, using the weight of the specimen before and after each test. The abrasion thickness loss was evaluated after 16 cycles using the formula indicated in equation 3.5. Böhme test EN13892-3 [87] procedure was used to perform the abrasion test of the specimens.

$$t = \frac{M1 - M2}{M1} * \frac{V}{A} \quad (3.5)$$

Where,

t : Thickness loss due to abrasion in mm

M1: Mass of the specimen before each test in g

M2: Mass of the specimen after each test g

A : Surface area (50cm²) of the specimen in mm²

V : Volume of the specimen in mm³



Figure 3. 12 Abrasion testing machine

3.6.5 Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity is generally carried out to check the quality of the concrete by determining an ultrasonic pulse velocity passing through a concrete specimen. According to Naville et al. [84], the UPV test can inspect the homogeneity of the concrete matrix and attributes that vary with time. In this work, ultrasonic pulse velocity test was conducted in compliance with Standard Test Method for Pulse Velocity through Concrete ASTM C 597-16 [88], to determine different sets of outcomes, using a range of concrete parameters such as recycled aggregate ratio, fiber content, and exposure to various degrees of temperature. Figure 3.13 displays the ultrasonic pulse velocity meter that was used in this experimental work.



Figure 3. 13 Ultrasonic pulse velocity meter

3.6.6 Sulphate Resistance Test

In this thesis, the sulfate resistance of the specimens was examined by determining the residual compressive performance, average variation in specimen's weight, and visual inspection. The test samples were soaked in the Magnesium Sulfate solution for two months after the nineteenth day of casting. Magnesium sulfate solution with a 10% concentration was utilized as the standard environment of exposure for all series of mixtures. The container in figure 3.14 shows the concrete samples immersed in the sulfate solution. To maintain the full immersion of the test samples

the volume proportion of the sulfate solution was significantly higher than the specimen volume.



Figure 3. 14 Specimens immersed in magnesium sulfate solution

3.6.7 High-Temperature Resistance Test

In the study, after a 90-day curing period, the specimens were subjected to elevated temperatures of 200, 600, and 1000°C with an electrically heated furnace. To represent an intended heat level, the furnace heat was set to rise at the rate of 5°C per minute. To facilitate the natural cooling process for the exposed specimens the furnace was kept at the target temperature for 1h before it was turned off.

3.6.8 Freezing-Thawing Test

In this study, each series of mixes were checked for freeze-thaw cycles, they have been exposed to freeze-thaw cycles a total of 60. The test methodology for this test was done in compliance with ASTM C666 (1997) [89] standard. The freezing and thawing period was 24hrs per cycle with the temperature fluctuating between -18°C to 4°C. After 60-days of exposure, the specimens were removed from the testing machine shown in figure 3.15 and its compressive performance difference and

weight loss were computed about the specimens kept at room temperature. Figure 3.15 displays the machine used for the freeze-thaw test.



Figure 3. 15 Freezing-thawing testing machine

4.1 Introduction

In this Chapter, the outcomes of all the experiments carried out, as discussed in Chapter 3, are presented and the results are discussed according to the objectives mentioned in Chapter 1. The experimental test results such as compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity, abrasion resistance, freeze-thaw, sulfate, and high-temperature resistance were discussed. In this section each test result appeared either in the form of a figure or table is the mean value of the results recorded from a minimum of three samples.

4.2 Strength Properties

4.2.1 Compressive Strengths

The 28 and 90 days compressive strength was investigated as shown in Figure 4.1 and Figure 4.2. Series of mixtures with the addition of recycled coarse aggregates of up to 40% at the interval of 10% were produced and compared with the reference mixture manufactured without recycled coarse aggregate. Also, the amount of steel fiber added was taken as the point of discussion in line with recycled aggregate content.

According to the figures shown the compressive strength results showed a slight improvement when the steel fiber percentage was raised from 0.3% to 0.6%. This might be related to the higher density of the steel fibers which positively contributes to the strength development of the geo-polymer concrete matrix. The enhancement originated essentially from the number of fibers encountering crack development. When the developing cracks reached the interface, the stress transfer will occur at the fiber matrix, which allows the fibrous composite specimens to resist additional compressive force, thus enhances the compressive performance of the mixtures with 0.6% over the 0.3% steel fiber.

The strength decrement rate with the incorporation of RCA is higher in the case of 0.6% steel fiber addition compared to its corresponding mix design produced using a 0.3% fiber ratio. The compressive strength data given in Figure 4.1 shows that generally the compressive performance of the samples was slightly decreased with the increase of recycled aggregate ratio, however, the incorporation of 40% recycled coarse aggregate recorded the highest reduction rate of 22.61% and 21.05% in case of 0.6% and 0.3% steel fiber addition, respectively. The inclusion of 10%, 20%, and 30% RCA resulted in a 4.75%, 8.61%, and 13.63% reduction in the compressive performance of the concrete specimens' prepared using 0.6% SF content. According to figure 4.2, the compressive strength of all the mixtures increased with the increase of the age from 28 to 90 days. The specimens gained most of their strength at the age of 28 days. Thus, only a slight rise was observed at the age of 90 days. Behforouz et al. [79] studied the influence of RCA on geopolymer concrete and reported approximately the same reductions in the compressive strength, with the incorporation of RCA. Also, the negative effect of RCA on the compressive strength of concrete was reported by Nuaklong et al. [63]. In conclusion, the compressive strength of geopolymer concrete produced with partial replacement of natural aggregates with recycled coarse aggregates found to be lower than that of natural aggregate concrete this is maybe due to the existence of defects in recycled aggregates, more water added in recycled aggregates, and a weak interfacial zone maintained in between an old and a new cement matrix [90, 91, 92]. The defects can lead to crack formation and low bond strength and thus decrease compressive strength. Regardless of the decrease in compressive strength, the substitution of 30% recycled coarse aggregates is adequately high for hiring in the construction industry. As a result, a proportion containing 0.6% steel fiber and 30% recycled aggregate can be considered as an optimum mix design in terms of both technical and environmental feasibility.

