



**RE-USE OF WASTE MATERIALS  
TO IMPROVE MECHANICAL  
PROPERTIES OF SOFT SOIL**

**Master Thesis**

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**RE-USE OF WASTE MATERIALS TO IMPROVE MECHANICAL  
PROPERTIES OF SOFT SOIL**

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**MASTER THESIS**

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## FINAL APPROVAL FOR THESIS

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## ÖZET

### YUMUŞAK ZEMİNLERİN MEKANİK ÖZELLİKLERİNİN İYİLEŞTİRİLMESİ İÇİN ATIK MALZEMELERİNİN KULLANIMI

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Bu çalışmada turba ve killi zemin gibi yumuşak zeminlerin mekanik özelliklerinin artırılması için çimento yerine atık malzeme (RM) kullanılması üzerine durulmuştur. Ayrıca, bu çalışmada atık malzeme içeriği, su/yüksek fırın cürufllu çimento oranı, kürlenme süresi ve sıcaklık etkisi araştırılmıştır. Çimentolu zeminin mekanik özelliklerini belirlemek için serbest basınç deneyi ve serbest rezonans deneyleri yapılmıştır. Bu deneyler sonucunda turba ve killi zemine atık malzemeler ilave edilerek zeminlerin mekanik özellikleri artırılmıştır. Atık malzemeler genel olarak kum, kırık taş, kırık tuğla ve kırık betondan oluşmaktadır. Kürlenme süreleri 28, 60, 90 ve 120 günden oluşmaktadır ve kürlenme süresindeki artış numunelerin serbest basınç dayanımını ve dinamik mukavemetini arttırmıştır. Su/yüksek fırın cürufllu çimento oranı 0.9 olan killi zeminlerde turbaya kıyasla daha düşük sonuçlar elde edilmiştir. Bu durum killi zeminlerin daha zor sıkıştırılması ile ilişkili olabilir. Sonuç olarak, atık malzemelerin çimento yerine kullanılması uzun vadede dayanım artışı için iyi sonuçlar vermiştir ve atık malzemeler gelecek için ümit verici yeni bir malzeme olarak değerlendirilebilir.

**Anahtar Kelimeler:** Atık malzemeler, Yüksek Fırın Cürufllu Çimento, Serbest Basınç Dayanımı, Küçük Gerilme Rijitliği.

## ABSTRACT

### RE-USE OF WASTE MATERIALS TO IMPROVE MECHANICAL PROPERTIES OF SOFT SOIL

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This thesis focused on the reuse of waste materials for geotechnical and geo-environmental purposes and the strength development of cement treated soft soils such as peat and clayey soil was studied. The effects of different parameters, such as recycled material content, curing time, curing temperature and the ratio of water to blastfurnace slag cement were investigated. The unconfined compression strength (UCS) and free-free resonance frequency tests were performed to understand the mechanical properties of cemented soil. It was found that a more performant mechanical behaviour of peat and clayey samples was found by adding recycled materials (RM) to the peat and clayey soil. RM composed out of sand, stones, crushed bricks and concrete. Moreover, curing time increases the specimens' ages for all four curing times (28,60, 90 and 120 days) and also increases the UCS of the specimens. The increment on strength was significant from 28 days to 120 days. On the other hand, significant lower results evaluated on clayey soil compared to peat for water/blastfurnace slag cement ratio of 0.9. This might be related to the fact that these clayey mixtures are very difficult to compact. It can be concluded that recycled material showed a good performance in long-term strength development and seemed to be a good material to be concerned in future.

**Keywords:** Recycled Materials, Blastfurnace Slag Cement, Unconfined Compressive Strength, Small-Strain Stiffness.

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Ecem Nur BARIŞOĞLU

**STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND  
RULES**

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Eskişehir Technical University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

Ecem Nur BARIŞOĞLU



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## LIST OF ABBREVIATIONS AND SYMBOLS

|           |  |
|-----------|--|
| BSC       | : Blastfurnace Slag Cement                             |
| CPT       | : Cone Penetration Test                                |
| DM        | : Dry Mixing   |
| DS        | : Dredged Sediments                                    |
| DSM       | : Deep Soil Mixing                                     |
| DW        | : Distilled Water                                      |
| FFR       | : Free-free Resonance                                  |
| HDPE      | : High-density Polyethylene                            |
| HYPER     | : HYdraulic PERformance                                |
| LL        | : Liquid Limit   |
| PI        | : Plasticity Index                                     |
| RGP       | : Recycled Glass Powder                                |
| RM        | : Recycled Material(s)                                 |
| UCS       | : Unconfined Compressive Strength                      |
| WM        | : Wet Mixing   |
| $E_0$     | : Small-Strain Modulus in Longitudinal Direction [GPa] |
| $G_0$     | : Small-Strain Modulus in Transversal Direction [GPa]  |
| $\rho$    | : Bulk Density   |
| $f_L$     | : Longitudinal Resonant Frequency                      |
| $f_T$     | : Transversal Resonant Frequency                       |
| $v_p$     | : Compressive Wave Velocity                            |
| $v_s$     | : Shear Wave Velocity                                  |
| $\lambda$ | : Wavelength   |

# **1. INTRODUCTION**

## **1.1. Problem Statement**

Green geotechnical construction can have a significant contribution to the sustainability and resilience of ground improvement projects. Geotechnical engineering plays an important role in sustainable projects. Many soil layers have unsatisfying hydraulic and mechanical properties because of natural diversity. Nowadays, still traditional materials used to improve these properties are energy consuming and in general relatively expensive. Using recycled and waste materials as an alternative to traditional materials can contribute to a sustainable society. To reuse of waste materials in various soil engineering applications were investigated in previous works. Examples of these wastes and recycled materials are waste tire, plastic waste, dredged sediments, recycled crushed concrete, recycled glass powder and so on.

Regarding to mechanical soil properties, in geotechnical engineering, the bearing capacity of soil has an important role with respect to foundation design and thus the stability of civil engineering structures. However, soft soil layers are often encountered in construction projects such that ground improvement needs to be fulfilled. For this reason the native soil is often in-situ mechanically deep-mixed with binders, such as cement, to improve the strength characteristics.

Maryland Department of the Environment established a guidance document which describes innovative solutions to reuse dredged sediments. First, the use of dredged sediments as a daily, intermediate or final cover as an alternative to traditional earthen material in landfills was suggested. Second, the reuse of dredged sediments in terms of soil and fill material was proposed. Di Emidio, Verastegui Flores and Bezuijen [1] evaluated the possible reuse of dredged sediments for hydraulic barriers in the field of geo-environmental engineering. Crawford [2] examined the beneficial reuse of dredged sediments for vertical cut-off wall backfill materials. For this purpose an appropriate mix of sediment and bentonite was investigated.