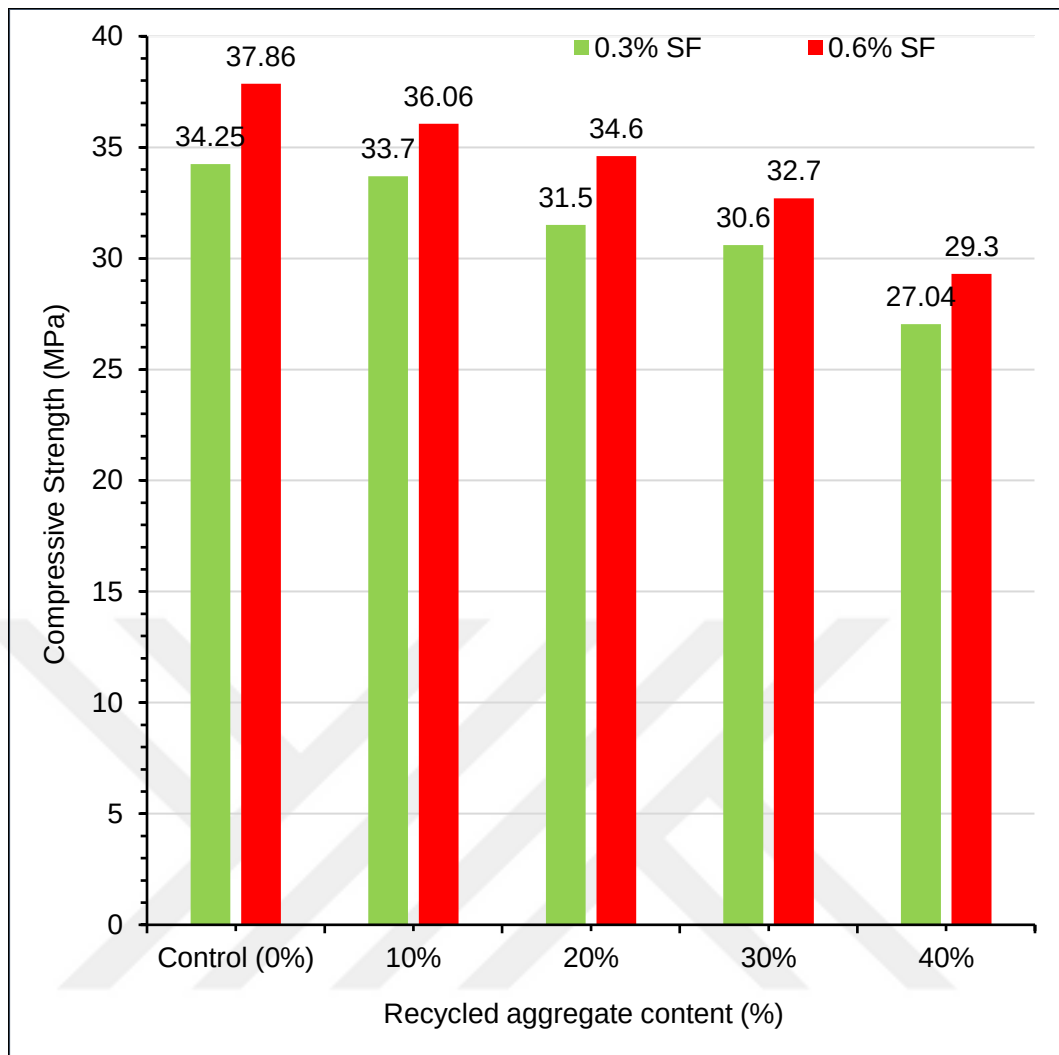


Figure 4. 1 The compressive strength at the age of 28-days

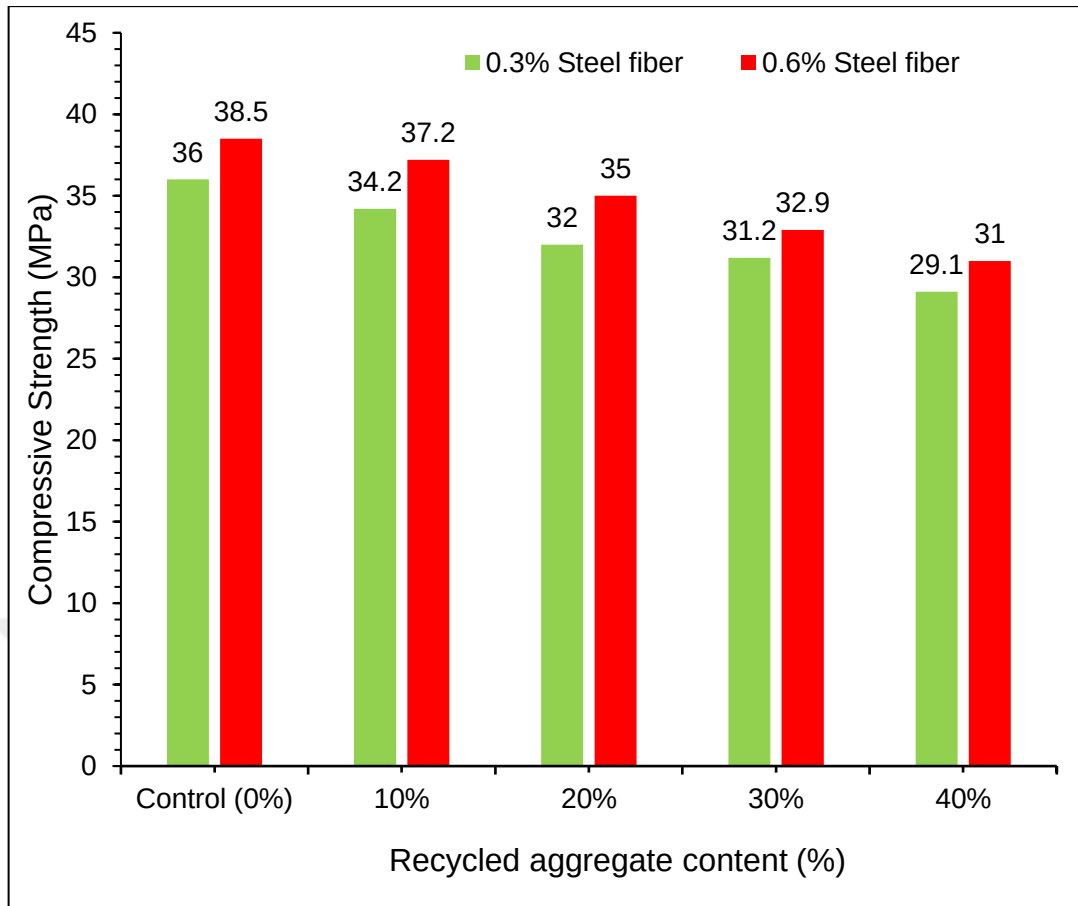


Figure 4. 2 Compressive strength at the age of 90-days

4.2.2 Splitting Tensile Strength

Tensile strength is among the vital properties of concrete as concrete structures are highly susceptible to cracking. The tensile strength results of all specimens as appeared in figure 4.3 and figure 4.4 indicated approximately similar patterns to those of compressive strength. The addition of 0.6% of SF resulted in a higher splitting tensile strength in comparison to 0.3% steel fiber incorporation. The reason for this is related to the fiber's ability, to increase ductility and interrupt crack formation in concrete members, which increases with the increase of fiber ratio up to its optimum content [93]. Also, when the splitting happened and proceeded, the steel fibers connecting the divided parts of the composites acted through the load transfer from the concrete matrix to the fibers and, finally, the fibers received the entire load from the concrete matrix and therefore the stress transfer enhanced the tensile strain potential of the 0.6% steel fiber more than its

counter 0.3% fiber due to the higher number of fibers bridging the split portion in 0.6% fiber-reinforced composites. Thus, 0.6% of steel fiber addition improved the splitting tensile strength of the matrix over the concrete with a 0.3% fiber ratio. The statement agrees with the report by Potrebowski [93] and Aamer Bhutta et al. [94] stated that the volume of fibers joining the fracture section directly affects the splitting tensile strength of fiber-reinforced concrete composites. At the 28 days strength, the application of 0.6% steel fiber without partial replacement of the recycled aggregate resulted in the highest splitting tensile strength. Incorporating 40% of RCA, resulted in a maximum reduction rate of 14.90% that is recorded as the greatest decrement rate throughout the mixtures produced. The RCA inclusion of up to 30%, showed only a slight drop in the highest reduction recording 7.58% and 5.59% of the reference specimen, in the case of 0.6% and 0.3% steel fiber ratio, respectively. As can be observed from figure 4.4 the splitting tensile strength of the specimens increased with the increase of age. The minimum and maximum increases were 3.4% and 9.7%, respectively. According to this study, the splitting tensile strength of the specimens was estimated as 9 to 10% of their corresponding compressive strength that is approximately the same trend as that of conventional concrete. In general, the splitting tensile strength of the samples was decreased with the increase of recycled aggregate content, however, the higher reduction rate was recorded higher with the increase of fiber ratio.

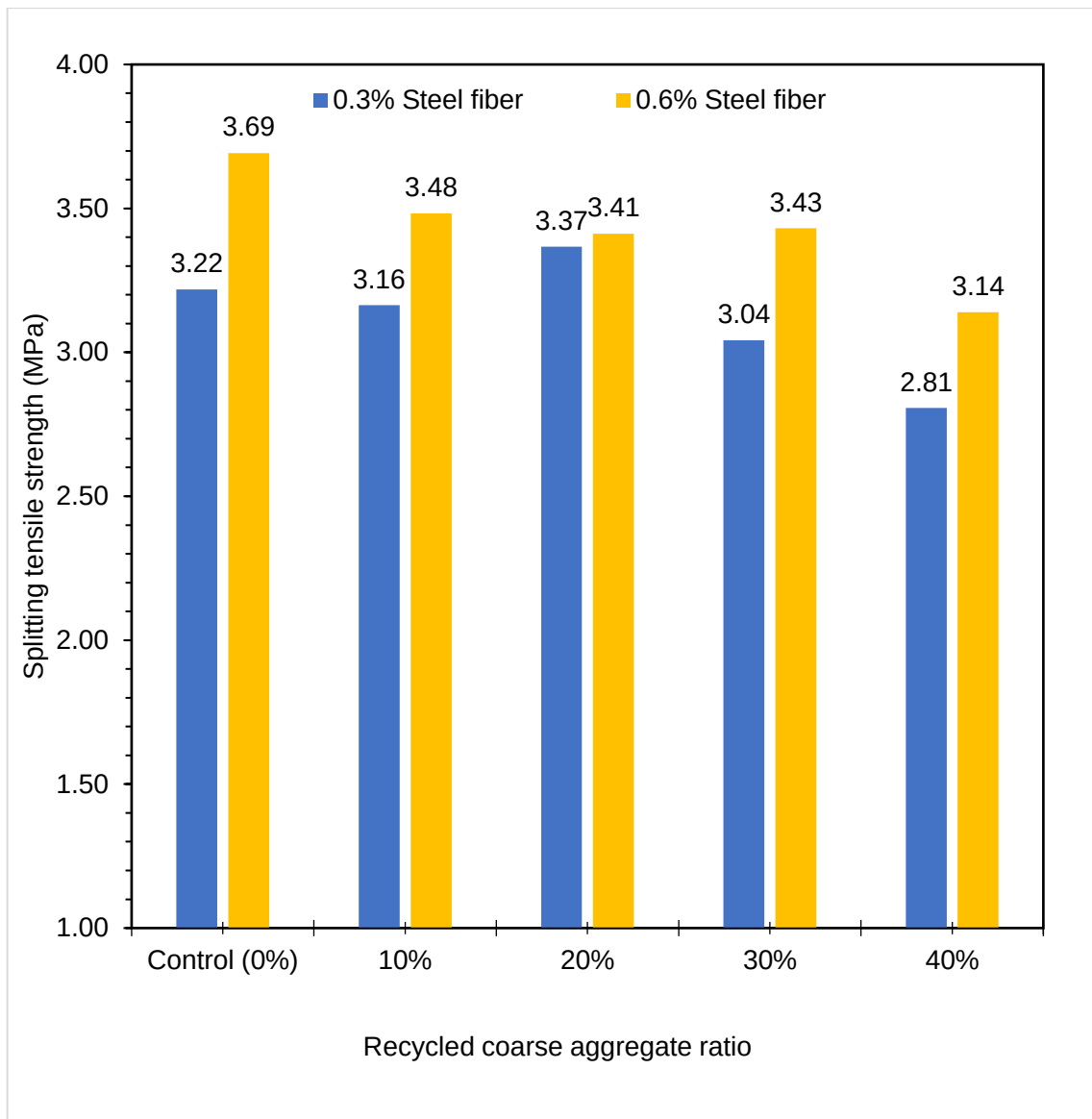


Figure 4.3 Splitting tensile strength at the age of 28-days

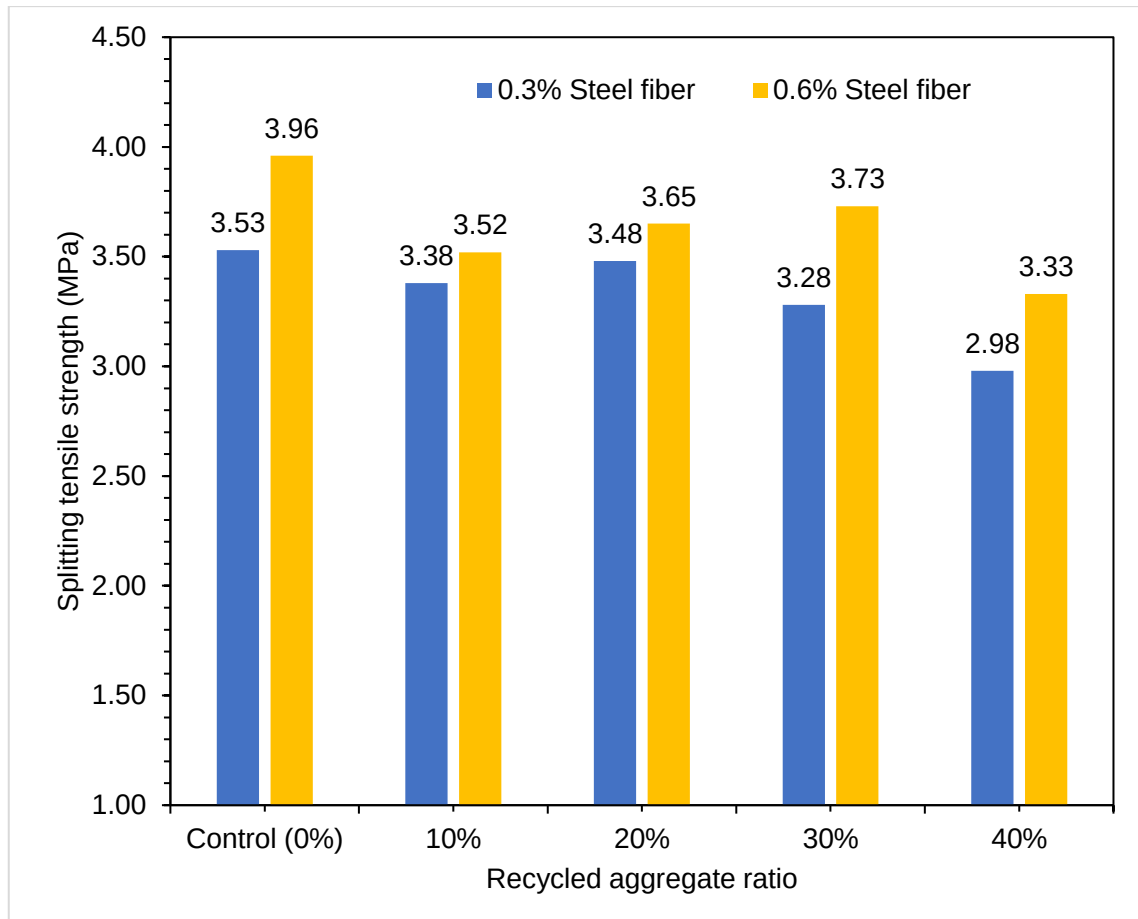


Figure 4.4 Splitting tensile strength at the age of 90-days

4.2.3 Flexural Strength

Figure 4.5, presents the flexural strength of geopolymer concrete mixtures prepared by incorporating a various proportion of recycled aggregate and steel fibers. According to fig 18, the mixtures produced without recycled coarse aggregate have possessed a higher value of flexural strength than that of the mixtures manufactured with recycled coarse aggregates, irrespective of the fiber content. This might be related to the low interfacial bond strength maintained between new mortar and old attached mortar. The finding agrees with a result obtained by Padmini et al. 2009 [95] and Nuaklong et al. [63] the flexural strength of the specimens kept on decreasing with the increase of the recycled coarse aggregate content in case of 0.3% and 0.6% fiber ratio. The decrement rate was decreased with the increase of the recycled aggregate content although the maximum fall in flexural strength occurred in concrete with an RCA proportion of 40%.