Several studies also focussed on the use of scrap tires in geotechnical applications, especially as embankment material. Tires can be used as lightweight material either in the form of powder, chips, shredded and as a whole. Singh [3] reported an increment of 8.00% in unconfined compressive strength for a pavement subgrade soil using shredded rubber tires. In addition, the use of waste tires as a fill material results in a more economical solution comparing the other alternatives [4].

Soil having poor mechanical properties can result into excessive settlements such that the serviceability limit state of structures can be exceeded which eventually can lead to failure. For this reason, the native soil is often in-situ mechanically deep-mixed with binders, such as cement, to improve the strength characteristics. Deep soil mixing (DSM) method has been introduced for various structural environmental functions as retaining structures, foundations, soil reinforcement, land and slope stabilization, in situ remediation and barriers against liquefaction. DSM method is used for strengthening of weak and permeable soil [5, 6].

## **1.2. Objective**

This research investigates the strength development of cement-treated peat and clayey soils under different curing conditions and water/blastfurnace slag cement ratio based on unconfined compression strength and stiffness. The unconfined compressive strength (UCS) and free-free resonance (FFR) tests were performed to understand the mechanical properties of cemented soil.

The parameters studied in this research as follows:

- Effect of the recycled material content
- Ratio of water- blastfurnace slag cement
- Curing time
- Temperature

## **2. STATE OF ART**

### **2.1. Reuse of Waste Materials in Geotechnical Engineering Applications**

The use of recycled waste materials has increasingly become popular over the last decade having enhanced environmental sensitivities. Many recycled construction wastes have adequate shear strength in relation to various geotechnical applications. This section describes the potential reuse of some promising waste materials to improve geotechnical engineering properties.

Guney et al. [7] studied on waste foundry sand with different percentages is used for replacing with natural fine sand. The results conducted from several tests showed that decrease in compressive and tensile strengths, and the elasticity modulus. It can be concluded that the slump and the workability of the fresh concrete decreases with the increase of the waste foundry sand ratio.

M. Tuncan, A. Tuncan and Cetin [8] investigated the effects of rubber and plastic concentrations and rubber particle sizes on properties of asphalt cement. The study proved that the strength of specimen is considerably increased by adding the plastic into asphalt cement. However, the strength of specimen is decreased by adding rubber into asphalt cement. Also, fly ash and marble powder used as filler materials are investigated in this study. Results showed that fly ash and marble powder are promising materials for replacing stone powder in the asphalt concrete specimens.

#### **2.1.1. Soil reinforcement using fibers**

Type of fiber has a significant role in soil stabilization properties for the fiber reinforced soil. The different fiber types causes different physical and mechanical properties in fiber reinforced soil. Furthermore, waste natural fibers should be widely utilized due to its renewal and sustainability.

Tran, Satomi and Takahashi [9] investigated the mechanical properties of soil reinforced with cornsilk fibers. Studies have proven that additional cornsilk fibres results in the improvement in compressive strength and stiffness property. In this study, additional amount of fibers (0.50, 1.00, 1.50, and 2.00%) as well as the fiber lengths (10.00, 30.00, and 50.00 mm) was investigated based on compaction test, unconfined compression test, and splitting tension test. It can therefore be concluded that cornsilk

fiber can be considered as the promising material for geotechnical engineering applications.

The effects of cornsilk fibers on mechanical properties of cemented soil was studied in a research of Tran, Satomi and Takahashi [10]. The effect of different parameters such as cornsilk fiber content (0.00%, 0.25%, 0.50%, and 1.00% by weight of dry soil), cement content (4.00%, 8.00%, and 12.00% by weight of dry soil) and curing time (7, 14, and 28 days), on the cement treated specimens was investigated by conducting compaction, compression, and splitting tension tests. The experimental results proved that increasing cornsilk fiber content in cemented soil increases the compressive and splitting tensile strength.

Hejazi et al. [11], evaluated the possible use of fiber materials in reinforced soils. The study reported that natural or synthetic fibers are applicable in geotechnical applications such as retaining wall, earthquake and soil foundation engineering and road construction due to beneficial and renewable in geotechnical applications.

The textile industry has one of the largest sectors generates waste per year. Many studies conducted to reduce and reuse of deposited carpet fibres in geotechnical applications. Soil reinforcement with geotextile fabrics are well-structured technique for soils have low tensile and shear strength. Studies have also proven that fibre reinforcement can improve the shear strength, compressive strength, bearing strength and the elastic modulus of soil [12].

### **2.1.2. The use of glass in geotechnical engineering**

Disfani et al. [13] studied the recycled crushed glass in road work applications. Geotechnical laboratory tests was conducted on recycled crushed glass being coarse, medium and fine sized. Laboratory tests indicated that medium and fine sized recycled glass has similar behaviour to natural aggregates. However, coarse recycled glass is inappropriate for geotechnical applications. It is concluded that recycled glass as a construction material behaved as natural aggregates in geotechnical applications particularly road works.

Bilondi, M. M. Toufigh and V. Toufigh [14] evaluated the possibility of using geopolymer based on recycled glass powder (RGP) to improve the mechanical behavior of clay soils. In this study, unconfined compressive strength test performed to

investigate the effect of different parameters such as the temperature, the curing time, the recycled glass powder content. Results showed that using recycled glass powder as a soil stabilizer has positive impact on the mechanical behaviour of soil. An increase in the curing time of stabilized specimens increased the UCS values and the highest strength reached for a period of 91 days. In conclusion, recycled glass powder geopolymers can be used as eco-friendly soil stabilizer.

### **2.1.3. The use of plastics in geotechnical engineering**

The amount of plastic wastes has increased year by year and the disposal becomes a critical problem. Waste plastic products have many side effects on the environment and human health. Therefore, it is necessary to re-utilize these plastic wastes effectively in geotechnical applications. The properties of soil can be improved and the use of plastic waste in geotechnical engineering can be encouraged. Various research programmes has been conducted to reuse waste plastic products into geotechnical applications.

Graettinger [15] explored the reuse of recycled plastic bottles as a lightweight geotechnical fill. The physical and mechanical characteristics of the recycled plastic bottle blocks were investigated by laboratory and field study. It was found that this material may be useful as a lightweight geotechnical fill over soft soils or behind the retaining walls. This study shows the use of deposited recycled plastic bottles as an environmentally friendly geotechnical engineering material.

An approach for the use plastic waste as reinforcement material in soil is developed by Sivakumar et al. [16]. Series of triaxial compression and one dimensional consolidation tests were performed to determine stress-strain-pore water pressure and compression behavior of plastic waste mixed soil and to observe the influence of plastic waste on shear strength of soil with various percentages. The experimental results proved that there is a positive improvement in the strength of soil with presence of plastic waste and the experimental results are in excellent agreement with analytical model.