The increasing steel fiber content in the GPC matrix provided considerable enhancement in flexural strength. The flexural strength of concrete mixtures produced without recycled aggregate and 0.6% steel fiber combined has been increased by 30% in comparison to the specimens prepared with no recycled aggregate and 0.3% fiber ratio. Additionally, the flexural strength of the mixtures with 10%, 20%, 30%, and 40% partial replacement of recycled aggregate has been increased by 32.57%, 29.04%, 3.13%, and 32.14%, respectively, when the fiber ratio increased from 0.3% to 0.6%. Therefore, the constructive contribution of steel fiber incorporation can overcome the drop in the flexural strength caused by the inclusion of RCA. This is in line with the investigation performed by Prabu et al. [96] and Behforouz et al. [79]

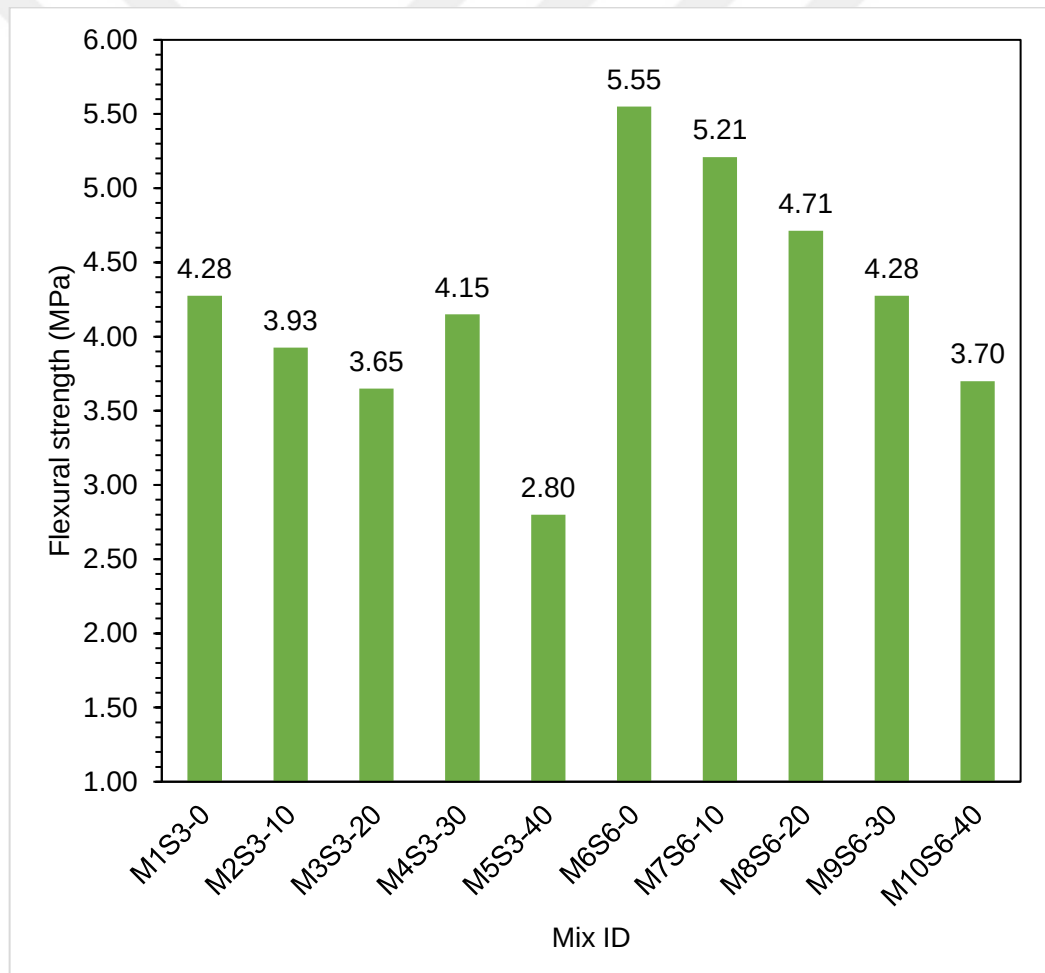


Figure 4. 5 Flexural Strength at the age of 90-Days

4.2.4 Load – Deflection and Flexural Toughness

Load-deflection behavior and flexural toughness, which provide information about the energy absorption capacity of a given specimen, are among the crucial parameters to determine the flexural characteristics of the test specimens. As the force-induced increases, the beam began to bend in the direction of the applied load, and cracks were formed along the bottom surface which is also known as the tension face of the test beam. Also, all the beam samples have experienced a flexural failure type. The load-deflection curve appears in figure 4.6. As can be seen from the figure increasing the fiber volume efficiently enhanced the ultimate force of the specimens due to the fiber's ability to curb crack formation within the concrete matrix [97]. The ultimate load of 0.6% steel fiber reinforced specimens have become higher than that of the specimens produced with the incorporation of 0.3% steel fiber ratio and therefore the ultimate load of the specimens is raised with the rise of fiber amount irrespective of the recycled aggregate content. Also, the deflection corresponding to the first crack force is increased with the increase of fiber amount. Furthermore, the incorporation of fibers is usually taken as the principal factor that is accountable for enhancing the flexural behavior of the specimens. Therefore, it is important to evaluate the effect of fiber content on the toughness properties. The standard specification JSCE-SF4 [98] was used to determine the toughness of the concrete mixtures. The flexural toughness factor of each mix design was also evaluated to learn the role of fibers in terms of improving the energy absorption capacity of the steel fiber reinforced geopolymer concrete samples. The flexural toughness factor of the specimens was evaluated according to Japanese standards as shown in section 3.5.3. The flexural toughness of the specimens is increased with the increase of fiber content which was demonstrated using toughness parameters in Table 4.1. On the other hand, no consistent relation was maintained between the toughness values and the amount of recycled coarse aggregate used. However, for the 0.6% of steel fiber ratio, the addition of recycled aggregate resulted in similar and sometimes better toughness values than 100% natural aggregate. Whereas, for the 0.3% of steel fiber, up to 20% increase of recycled aggregate caused improvement in the toughness values and toughness index.

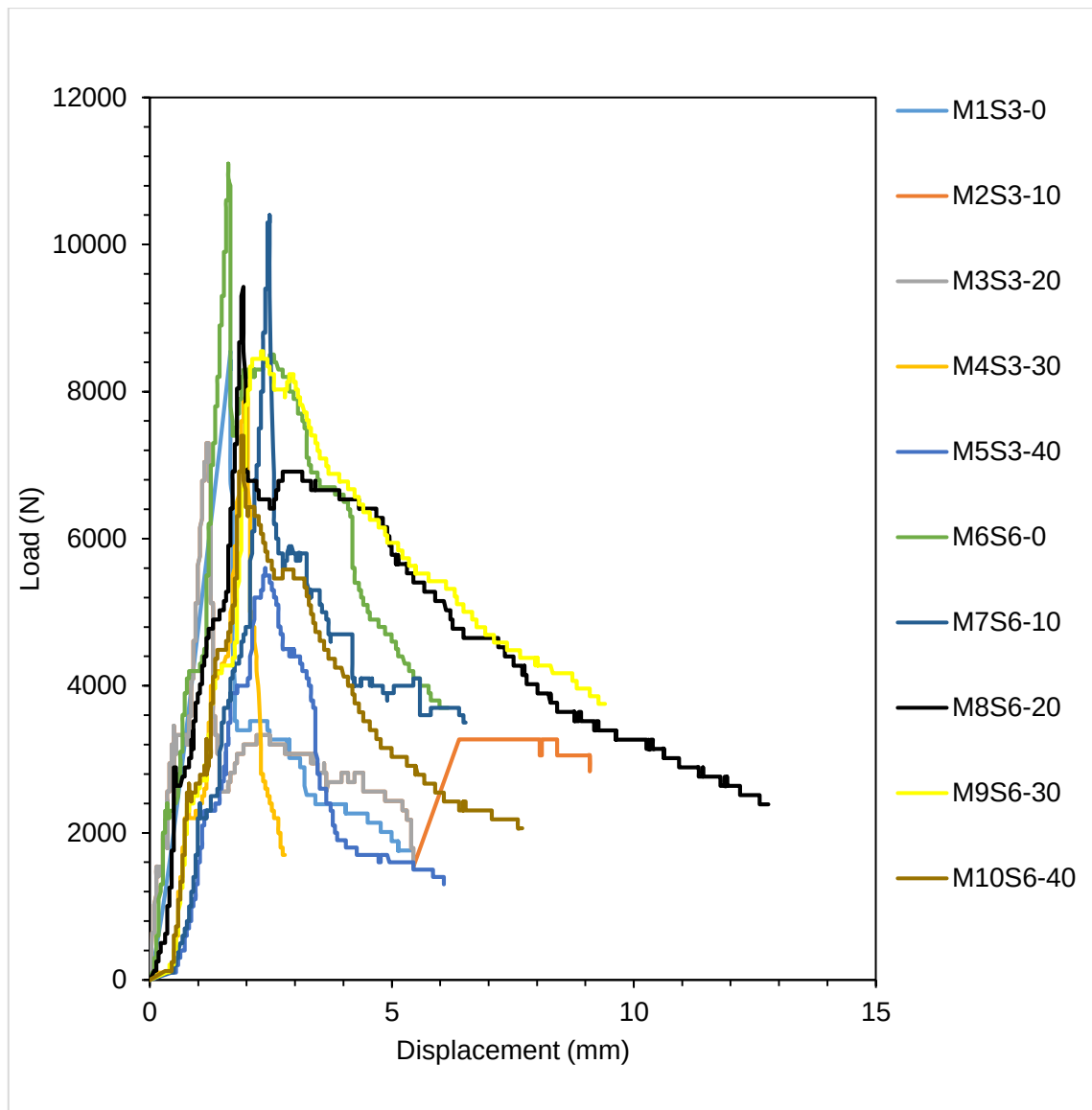


Figure 4. 6 Load - deflection curve of different mixtures

Table 4. 1 Flexural toughness and flexural toughness factor of the concrete mixtures

Mix ID	Flexural Toughness (Nmm)	Flexural toughness factor
M1S3-0	16655	2.54
M2S3-10	27449	6.55
M3S3-20	16503	3.94
M4S3-30	8177	1.51
M5S3-40	14666	2.82
M6S6-0	35228	5.16
M7S6-10	25580	3.54
M8S6-20	56937	8.00
M9S6-30	48014	5.95
M10S6-40	26463	5.15

4.2.5 Abrasion Resistance

Abrasion is defined as the wearing out of coarse particles by friction due to exposure to various external loads. In concrete structures wearing out of aggregate particles happens because of rubbing, skidding, or sliding of heavy objects on its surface [99]. It can be seen in pavements, stairs, floors, and hydraulic structures due to erosion and scour. Therefore, concrete members should be strong enough to resist the upcoming abrasive force. In this experimental work, a combined effect of steel fibers and partial replacement of NCA by the different proportions of recycled aggregate will be discussed provided that all the other ingredients are kept constant. An

individual effect of fibers and recycled coarse aggregate on the abrasion resistance of concrete has been addressed in various studies and observed that fibers and RCA either reduced or improved the abrasion resistance of concrete. For instance, Ganesan et al. [100] revealed that the specimens with higher steel fiber content experienced the lowest thickness loss and therefore possess a better abrasion resistance. This might be related to the enhanced density of steel fiber reinforced geopolymer concrete specimens because the fibers surrounded by the concrete would play a role of bridging micro-cracks and sometimes filling the small openings, which in turn reduces interconnecting pores to a minimum and leads to a lower weight loss and a higher abrasion resistance. According to the results given in Table 4.2, the average wear of all the samples appeared to be less than 1mm. Compared to 0.3% steel fiber inclusion, geopolymer concrete with a 0.6% steel fiber ratio recorded lower abrasion loss. This indicates that the abrasion resistance of the matrix improved with the increase of fiber ratio. This is due to the higher density of steel fiber reinforced geopolymer concrete specimens which were enhanced due to the better unit weight of steel fibers. And also, the fibers are short and randomly distributed throughout the mix that allows them to arrest micro-cracks and minimize pores in a resulting concrete matrix. Thus, the conclusion agrees with the summaries explained above.