Soil stabilization improves the physical and mechanical properties of weak soils by adding stabilizers like cement, lime and etc. but these additives also have become expensive in recent years. Many researchers offered to use recycling materials as a soil stabilizer to reduce the prices in the soil improvement techniques.

Peddaiah, Burman and Sreedeeep [17] presented a detailed study using waste plastic bottles in soil improvement techniques. The aim of this research is to investigate the effect of plastic bottle strips on silty sand by performing compaction, direct shear and California bearing ratio (CBR) tests. It was found that improvement in engineering properties of silty sand is achieved at 0.40% plastic content with strip size of 15.00 mm × 15.00 mm based on experimental program. Generally, this study indicated plastic can be used as an effective soil stabilizer as well as economical solution for stabilizing weak soil.

Dhatrak and Konmare [18] after investigating performance of plastic waste mixed soil as a geotechnical material, it was observed that waste plastic bottle chips are an alternative method to improve the sub grade soil of pavement. In this study, a series of experiments are performed on soil mixed with different percentages of plastic (0.50%, 1.00%, 1.50%, 2.00% & 2.50%) to calculate california bearing ratio. The results demonstrated that the soil strength increases by adding plastic waste strips.

The consumption of single-use plastic material in municipal solid waste growing around the world. These disposable plastics reach the waste stream more quickly as their usage life shortly.

Chebete and Kalumba [19] presented a laboratory investigation on sandy soils to reduce the abundant amount of plastic bag waste. The interaction between high-density polyethylene (HDPE) and two medium dense quartz sands with either round or angular shaped particles was studied. The HDPE waste was added to the soil in the form of strips of distinct rectangular dimensions. A series of direct shear tests and bench-scraper plate loading tests were performed. Strips of shredded plastic material were used as reinforcement inclusions at concentrations of up to 0.30% by weight. Highest improvement was observed on plastic strips which has a length of 15.00 mm, width of 6.00 mm, concentration of 0.10% and perforation diameter of 2.00 mm plastic strips based on laboratory results. It was concluded that this material in sandy soils can be used as soil reinforcement in geotechnical applications.

Ilies et al. [20] tried to reuse polyethylene waste in a silty clay and compared this material to the traditional use of cement. The main conclusion resulting from this research was that an addition of 4.00% PET by mass resulted into notable improvements of the original soil. Compared to mixtures having the same amount of cement, the cohesion and internal friction angle of the PET added sample were 52.00% and 63.00% lower, respectively.

The use of plastic bottle waste as an alternative for conventional geogrids was studied by Trudeep and Tejaskumar [21]. The aim of the study is to improve the load-settlement behaviour of soil. Ultimate bearing capacity are increased compared to the unreinforced soil. Based on this outcome, the use of waste plastic as a base material for geogrids was considered as promising material for soil improvement.

## **2.2. Mechanical Properties of Stabilized Soil**

### **2.2.1. The deep soil mixing (DSM) method**

One of the biggest challenges in construction projects is to encounter with soft soil layers which will create stability problems as well as excessive settlements. A series of research have been conducted to resolve these difficulties so far and various ground improvement techniques have been developed and applied into the construction site.

The DSM is a deep in-situ soil ground improvement technique using cement and/or lime as a stabilizing agents and was introduced first in Japan and in the Scandinavian countries. The DSM method have been used since middle of seventies and then spread to China, South East Asia and recently to other parts of world including USA, put into practice in various of ground improvement projects so far. Nowadays, the use of the DSM method in ground improvement is increasing across the world year by year. Lately, the DSM method has also been introduced for various structural environmental functions as retaining structures, foundations, soil reinforcement, land and slope stabilization, in situ remediation and barriers against liquefaction. Moreover the Euro Soil Stab [22] also suggests the use of DSM to increase the dynamic stiffness of soft soils, i.e. to reduce vibrations to the surroundings as well as to improve the dynamic performance.

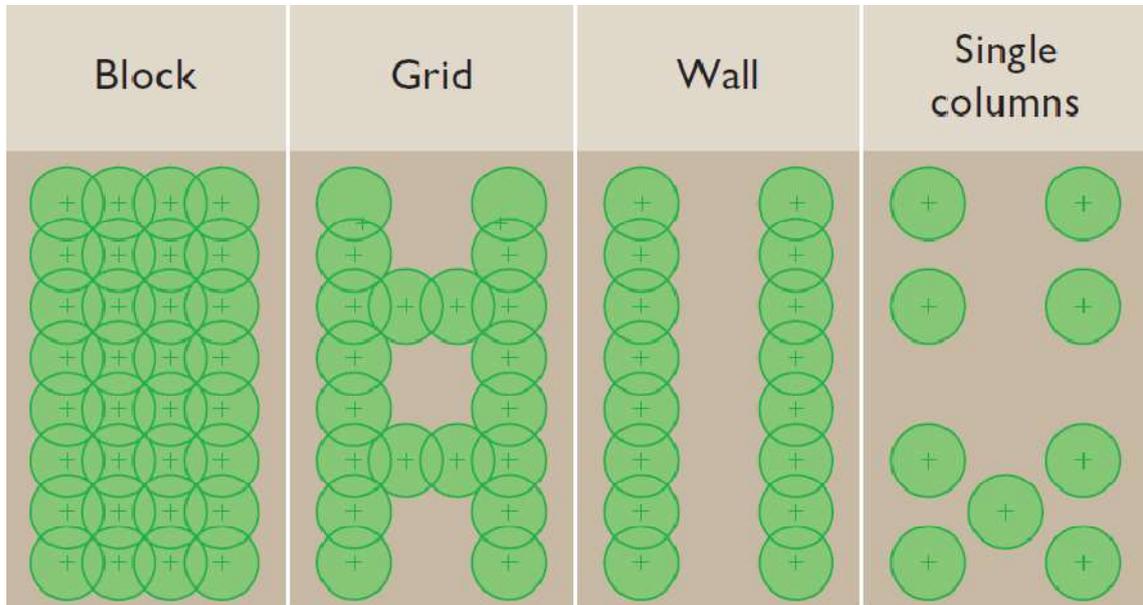
Overall, it can be concluded that the DSM method is used for strengthening and sealing of weak and permeable soil. The final treated soil has a higher strength, lower permeability and lower compressibility than the soft soil [5, 22, 23].

Several studies were conducted to explain DSM method. Onur et al. [24] studied on the design of deep soil mixing method with case studies to produce results to literature. In consequence of this study, it is expected that the recognition and application of deep soil mixing method will increase. Also this study gives different perspective and alternative method for the engineer and contractors.

Deep soil mixing is an in-situ ground improvement technique that enhances the characteristics of weak soil by mechanically and possibly hydraulically or pneumatically mixing them with additives based on cement and lime which are injected using a specially designed machine. Additives such as cement, fly ash, lime and bentonite can be used to stabilize the soft soil. Regarding the injection of the binder into the ground, in general there are two types of installation methods. Either the soil and binder are mixed using without water (dry mixing method), or additional water is added during mixing such that the binder is injected with a slurry (wet mixing method). The former method is more appropriate for soft soils with very high moisture content and thus allowing chemical reaction of dry injected binders with the soil. The latter method is generally used in soils having a water content lower than 60.00% and is more frequently used. The wet mixing method is also more suitable in soft clays, silts and fine-grained sand with lower water content and in stratified ground conditions including interbedded soft and stiff or dense soil layers [5, 6, 22, 23].

In the wet mixing method, a mixture of additive and water eventually in combination with sand is injected and mixed with the soil. It is important to note that the water-binder mixture (generally a weight ratio between 0.60 and 0.80) is injected at relatively low pressures (compared to e.g. jet grouting) of about  $< 5$  bar. Typical values of injected amounts of binder are typically between 350.00 and 450.00 kg/m<sup>3</sup>. The composition and volume of injected slurry depend the required properties of stabilized soil considering the strength and/or sealing functions. In the case of dry mixing method, the soil is directly mixed with the binder which directly reacts with the soil and forms a soil mortar. With the dry and wet mixing methods, different patterns can be created using soil-cement columns, rectangular panels, continuous barriers or global

mass stabilization. Regarding the design of DSM columns, Figure 2.1 shows some possible patterns such as block, grid, wall, single columns [5, 6].



**Figure 2.1.** Possible patterns of DSM columns [6]

A distinction can be made between mass stabilization and column stabilization in the DSM method. Both systems offer wet and dry soil mixing solutions which enable the additives to be placed as a wet slurry or a dry powder. They are able to tackle some of the most difficult soil conditions ranging from flood plains and soft soils through the contaminated land [5, 22, 23].

Mass mixing is used in situations where a whole area of very soft or contaminated ground requires improvement. The procedure involves mixing a cementitious binder into peat, silts or soft clay and is carried out with a mixing tool that has been installed on an excavator machine. By mixing in both the horizontal and the vertical direction the substances combine to form a much improved structural quality material that in some instances can be used as fill. Mass mixing is applied at depths between one to six meters and applications include mass stabilization of dredging mud, canal management, road construction, ground strengthening and land remediation [5, 22, 23].

Soil mixed columns may be single or overlapping triple columns installed up to 23.00 m in depth for installation of cut-off walls or to improve the bearing capacity of the soil for example on embankments at risk of soil erosion. Retaining walls for flood

defence schemes, cofferdams or any other purpose may be economically built using soil mixing if the ground conditions are suitable. Granular materials such as sands and gravels are mixed with cement slurry to form solid walls [5, 22, 23]. It should be noted that this study mainly focusses on column stabilization.

### **2.2.2. Basic mechanism of stabilization**

In the majority of the cases, cement and/or lime are used as an additive in the DSM method. Specifically, Keller [6] advises to use lime in plastic clays and silts, while blastfurnace slag is suggested in organic soils. Nowadays, industrial wastes having self-hardening properties are also attempted to be used as an additive. Potential additive materials mainly contain calcium oxide (CaO), silicon dioxide (SiO<sub>2</sub>), aluminium oxide (Al<sub>2</sub>O<sub>3</sub>), magnesium oxide (MgO), iron oxide (Fe<sub>2</sub>O<sub>3</sub>) which causes pozzolanic strength reactions. Therefore, various types of slag (blastfurnace slag, converter slag, stainless steel slag) and various types of ash (coal ash, incinerated paper ash, incinerated sewage ash) are qualified as usable [25].

#### **2.2.2.1. Lime-type stabilizing agent**

Lime is mainly used in clayey soils and is available in two forms, either as quicklime (CaO) or hydrated lime (Ca(OH)<sub>2</sub>). Quicklime has a large amount of calcium oxide (CaO). When it is mixed with soil, it absorbs moisture in the soil and becomes hydrated lime or calcium hydroxide (Ca(OH)<sub>2</sub>). This reaction can be given below [25, 26]:



During the hydration reaction (or: slaking process), quicklime doubles in volume and water content of soft soil is reduced therefore increasing is observed in shear strength. As a result of volume increase, the slaking of lime in the field may increase the horizontal stress and this causes displacement or consolidation of the surrounding soil. A visualization of the lime stabilization process is presented in Figure 2.2 [25, 26].

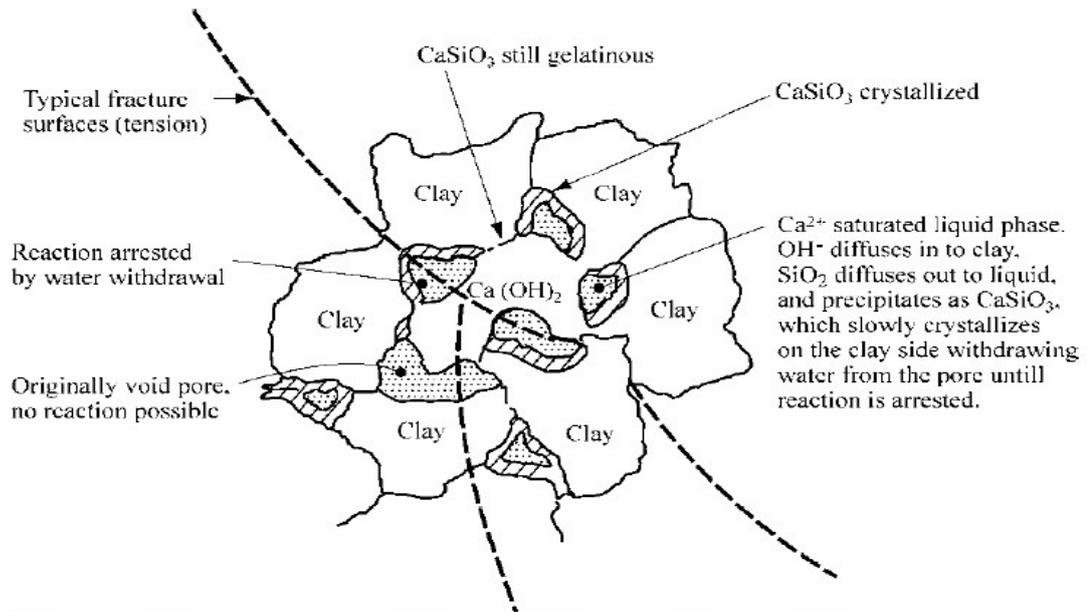
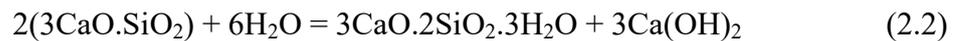


Figure 2.2. Lime stabilization mechanism [25, 26]