On the other hand, both weight loss and abrasion depth of the GPC specimens have been increased with the increase of recycled aggregate content. Nevertheless, the rate of reduction for 0.3% steel fiber addition resulted slightly lower than its corresponding 0.6% steel fiber ratio mix designs. The maximum increment in wear to the control specimen (Specimen without recycled aggregate) was recorded as 18.03% and 21.8% in the case of 0.3% and 0.6% steel fiber addition, respectively, at 40% recycled coarse aggregate replacement. In general, the utilization of RCA in fly ash/slag-based geopolymer concrete resulted in a higher abrasion loss than a virgin aggregate concrete matrix. This statement is consistent with the investigation performed by Nuaklong et al. [63] However, up to 30% partial replacement of recycled aggregate doesn't cause a significant reduction to control samples. These findings demonstrate that the incorporation of up to 30% RCA, would be acceptable.

Table 4. 2 Abrasion resistance test results

Mix ID	Initial Weight (g)	Final Weight (g)	% weight loss	Average wear in (mm)	% Increment in wear with respect to control specimen
M1S3-0	822	818	0.49	0.61	control
M2S3-10	812	807.5	0.55	0.645	5.74
M3S3-20	808.5	803.5	0.62	0.67	9.84
M4S3-30	806.5	801	0.68	0.69	13.11
M5S3-40	802.5	796	0.81	0.72	18.03
M6S6-0	825.5	822	0.42	0.47	control
M7S6-10	816.5	812.5	0.49	0.5	6.38
M8S6-20	812.5	807.5	0.62	0.52	10.64
M9S6-30	797.5	792	0.69	0.54	14.89
M10S6-40	808	802	0.74	0.57	21.28

4.2.6 Ultrasonic Pulse Velocity Test (UPV)

UPV test is a non-destructive test used to assess the homogeneity of the matrix and the dynamics in the structure of the mortar or concrete products. The concrete properties such as density, modulus of elasticity, and Poisson's ratio have a significant effect in determining the magnitude of the velocity of the ultrasonic pulse. According to Mouhcine et al. [101] ultrasonic pulse velocity test is illustrated as an appropriate method to determine the qualitative properties of concrete such as the existence of defects, uniformity, and homogeneity of the matrix. It is therefore possible to determine the effect of temperature, freeze-thaw action, and sulfate attack on the resulting geopolymer concrete matrix using sonic evaluations.

In this study, ultrasonic pulse velocity tests were carried out on the fly/slag-based geopolymer specimens to assess the influence of introducing different materials and

various conditions (like high temperature, freeze-thaw action, and sulfate attack) on the sonic speed of the geopolymer samples. The velocity measurement was performed by using sensors of 5cm diameter and 54 kHz frequency by direct transmission mode.

From figure 4.7, it is possible to note that incorporating recycled aggregates induces a reduction in UPV. Also, it can be inferred that increasing fiber content doesn't provide a significant enhancement in UPV. In the case of 0%, 10%, and 20% recycled aggregate ratio, there is only a slight improvement in the sonic velocity of the specimens with the increase of fiber content. Whereas, the specimens produced with the addition of 30% and 40% recycled aggregate experienced a slight reduction in the UPV when the steel fiber ratio increases from 0.3% to 0.6%.

UPV decreased with the increase of recycled aggregate amount. For 10%, 20%, 30% and 40% of recycled aggregate, the ultrasonic pulse velocity shows reduction of 2.1%, 4.2%, 5.2% and 6.2%, respectively, compared with non-recycled aggregate proportion (0% recycled aggregate) in the case of 0.3% fiber addition. Additionally, for 0.6% steel fiber, the magnitude of the ultrasonic pulse velocity dropped by 3.2%, 6.5%, 8.5% and 10.4% compared with reference specimen to 10%, 20%, 30% and 40% recycled aggregate incorporation, respectively. As mentioned above, ultrasonic velocity can be affected by the density and the level of uniformity of the resulting matrix. The sound velocity usually doesn't travel faster through liquid and gas. The concretes produced in this investigation include a different proportion of RCA; and therefore the inclusion of recycled aggregate in some level endowed to the development of voids filled with air. As a result, the introduction of certain amounts of recycled aggregate reduced the sonic velocity of the mix due to its low density and existence of some defects on the surface of RCA which might lead to the formation of micro-cracks in the concrete matrix.

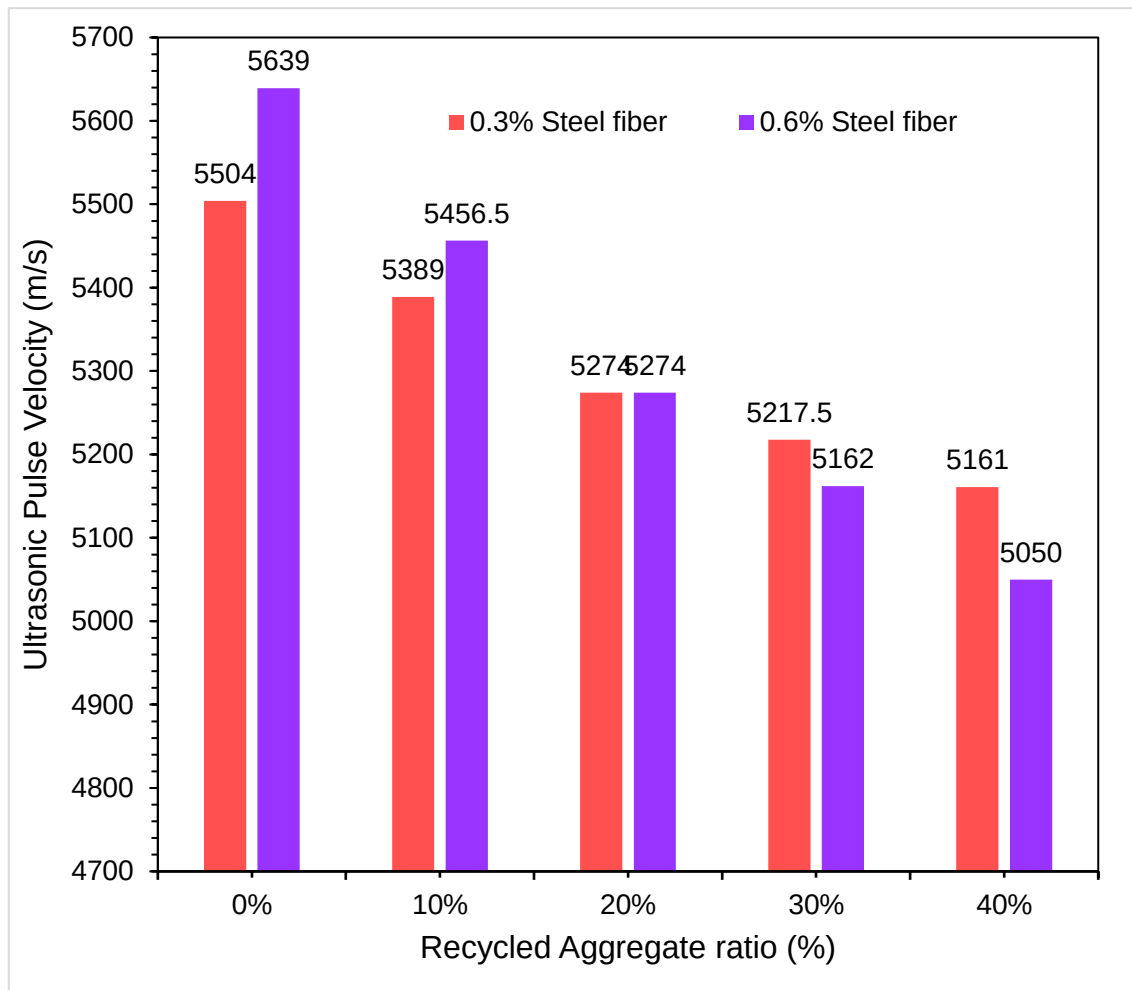


Figure 4. 7 90 days ultrasonic pulse velocity test result

4.2.7 High-Temperature Test

Series of experiments were performed to investigate the temperature resistance of steel fiber reinforced fly ash/slag-based geopolymer concrete produced with the partial replacement of recycled aggregate. The test samples were subjected to 200 °C, 600 °C, and 1000°C, after 90 days curing period, at the rate of 5 °C/min in a vacuum atmosphere. The influence of the temperature was assessed based on observation, change in weight, and change in compressive strength. However, the specimens subjected to a temperature of 1000°C were assessed based on their weight change only. Furthermore, the UPV test was performed before and after the specimens were exposed to the target temperature.

4.2.7.1 Observation

Figures 4.8 and 4.9, illustrate the physical appearance of the subjected and unexposed geopolymer concrete specimens to the high temperatures of 200 °C, 600°C, and 1000°C, consecutively. It can be observed that the specimens undergo a color change, corner breakages, and cracks which appear worse with the rise of temperature. The concrete specimens exposed to 1000 °C experienced the highest thermal crack distribution and crack width. And also, the decomposition of the concrete matrix was observed which in turn resulted in breakage and spalling. The coarse aggregates after the target temperature of 1000 °C altered to white and light yellow. This might be due to the decomposition of limestone coarse aggregates after an elevated temperature of 1000°C [102]. After the cooling period of 3 days, it can be seen that the coarse aggregates have highly deteriorated. The decomposition of coarse aggregates and vast distribution of cracks leads to failure of the concrete structure without any induced load; as a result, it was not possible to conduct ultrasonic pulse velocity and compressive strength tests (figure 4.9).

The visual appearance change was seen in all specimens irrespective of the proportion of the ingredients. The color of specimens subjected to 200°C, 600°C, and 1000 °C changed to dark gray, light red, and light yellow respectively. This is characterized by the oxidation changes derived from ferric oxide content in fly ash/slag-based geopolymer [103].