#### 2.2.2.2. Cement type binder

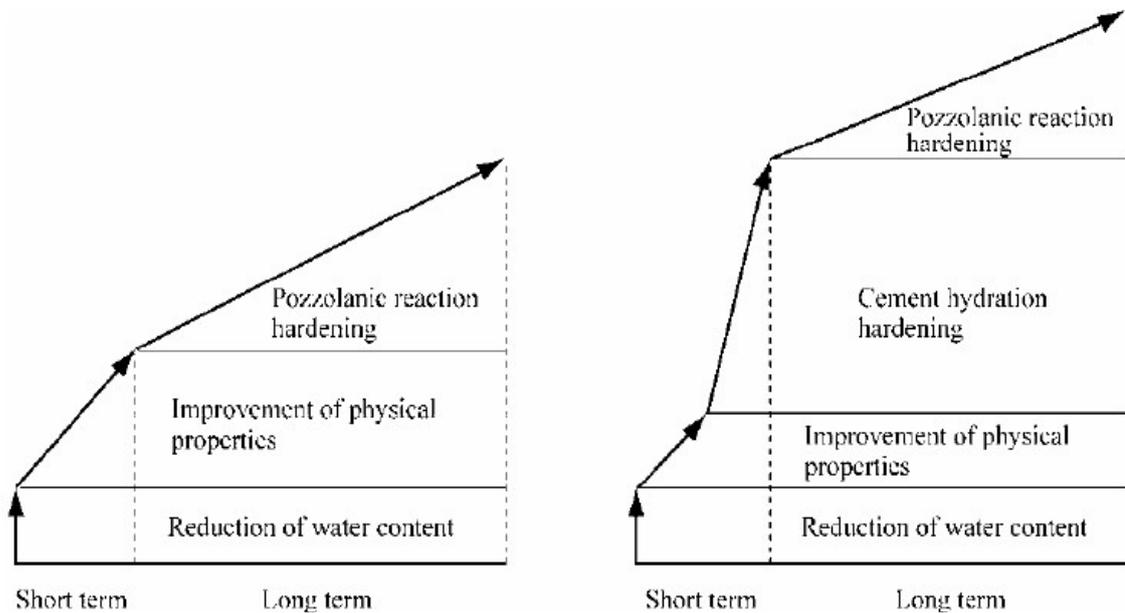
Portland cement or blastfurnace slag cement can be used to stabilize the soil as an additive. Portland cement is composed of gypsum and cement clinker grinded to powder. Main chemical composition of cement clinker is  $3\text{CaO}.\text{SiO}_2$ ,  $2\text{CaO}.\text{SiO}_3$ ,  $3\text{CaO}.\text{Al}_2\text{O}_3$  and  $4\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3$ . A cement mineral reacts with water in the following reaction to produce the cement hydration products [25, 26, 27].



The cement hydration products have a high strength which increases with time. During this hydration process calcium hydroxide is also released which causes the pozzolanic reaction as in the case of lime stabilization. Although this pozzolanic hardening of cement occurs to a much lesser degree compared to lime [25, 26].

### 2.2.2.3. Difference in strength increment with time between lime and cement

In the ground improvement using lime and cement depending on the same chemical reactions, strength increment difference can occur between lime and cement. Figure 2.3 shows the process of chemical reactions with time for both soil mixtures with lime and cement. For both binders, first the reduction of the water content takes place in case of the binder added in its dry form, which results into a slight increase of the strength. Then the plasticity of the soil is improved (improvement of physical properties) for both binders as a result of the cation exchange [25].



**Figure 2.3.** Representation of stabilization processes in time for lime (left) and cement (right) [25]

It should be noted that the rate of the chemical processes taking place as a rate of hardening, increases while the temperature increases. In the field, there will be a significant increase in temperature in the stabilized soil because of the large dimensions of the stabilized soil columns and the insulation effect of the surrounding soil. This effect of heat generation is normal in the normal laboratory testing conditions since the samples are small and cured at a constant temperature [26].

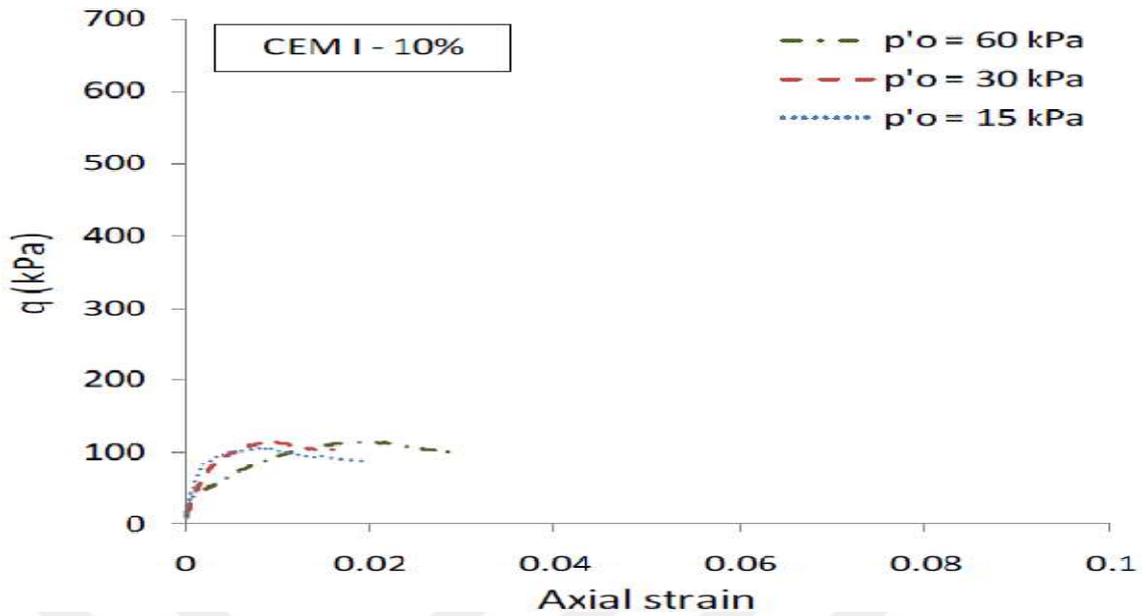
### **2.2.3. Fundamental behaviour of cemented soils**

In this section, the fundamental stress-strain behaviour of artificially cemented kaolinite clay will be discussed to get a better understanding regarding the behaviour of the considered cemented soil in this study.