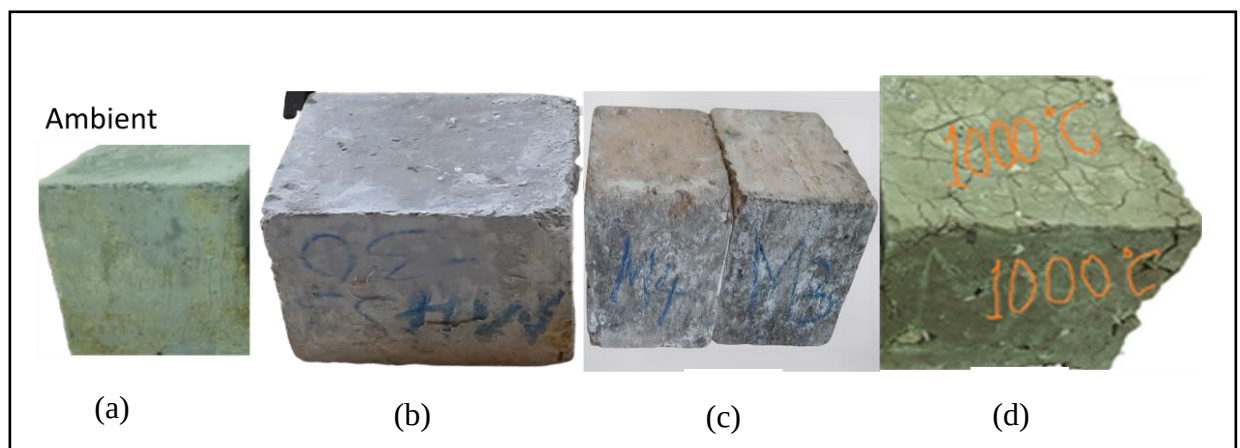


Figure 4. 8 Surface changes of the specimens after exposure to temperature. (a) Ambient temperature (b) After 200°C (b) After 600°C (d) After 1000°C

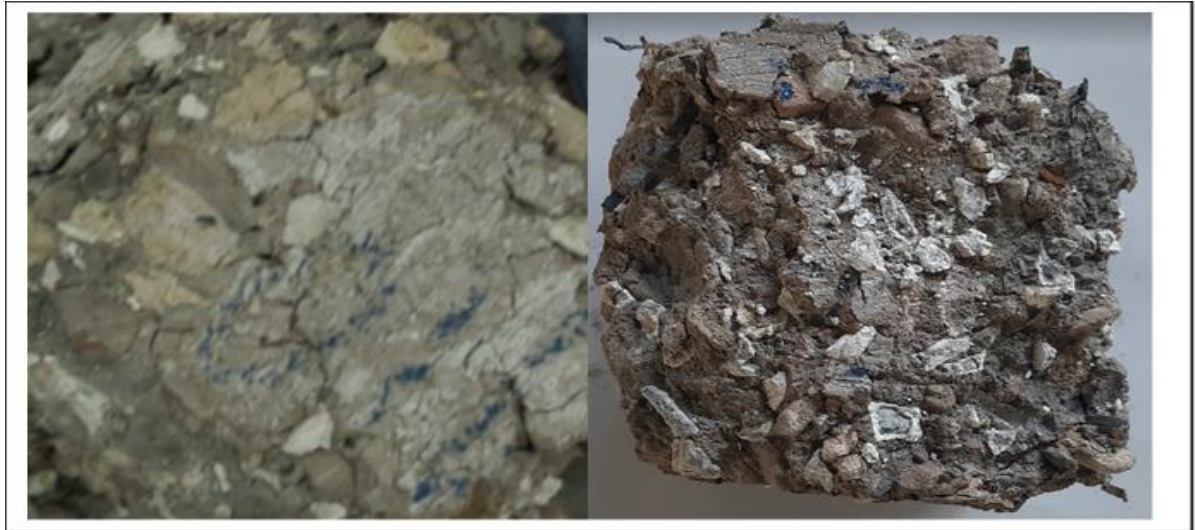


Figure 4. 9 Specimens exposed to 1000°C after waiting at the curing room for three days

4.2.7.2 Mass Loss

Table 4.3 and figure 4.10 demonstrated that at any specified temperature, the weight loss in reference specimens was lower than that of the specimens produced with the incorporation of the recycled aggregate. Moreover, the reduction rate was increased with the increase of the recycled aggregate ratio that was attributed to a higher amount of water released from the recycled aggregate because as shown in Table 3.2 recycled aggregate possesses a higher water absorption capacity than natural aggregate. The same result was reported in the study by Lanyerie et al. [104]. The maximum weight loss at 200°C, 600°C, and 1000 °C was recorded as 2%, 10%, and 14% of the specimens at normal temperature, respectively. As mentioned in the previous section both recycled and natural aggregates were moisturized to maintain the surface saturated state of the aggregates which was done based on the water absorption capacity of the aggregate type. As a result, the mixes with recycled aggregates contain higher water content in comparison to virgin aggregate concrete mixes. It can also be seen that the rate of weight loss from 200 °C to 600 °C has dramatically increased for nearly all concrete mixtures. In the study by Duxson et al. [105], it was illustrated that a couple of effects known as dihydroxylation and water evaporation are identified as the main contributors to the weight loss of geopolymer matrix at elevated temperature. The type of water in a dried geopolymer matrix can exist as a physical, chemical, and hydroxyl type. And also, each type of moisture

evaporates at a distinct temperature range. For instance, the hydroxyl group departs at temperatures exceeding 300°C, whereas the chemical and physical ones depart at 100~300°C and 20~100°C, respectively. Therefore, the abrupt mass loss from 200 °C to 600 °C might be due to the complete occurrence of both dihydroxylation and water evaporation. At 600°C and 1000°C both the magnitude of mass loss and the rate of mass loss shown a slight increment with the increase of the fiber content. At a temperature higher than 750°C geopolymer concrete matrix experiences decomposition of carbonate species which leads to the weakening of interfacial bond strength of the resulting matrix [106]. Therefore, the decomposition of carbonate families can be the cause of the highest weight loss at 1000 °C.

Table 4. 3 Weight changes after exposure to different temperature

Mix ID	Initial weight (g)	Weight After (g)			Weight Loss (%)		
		200 °C	600 °C	1000 °C	200 °C	600 °C	1000 °C
M1S3 – 0	2391	2360	2280	2250	1.30	4.64	5.90
M2S3 – 10	2384	2349	2266.5	2203	1.47	4.93	7.59
M3S3 – 20	2381	2345.5	2240	2181	1.49	5.92	8.40
M4S3 – 30	2286.5	2250	2147	2105	1.60	6.10	7.94
M5S3 – 40	2266.5	2230	2131	2092	1.61	5.98	7.70
M6S6 – 0	2397	2368	2291.5	2167	1.21	4.40	9.60
M7S6 – 10	2387	2347	2193.5	2067	1.68	8.11	13.41
M8S6 – 20	2382	2337	2163	2056	1.89	9.19	13.69
M9S6 – 30	2334	2290	2119.5	2045	1.89	9.19	12.38
M10S6 – 40	2324	2283	2100	2016.5	1.76	9.64	13.23

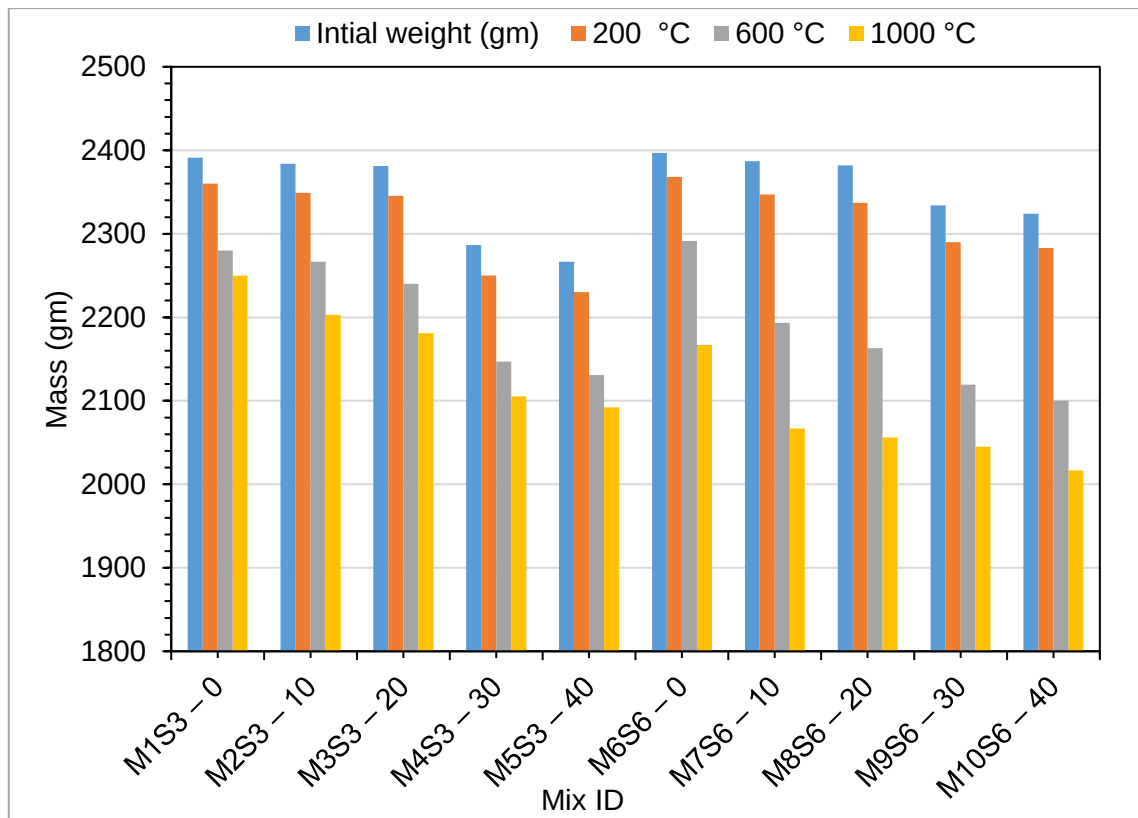


Figure 4. 10 Weight of the specimens after exposure to elevated temperature

4.2.7.3 Ultrasonic Pulse Velocity

Table 4.4 shows the ultrasonic pulse velocities of mixtures with and without recycled aggregate subjected to an elevated temperature of 200 °C and 600 °C. From Table 4.4 and Figure 4.11, it can be observed that the specimens manufactured without recycled aggregate resulted in a higher magnitude of the ultrasonic pulse velocity both in the case of 0.3% and 0.6% steel fiber content.

Moreover, at any target temperature, the ultrasonic pulse velocity values of all mixtures dropped with the rise of recycled aggregate content. However, a change in the content of the fiber doesn't cause a significant effect on the magnitude of ultrasonic pulse velocity. At 200 °C, a drop in ultrasonic pulse velocity was 8.5%. This might be related to less or no development of defects such as cracks and pores during this level of heat exposure. Nevertheless, when the intensity of heat grows to 600 °C the pulse velocity has significantly dropped with a minimum and maximum reduction rate of 29.5% to 53%, respectively. This may be attributed to the higher

crack width, significant weight loss which results in a reduced density of the specimens. Furthermore, the defects in the geopolymer concrete specimens were raised seriously as the sample was subjected to a high temperature of 1000 °C. Especially, after the standing time of 3 days in the curing room, the specimens exposed to 1000 °C become inappropriate to conduct the ultrasonic pulse velocity and compressive strength as shown in fig 4.8.