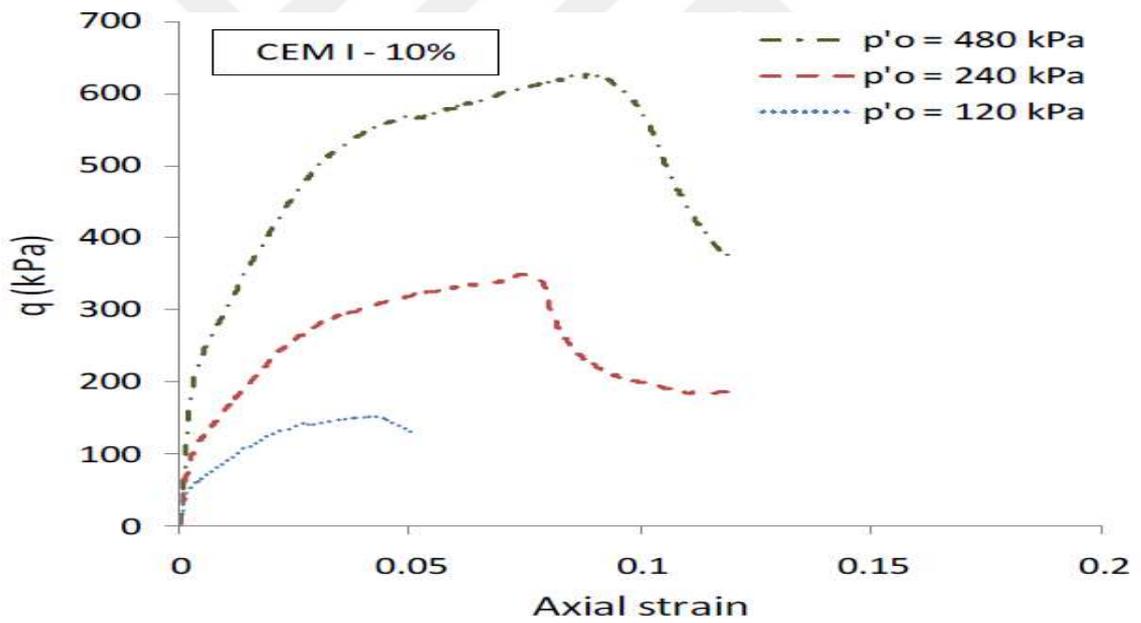
#### ***2.2.3.1. Two-phased behaviour***

Verástegui Flores, Di Emidio and Van Impe [28] carried out an experimental program to observe the strength and compressibility on kaolinite clay with Portland cement and blastfurnace slag cement at different dosages by conducting tri-axial compression and oedometer tests. The results showed that stiffness ( $G_0$ ) and strength (UCS) increases logarithmically with time in cement treated kaolinite clay samples. However, higher results observed in cement treated samples compared to non-cemented samples. Besides, blastfurnace slag cement produces a slower hardening rate at early stage after mixing comparing with Portland cement.

Figures 2.4 and 2.5 show the results of tri-axial CU test (with constant strain rate) for different confining stresses ( $p'_o$ ) in which the deviatoric stress ( $q$ ) is expressed as a function of the axial strain. Samples with a cement content of 10.00% by mass, relative to the dry mass of the kaolinite clay were tested. The water content was set at 1.50 times the liquid limit (LL) [29].



**Figure 2.4.** Tri-axial CU test results - deviator stress ( $q$ ) at low confining stresses (before isotropic yielding stress) [29]



**Figure 2.5.** Tri-axial CU test results - deviator stress ( $q$ ) at high confining stresses (beyond isotropic yielding stress) [29]

#### 2.2.4. The difference between Portland cement and blastfurnace slag cement

Ordinary Portland cement (Type I) is admirably suitable to use in general concrete construction when there is no exposure to sulfates in the soil or groundwater. Indeed, the standard requires only that it is made of 95.00 to 100.00% of Portland cement clinker and 0.00 to 5.00% of minor additional constituents, all by mass, the percentages being those of the total mass except calcium sulfate and manufacturing additives such as grinding aids. Portland cement clinker is a hydraulic material which can consist of not less than two-thirds by mass of calcium silicates ((CaO)<sub>3</sub> · SiO<sub>2</sub> and (CaO)<sub>2</sub> · SiO<sub>2</sub>), the remainder containing aluminium oxide (Al<sub>2</sub>O<sub>3</sub>), iron oxide (Fe<sub>2</sub>O<sub>3</sub>) and other oxides. The ratio by mass (CaO)/(SiO<sub>2</sub>) can be not less than 2.00. The content of magnesium oxide (MgO) cannot exceed 5.00 % (m/m) [30, 31].

Table 2.1 represents compressive strength requirements of cement according to BS 12:1996 [32].

**Table 2.1.** *Compressive strength requirements of cement according to BS 12:1996[32]*

| Class | Minimum strength,<br>Mpa at the age of: |        |         | Maximum strength,<br>Mpa at the age of: |
|-------|---|--------|---------|---|
|       | 2 days                                  | 7 days | 28 days | 28 days                                 |
| 32.50 | -                                       | 16.00  |         |   |
|       |   |        | 32.50   | 52.50                                   |
| 32.50 | 10.00                                   | -      |         |   |
|       |   |        | 42.50   | 62.50                                   |
| 42.50 | 10.00                                   | -      |         |   |
|       |   |        | 42.50   | 62.50                                   |
| 42.50 | 20.00                                   | -      |         |   |
|       |   |        | 52.50   | -                                       |
| 52.50 | 20.00                                   | -      |         |   |
|       |   |        | 62.50   | -                                       |
| 62.50 | 20.00                                   | -      |         |   |
|       |   |        | 62.50   | -                                       |

Blastfurnace slag cement consists of an intimate mixture of Portland cement and ground granulated blastfurnace slag. This slag is a waste product in the manufacture of pig iron, about 300.00 kg of slag being produced for each ton of pig iron. Chemically, slag is a mixture of lime, silica, and alumina, that is, the same oxides that make up Portland cement but not in the same proportions. There exist also non-ferrous slags; their use in concrete may become developed in the future. Blastfurnace slag cement is generally recognized that the rate of hardening of slag cement is somewhat slower than that of ordinary Portland cement during the first 28 days but thereafter increases so that the strengths become close to or even exceed those of Portland cement at 12 months [30, 31].

The blastfurnace slag cement is more sulfate resistant than Portland cement. Granulated blastfurnace slag by itself is hydraulically very weak. Due to its glassy structure, a highly alkaline medium is required to disintegrate the silicate–aluminate network of the slag glass; the liberated free lime during the hydration of Portland cement clinker is normally used to provide this alkalinity. The idea of adding slags and pozzolans such as fly ash, rice husk ash or silica fume to Portland cement concrete is widely practised because it helps to reduce cost and to conserve energy resources and environment. Burning of rice husk ash at low temperature (450–600 °C) yields a silica ash consisting of 85.00–94.00% amorphous silica with high surface area. Table 2.2 presents the constituents of Portland cement [30, 31, 32].