Table 4.4 Ultrasonic pulse velocity

Mix ID	Ultrasonic Pulse Velocity (m/s)			Drop-in ultrasonic Pulse Velocity (%)	
	At Normal Condition	200 °C	600 °C	200 °C	600 °C
M1S3 – 0	5504	5183.502	3883	5.82	29.45
M2S3 – 10	5389	5040.008	3650	6.47	32.269
M3S3 – 20	5274	4831.39	2950	8.39	44.06
M4S3 – 30	5217.5	4844.668	2789	7.14	46.54
M5S3 – 40	5161	4690.504	2570	9.11	50.20
M6S6 – 0	5639	5313.128	3350	5.77	40.59
M7S6 – 10	5456.5	5091.883	3053	6.68	44.04
M8S6 – 20	5274	4859.188	2597	7.86	50.75
M9S6 – 30	5162	4733	2391	8.31	53.68
M10S6 – 40	5050	4678	2511	7.36	50.27

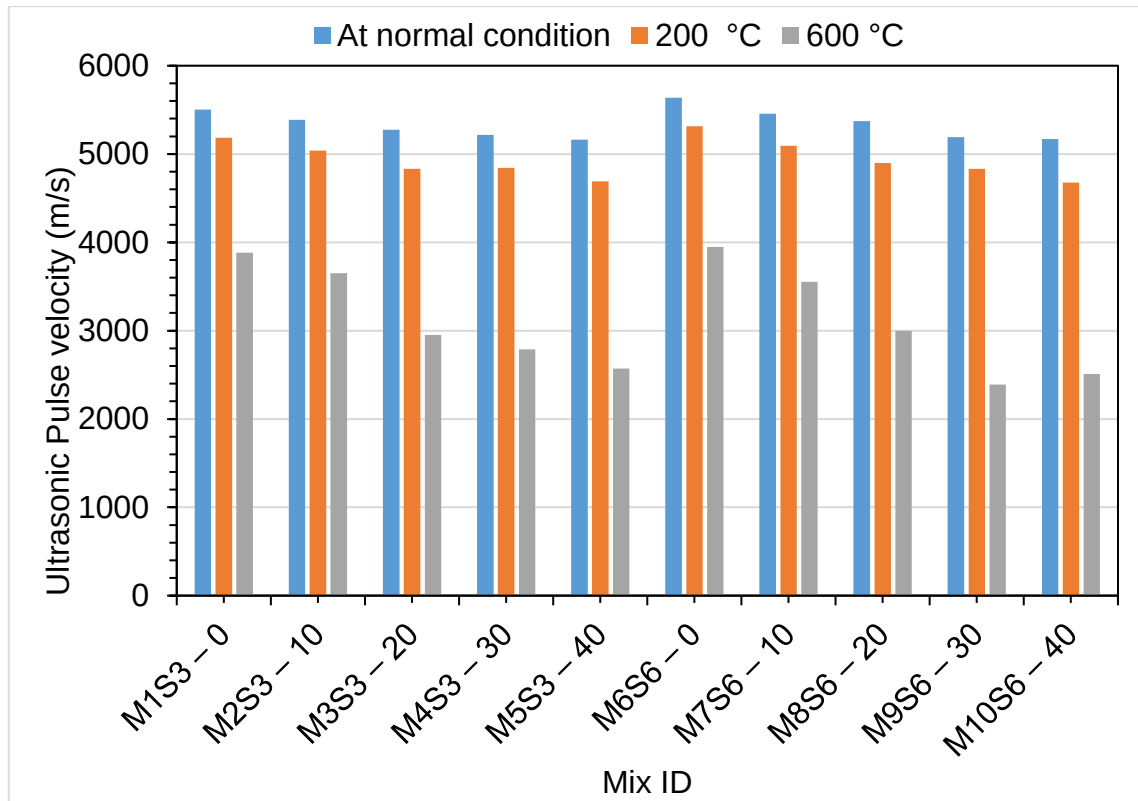


Figure 4.11 Measured UPV of specimens after exposure to elevated temperature

4.2.7.4 Compressive Strength

The effect of high temperature on the residual compressive strength of the concrete samples manufactured with different proportions of RCA is given in Fig 4.12. In figure 4.12, the residual compressive strength of the specimens is the ratio of strength at elevated temperature to that of ambient temperature. Results indicated that for all concrete specimens subjected to a temperature of 200°C the residual compressive strength improved in the range of 5-16%, as compared to their initial compressive strength at room temperature. The geopolymerization of base materials activated during heating contributes to the strength behavior and therefore continuation of geopolymerization has resulted in a strength gain at this temperature. The performance improvement character of the geopolymeric products after the elevated temperature exposure was also reported in the previous studies by Abdulkareem et al. [107] and Hammad et al. Also, the steel fiber added

might be partly responsible for the possible enhancement of the resulting strength [108].

Figure 4.12 illustrates that the residual compressive performance of the concrete mixtures reduced as the temperature rises from 200°C to 600°C. For instance, the NCA concrete mixtures fabricated with a steel ratio of 0.3% and 0.6% have experienced a compressive strength loss of 7.5% and 10%, respectively, after subjected to a temperature of 600°C; whereas the concrete specimens with RCA had a compressive strength loss of 13-21% compared to their initial strength at normal temperature. Moreover, the mixtures containing a higher ratio of steel fiber have experienced lower strength change after exposure temperature of both 200°C and 600°C.

The residual compressive strength of the control samples recorded a higher magnitude than that of the mixtures produced with recycled aggregates, after exposure to elevated temperatures of 200°C and 600°C. When the geopolymer concrete was subjected to an elevated temperature of 1000°C decomposition of limestone coarse aggregate and that of limestone crushed sand led to structural failure due to the deterioration caused by the expansion of burnt limestone products [105]. Additionally, the thermal incompatibility among aggregates and cement paste which can cause interconnected cracks at the interfacial zone of the geopolymer concrete matrix can be a possible reason for the concrete matrix disintegration at this temperature [109,110].

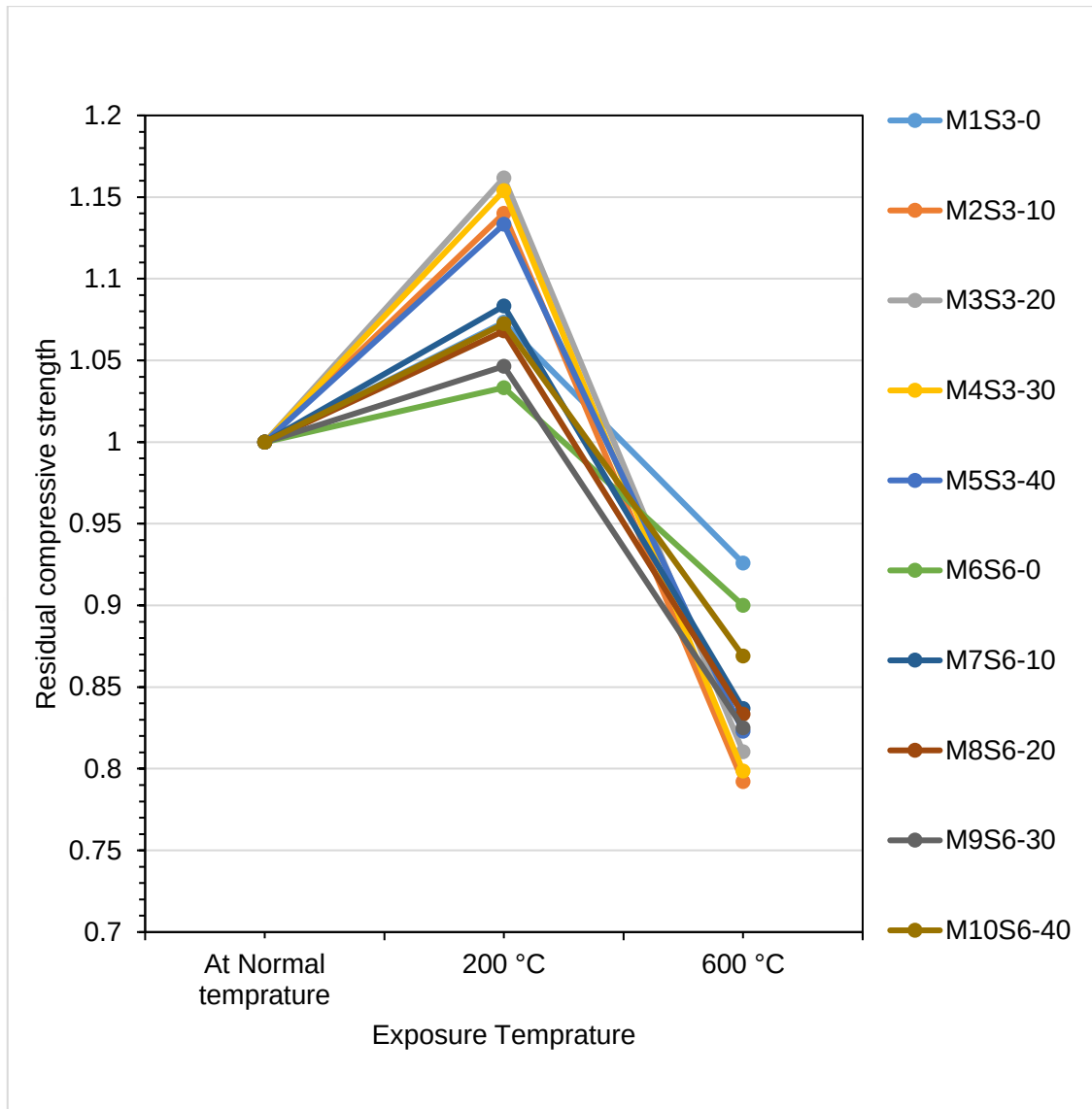


Figure 4. 12 Residual compressive strength

4.2.8 Sulphate Resistance Test

Chemical attack is among the serious problems for concrete that can deteriorate the physical, chemical, and mechanical properties of the concrete matrix [111,112]. In this experimental work, the resistance to chemical attack of concrete samples was evaluated by performing a magnesium sulfate test. The influence of sulfate on the physical appearance, strength characteristics, mass change, and ultrasonic pulse velocity was assessed. The physical appearance of the concrete samples after immersed in 10% of the sulfuric acid solution for 60 days showed that no significant

change was observed in the appearance of the subjected samples. No specimen has shown the effect of surface deterioration or spalling. However, the specimens produced from 100% natural aggregate experienced some signs of surface cracking and small voids. The outcomes of the magnesium sulfate resistance test have appeared in Table 4.5, 4.6, and Table 4.7. Also, the bar graphs in Figures 4.13, 4.14, and 4.15 are constructed for further clarification. Maximum mass gain experienced by 0.3% of steel fiber incorporation was 4.03% whereas for 0.6% it was 4.7%. When the geopolymer concrete samples are exposed to sulfate solution the calcium and aluminum phase in geopolymeric products could react with the SO_4^{2-} in the solution to give CaSO_4 and ettringite which improves the density of the concrete matrix and therefore this results in a weight gain [113]. For both 0.3% and 0.6% of steel fiber addition, a percent of mass gain was increased with the increase of recycled aggregate ratio. Rise in mass with the increase of recycled coarse aggregate content might be related to the recycled aggregates possessing a higher volume of pores to safeguard newly occurred minerals from acid attack [113]. However, further stay (more than 2 months) in the sulfuric environment might have decreased the weight of the specimens produced with recycled aggregate due to the weaker microstructure of the recycled aggregate. The compressive strength of the concrete mixtures has shown both rise and fall after exposed to sulfate attack. Incorporation of the recycled coarse aggregate ratio of 20%, 30%, and 40% have resulted in a gain in compressive strength whereas 0% and 10% have experienced a minimal loss in their compressive performance. The possible cause for the rise in the compressive strength of the samples could be the occurrence of the denser microstructure due to the formation of calcium sulfate and ettringite in the existence of the initial SO_4^{2-} attack which might help to the filling of the micro-pores. After exposed to sulfate attack, the ultrasonic pulse velocity of the specimens was increased with the increase of recycled coarse aggregate and fiber ratio. The rise in the magnitude of ultrasonic pulse velocity went hand in hand with weight gain because of the aforementioned reason. The maximum ultrasonic pulse velocity increase for 0.3% and 0.6% of steel fiber volume was 5.81% and 6.38%, respectively. Veerendra Babu et al. [114] also reported the rise in the compressive strength of the geopolymer concrete specimens exposed to magnesium sulfate.

Table 4. 5 Results of sulfate resistance test in terms of weight

Mix ID	Mass of specimens before exposed to sulfate attack (g)	Mass of specimens after exposed to sulfate attack (g)	% gain in weight
M1S3 – 0	2307.20	2376.40	3.00
M2S3 – 10	2235.80	2315.00	3.54
M3S3 – 20	2281.10	2356.00	3.28
M4S3 – 30	2242.00	2325.00	3.70
M5S3 – 40	2245.40	2336.00	4.03
M6S6 – 0	2323.90	2395.00	3.06
M7S6 – 10	2256.50	2335.00	3.48
M8S6 – 20	2238.10	2333.00	4.24
M9S6 – 30	2221.80	2326.00	4.69
M10S6 – 40	2256.90	2363.00	4.70

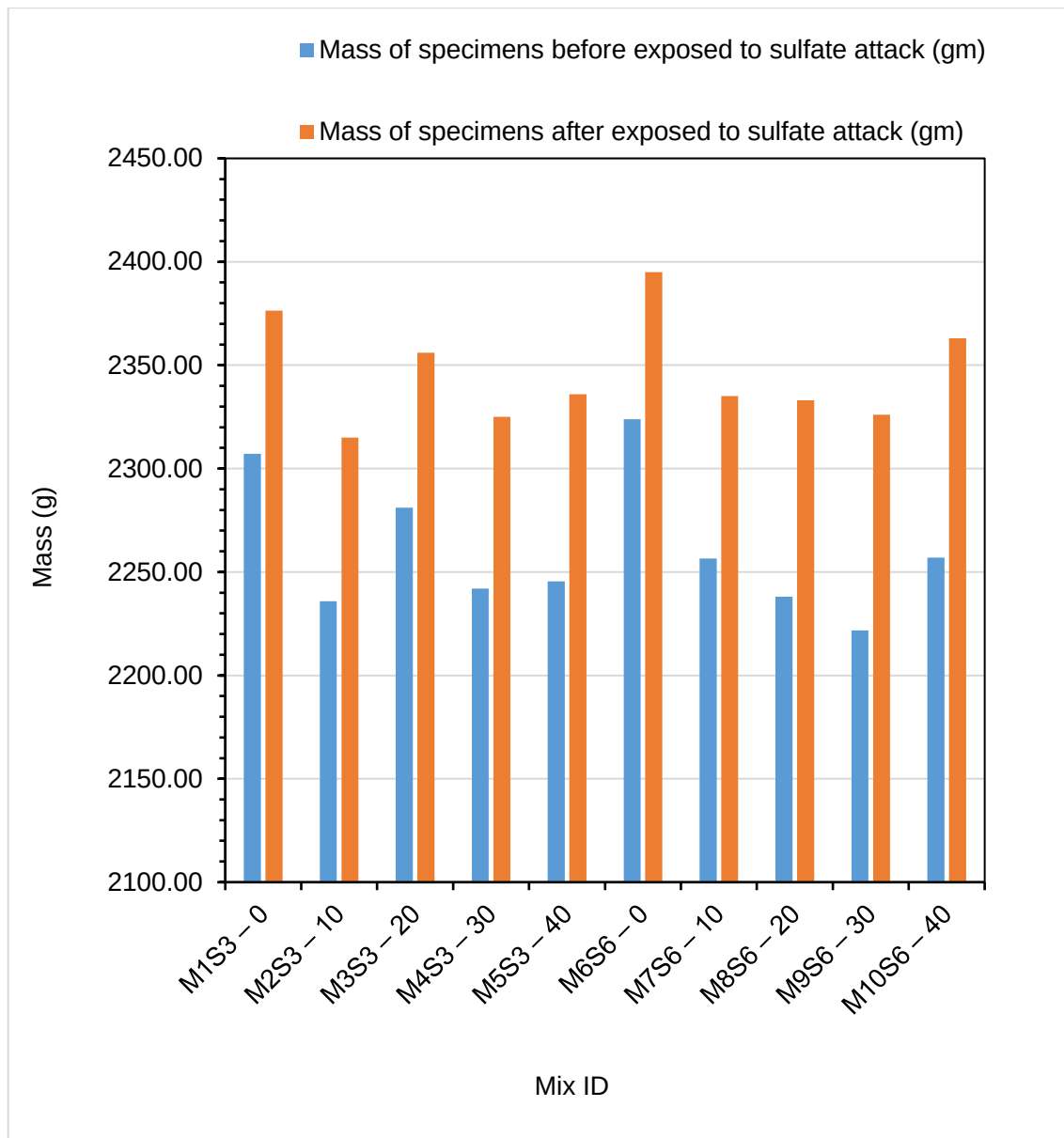


Figure 4.13 Weight of specimens after and before exposure to sulfate attack

Table 4. 6 Results of sulfate resistance test in terms of compressive strength

Mix ID	Initial Compressive Strength (MPa)	Final Compressive Strength (MPa)	% Loss in Compressive strength	% Gain in Compressive strength
M1S3 – 0	36.00	33.00	1.39	-
M2S3 – 10	34.20	34	-	0.88
M3S3 – 20	32.00	35.50	-	10.94
M4S3 – 30	31.20	32.50	-	4.17
M5S3 – 40	29.10	31.20	-	7.22
M6S6 – 0	38.50	37.80	1.82	-
M7S6 – 10	37.20	35.20	1.88	-
M8S6 – 20	35.00	38.00	-	8.57
M9S6 – 30	32.90	33.60	-	2.13
M10S6 – 40	31.00	32.50	-	4.84

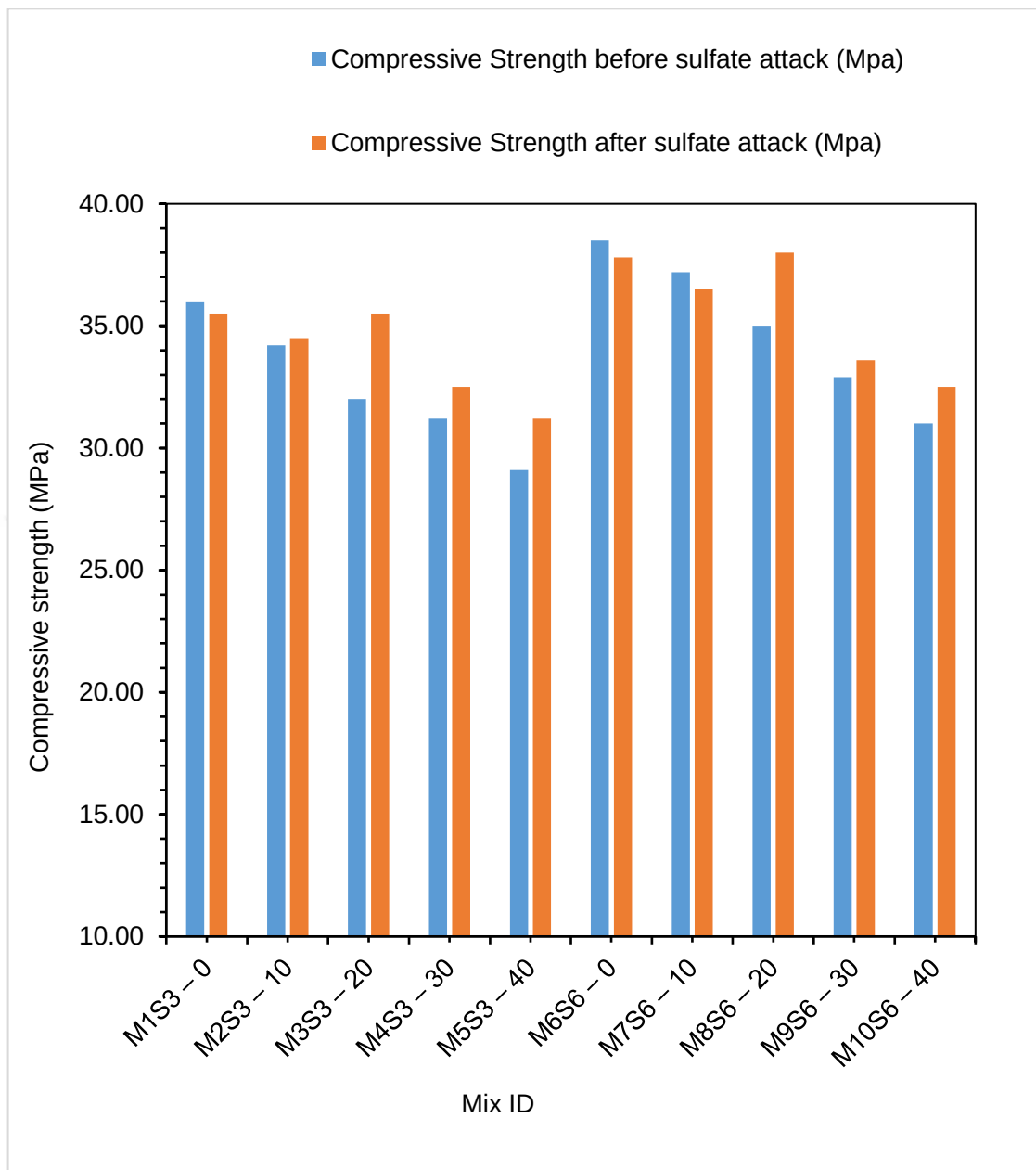


Figure 4.14 Specimens compressive strength before and after sulfate attack

Table 4. 7 Results of sulfate resistance test in terms of UPV

Mix ID	UPV of specimens before exposed to sulfate attack (m/s)	UPV of specimens after exposed to sulfate attack (m/s)	% increase in UPV
M1S3 – 0	5504	5702	3.60
M2S3 – 10	5389	5680	5.40
M3S3 – 20	5274	5568	5.57
M4S3 – 30	5217.5	5517	5.74
M5S3 – 40	5161	5461	5.81
M6S6 – 0	5639	5923	5.04
M7S6 – 10	5456.5	5725	4.92
M8S6 – 20	5274	5565	5.52
M9S6 – 30	5162	5452	5.62
M10S6 – 40	5050	5372	6.38