**Table 2.2.** *Constituents of Portland cement*

| <b>Constituents</b>            | <b>% by mass</b> |
|--------------------------------|------------------|
| SiO <sub>2</sub>               | 27.00-39.00%     |
| Al <sub>2</sub> O <sub>3</sub> | 8.00- 20.00%     |
| CaO                            | 38.00-50.00%     |
| MgO                            | <10.00%          |

### 2.2.5. Influence of the type of cement on the strength increment with time

Verástegui Flores and Di Emidio [28] studied the small-strain shear modulus and strength increment with time of cement-treated kaolinite clay, using both Portland cement (CEM I 52.5 N) and blastfurnace slag cement (CEMIII/B 32.5 N LH HSR LA). For this purpose, bender element and (UCS) tests were conducted.

The small-strain shear modulus ( $G_0$ ) is typically related to small shear-strain level with a maximum of about 10.00-3.00%. Therefore, the material is considered to be an elastic in this case. In general, ( $G_0$ ) is depending on distinct factor such as stress history, stress level, void ratio, soil fabric and the stiffness of the soil skeleton. These factors are determined by interparticle contacts and in this way an increase in ( $G_0$ ) can be expected with increasing interparticle cementation [28].

In this study, it was concluded that the small-strain shear modulus increases with time. The largest strength increment occurred for the Portland cement during the first month of hardening, however afterwards not a significant strength increment was measured shown in Figure 2.6. Logically, the ( $G_0$ ) also increased with increasing cement content. Similarly, the ( $G_0$ ) of the samples containing blastfurnace slag cement increased with time at a different trend shown in Figure 2.7. The small-strain stiffness after 28 days as well as the final stiffness is much larger compared to the case of Portland cement [28].

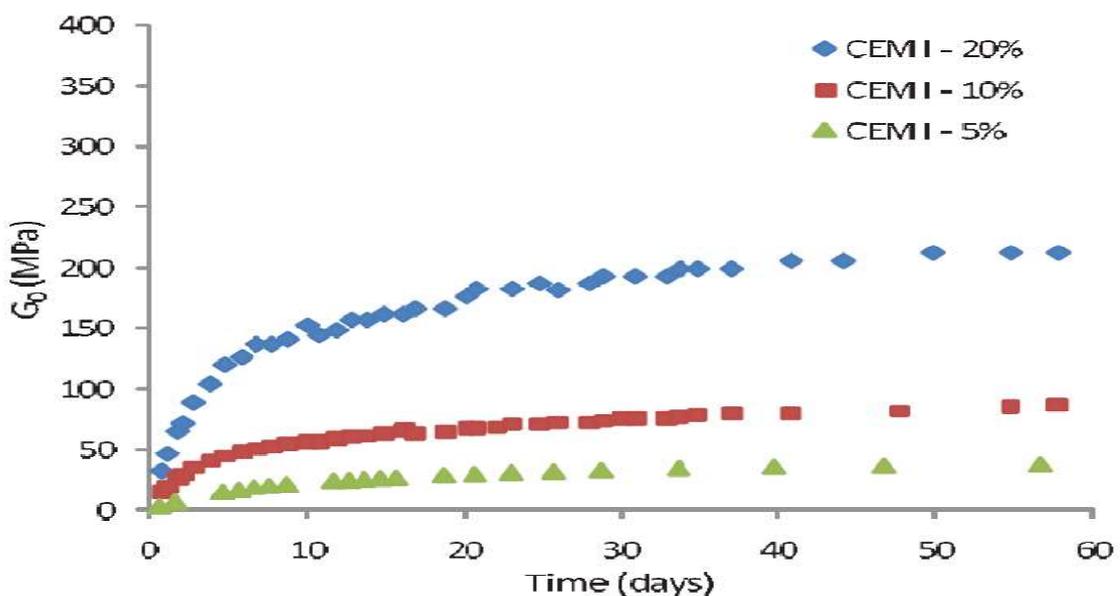
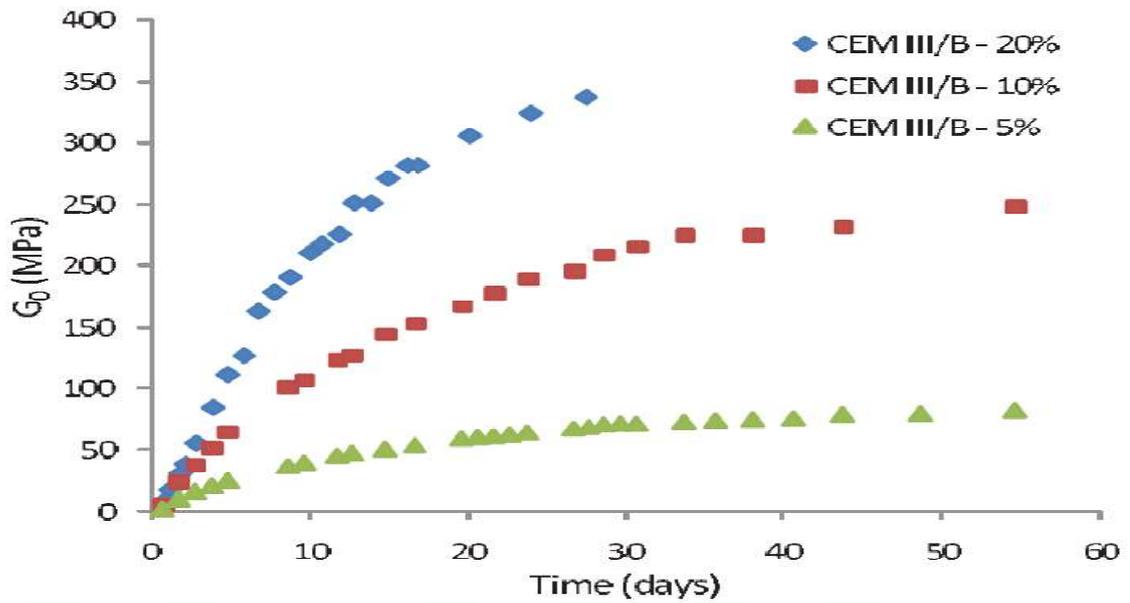


Figure 2.6. ( $G_0$ ) monitoring during Portland cement hydration [28]



**Figure 2.7.** ( $G_0$ ) monitoring during blastfurnace slag cement hydration [28]

The UCS was also studied for the different cement types and amounts. The results of the UCS with time are given in Figures 2.8 and 2.9 for Portland cement and blastfurnace slag cement, respectively. Mainly, the compressive strength of the kaolinite clay containing 20.00% blastfurnace slag cement was much larger than the kaolinite clay treated with Portland cement. In addition, for both cement types, Figure 2.10 and Figure 2.11 show the normalized ( $G_0$ ) as a function of the normalized UCS (obtained by dividing the measurements by UCS 28 days). The results suggest that the increase in small-strain stiffness and strength are closely related and follow similar trends [28].