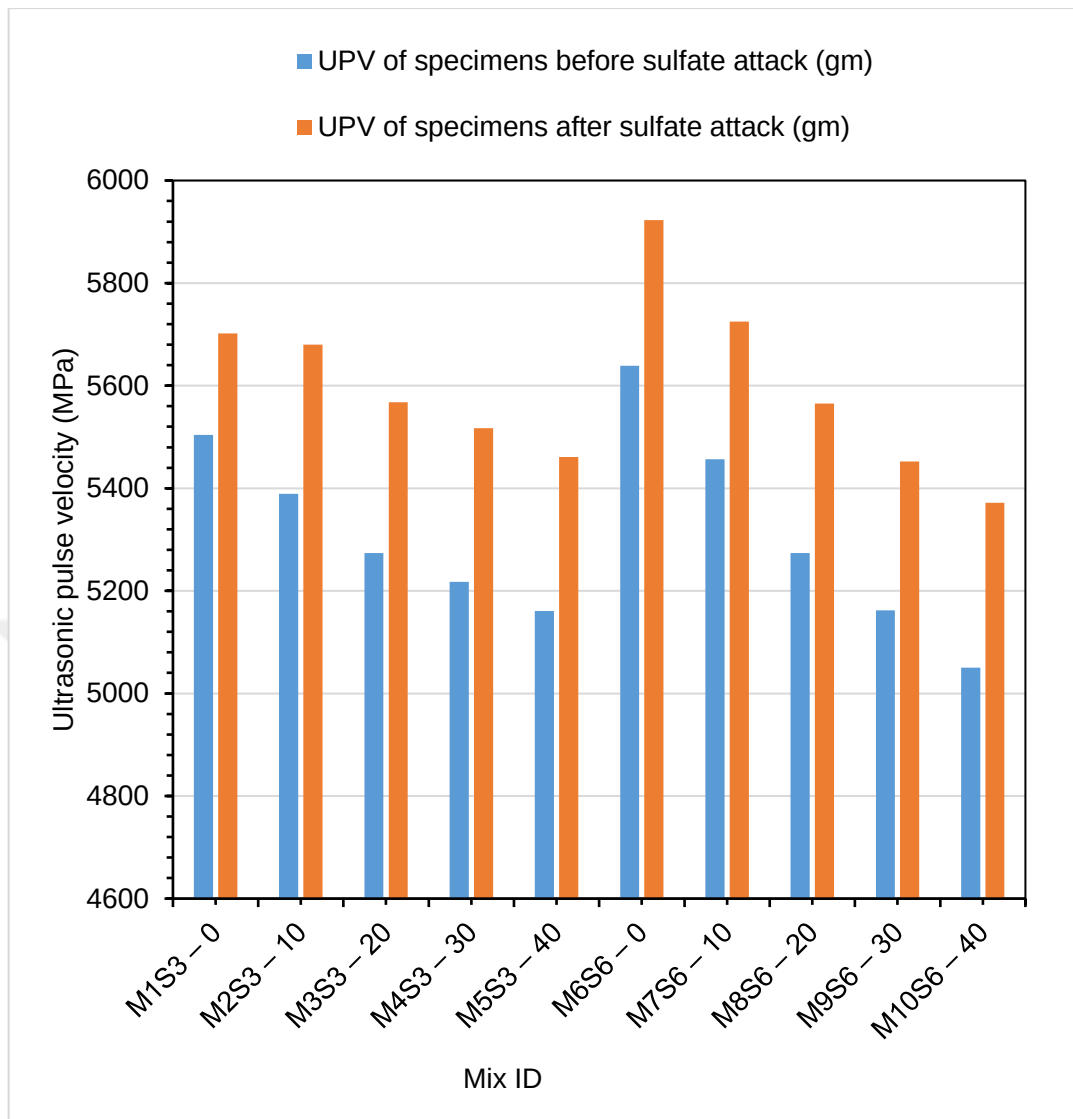


Figure 4.15 Ultrasonic pulse velocity before and after the sulfate attack

4.2.9 Freezing-Thawing Test

In this study, change in compressive strength, change in weight and ultrasonic pulse velocity magnitude change were used to assess the impact of freezing-thawing on the geopolymer concrete mixtures. Test results indicated that 0.3% and 0.6% of steel fiber reinforced geopolymer concrete mixtures suffered insignificant mass reduction and less than a 10% decrease in compressive performance. The minimal weight loss is mainly related to the concrete surface and edge defects due to the freezing and thawing effects. It can also be observed from Table 4.8 that the specimens produced with the partial replacement of recycled coarse aggregate have

resulted in a lower weight than that of the specimens prepared from 100% natural aggregate. The mixtures having 40% recycled coarse aggregate have experienced the maximum loss in terms of compressive strength. The loss in compressive strength was reduced with the increase of fiber content. As was observed in previous sections the reduction in compressive strength caused due to the inclusion of recycled aggregate shall be compensated by the addition of fibers in the concrete mixture. Generally, the concrete mixtures with recycled concrete aggregates resulted in a lower compressive strength than the control specimens. However, the rate of reduction is not statistically significant. The possible reason for this is: the effect of freezing and thawing in the concrete can be expressed in terms of matrix and aggregate. Primarily, the freezing and thawing effect on the matrix bases on the interconnected voids and saturation level of concrete which can be interrupted by the addition of fibers; whereas, the effect on the aggregates relates to the porosity of aggregates which can be mitigated with the incorporation of dense matrix [100]. In this study, the synergetic effect of fibers and dense matrix such as slag has enhanced the freezing and thawing resistance of the steel fiber reinforced geopolymer concrete specimens. Due to that, the specimens showed better performance against the freezing and thawing effect. The ultrasonic pulse velocity of the concrete samples also has the same trend as that of compressive strength and weight of the specimen.

Table 4. 8 Results before and after freezing and thawing test

Mix ID	Mass before the test (g)	Mass after the test (g)	Initial Compressive Strength (MPa)	Final Compressive Strength (MPa)	UPV before test (m/s)	UPV after test (m/s)
M1S3 – 0	2391	2351.00	36.00	34.00	5504	5497
M2S3-10	2384	2332.45	34.20	31.5	5389	5269
M3S3-20	2381	2341.30	32.00	29.50	5274	5273
M4S3-30	2286	2270.00	31.20	28.57	5217.5	5210
M5S3-40	2266	2246.30	29.10	26.39	5161	4897
M6S6 – 0	2397	2353.70	38.50	37.42	5639	5469
M7S6-10	2387	2356.00	37.20	35.65	5456	5460
M8S6-20	2382	2324.00	35.00	32.86	5274	5255
M9S6-30	2334	2306.00	32.90	31.12	5162	5047
M10S6-40	2324	2322.00	31.00	29.00	5050	4940

CONCLUSION AND RECOMMENDATION

5.1 General Overview

In this section of the study, a summary of the experiments carried out is presented, the main conclusions depending on the experimental outcomes are listed, and finally, suggestions and recommendations are made for future investigations.

The main goal of this study is to produce a geopolymer concrete where recycled coarse aggregate is used as a partial substitute of the natural coarse aggregate. Among several constructions and demolition wastes recycled coarse aggregate holds a major share of the total construction and demolition wastes, worldwide. Also, the utilization of recycled aggregate helps to reduce the consumption of virgin aggregate and therefore it would have a significant role to maintain the balance of a natural ecosystem. Thus, it is important to study the feasibility of the recycled aggregate for utilization in concrete production. In this study, to have a better understanding of the mechanical and durability properties of steel fiber reinforced fly ash/slag based GPC manufactured with the partial replacement of recycled aggregate the following tests were conducted: Compressive strength, splitting tensile strength, flexural strength, ultrasonic pulse velocity, high-temperature resistance, sulfate resistance, freezing-thawing, and abrasion resistance. The compressive strength and splitting tensile strength were conducted to determine the mechanical performance of the concrete mixtures. Three-point bending tests were performed to characterize the flexural characteristics of the resulting geopolymer concrete specimens. Whereas, the durability properties of the steel fiber reinforced fly ash/slag-based GPC was determined using high-temperature resistance, sulfate resistance, freezing-thawing, and abrasion resistance test results.

5.2 Overall Experimental Findings

- The oiling of the molds is a crucial step in the geopolymer concrete production process, applying oil just before casting simplifies the specimens demolding step.

Nevertheless, using ordinary oil does not contribute to the easier and safe demolding of the concrete samples instead employing grease oil is highly recommended in the case of the geopolymer concrete manufacturing process.

- As illustrated in the previous section, chemical liquids sodium hydroxide and sodium silicate were merged 24hrs ahead of mixing time. This has contributed to the full occurrence of the exothermic reaction and given enough time to cool down and avoid possible hand caps which could happen due to the instability of the solution.
- Selecting a manual high speed and a high shear drill mixer has significantly improved the workability, flowability, and homogeneity of the resulting geopolymer concrete matrix than a conventional laboratory mixer.
- The chemical liquid to binder ratio is a vital parameter that influences the out coming concrete matrix and its final results as well. In this experimental work, no extra activator was employed to depolymerize the base materials. In the study, a liquid to binder ratio of 0.5 was adopted and desirable results were obtained.
- The water absorption capacity of the recycled aggregate is usually higher than that of natural aggregate and therefore utilization of recycled coarse aggregates reduces workability characteristics of the resulting concrete mix. In this investigation, the dry surface saturated state of the recycled aggregates was maintained by adding water based on the calculated absorption capacity of the recycled aggregates.
- Early demolding (less than 24hrs) of the specimens could cause a drop in the overall strength properties of the resulting concrete samples. In this study, all specimens were demolded after 24hrs and kept in a dry-curing room until the intended date of the test.

5.3 Conclusions

- Generally speaking, the specimens with the addition of RCA of up to 30% possessed promising overall properties when compared to the samples prepared with 100% natural aggregate proportion. However, the strength properties of the specimens were decreased with the increase of recycled coarse aggregate ratio. This is attributed to the presence of defects on the recycled aggregates and the weak bond

formed between an old attached mortar and a new mortar formed from fly ash and slag.

- Recycled aggregate incorporation of 40% has caused a significant reduction in strength properties such as compressive strength, splitting tensile strength, and flexural performance with a maximum reduction rate of 22.61%, 15%, and 34.5%, respectively, about control specimens.
- The compressive strength, splitting tensile strength, and flexural strength of all the mixtures were improved when the fiber content rises from 0.3% to 0.6%. Also, the toughness of the concrete specimens was increased with the increase of fiber ratio. However, no consistent correlation was maintained between the recycled aggregate ratio and toughness values of the samples.
- The specimen's ability to resist the abrasion effect was found to be prospective. In this study, the concrete mixtures subjected to the abrasion test suffered less than 1mm abrasion loss although the wear thickness was increased with the increase of the recycled aggregate content. Whereas, the wear thickness was reduced with the increase of fiber content from 0.3% to 0.6%.
- The overall freezing-thawing resistance of fly ash/slag-based geopolymer concrete with partial incorporation of recycled aggregates was approximately similar to that of the specimens produced with natural aggregates only. According to the findings from the study, no significant effect was observed in the freezing-thawing resistance parameters with the increase of fiber content.
- When exposed to sulfate attack the specimens with partial substitution of recycled aggregates have resulted in a better performance than the control specimens.
- When subjected to a temperature of 200°C the compressive strength of all the specimens in comparison to the original strength was increased irrespective of the aggregate type. While at 600°C the specimens manufactured with the recycled aggregate started losing their original strength. The maximum reduction recorded 21% of the initial strength which was seen at the specimen prepared with 30% recycled aggregate and 0.3% steel fiber content.

5.4 Recommendations

- Detail examination must be carried out on the setting time and workability of fly ash/slag-based GPC produced with the incorporation of recycled aggregate. The fast hardening of the mixtures caused the casting of the several molds to a laborious activity, an effort must be invested to lengthen hardening time and to improve the workability of the mixtures.
- In the matter of fibers, further investigation should be made to determine an optimum dosage of fiber. Also, various fiber types and aspect ratios could be done to conduct a new study.
- The durability characteristics such as sulfate attack and freezing-thawing resistance of the specimens must be examined to obtain more results. In this study only the exposure period of 60 days was considered, making it challenging to draw a proper conclusion. A more detailed investigation can be conducted to determine the long and short-term effects of sulfate attack and freezing-thawing in different properties of geopolymer concrete mixtures containing recycled aggregate.
- In this study, the influence of elevated temperature, sulfate attack, and freezing-thawing was evaluated in terms of weight loss, compressive strength, and ultrasonic pulse velocity. A further study could be made by considering an effect of the aforementioned parameters in terms of splitting tensile strength, modulus of elasticity, and flexural characteristics of the resulting concrete specimens.
- This experimental work examined some mechanical and durability characteristics of fly ash/slag-based geopolymer concrete with recycled aggregate. Only a few studies addressed the microstructural properties of geopolymer concrete with recycled aggregate. Therefore, further investigation must be done on the microstructural analysis of the mixtures.

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PUBLICATIONS FROM THE THESIS

Conference Papers

1. Asfaw Mekonnen LAKEW, Orhan CANPOLAT, Mukhallad M. al-MASHHADANI Steel fiber reinforced geopolymer concrete: Mechanical assessment. 6th International Conference on Green Design and Manufacture 2020, 23-24 July 2020, Seoul, South Korea PP.1-8.