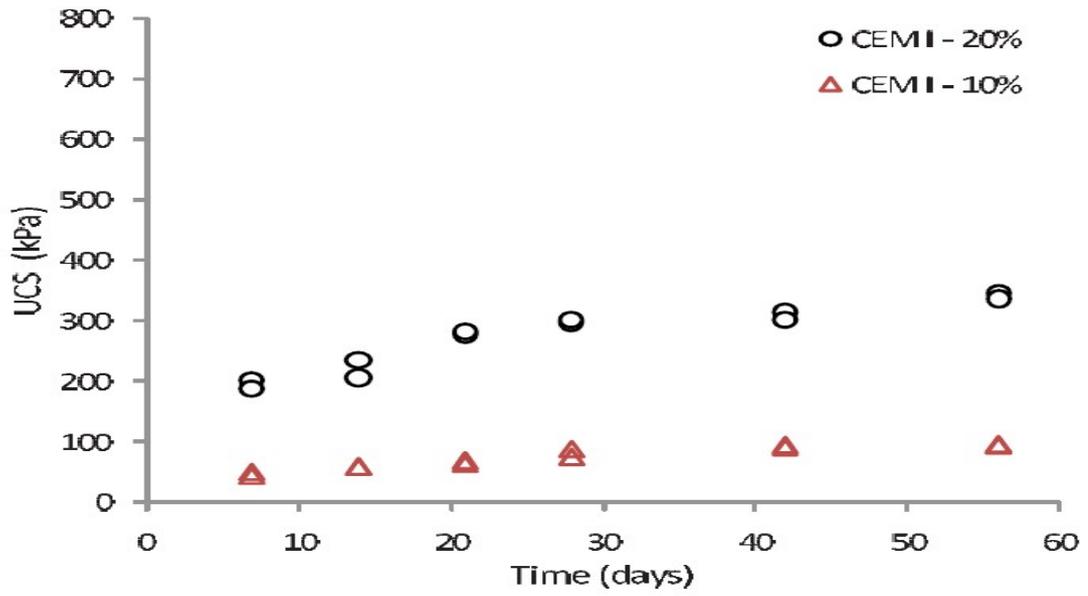


Figure 2.8. UCS with time for Portland cement treated soil [28]

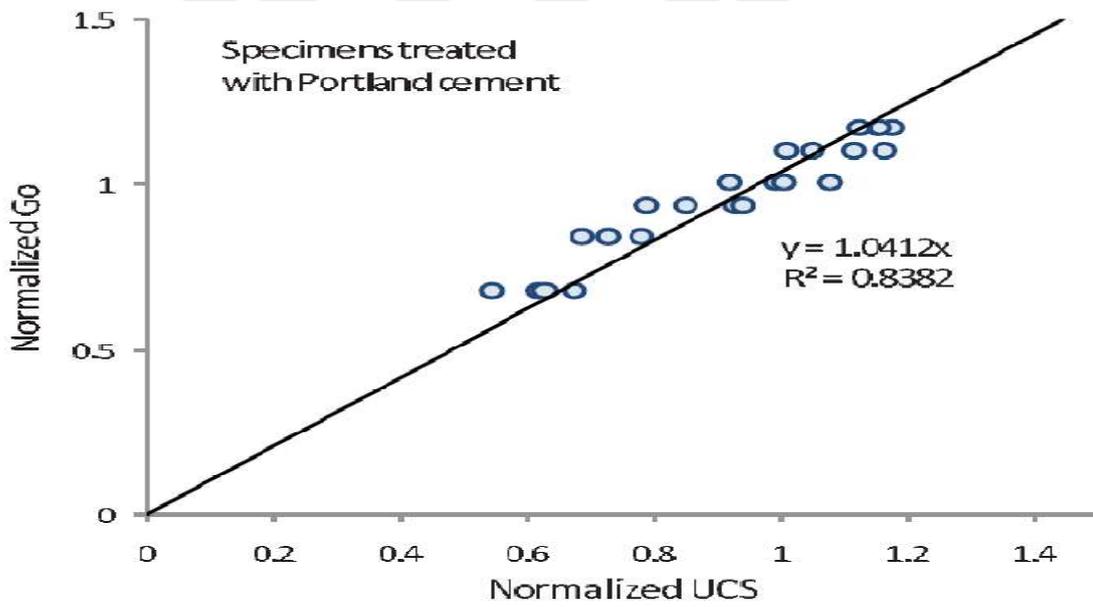


Figure 2.9. Normalized ( $G_0$ ) in function of normalized UCS for Portland cement treated soil [28]

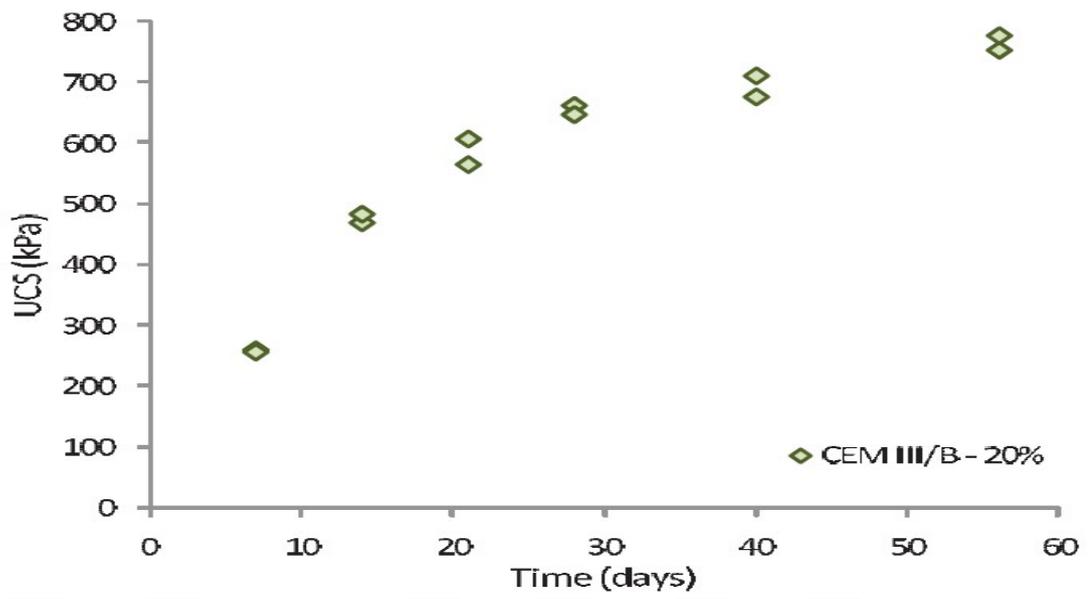


Figure 2.10. UCS with time for blastfurnace slag cement treated soil [28]

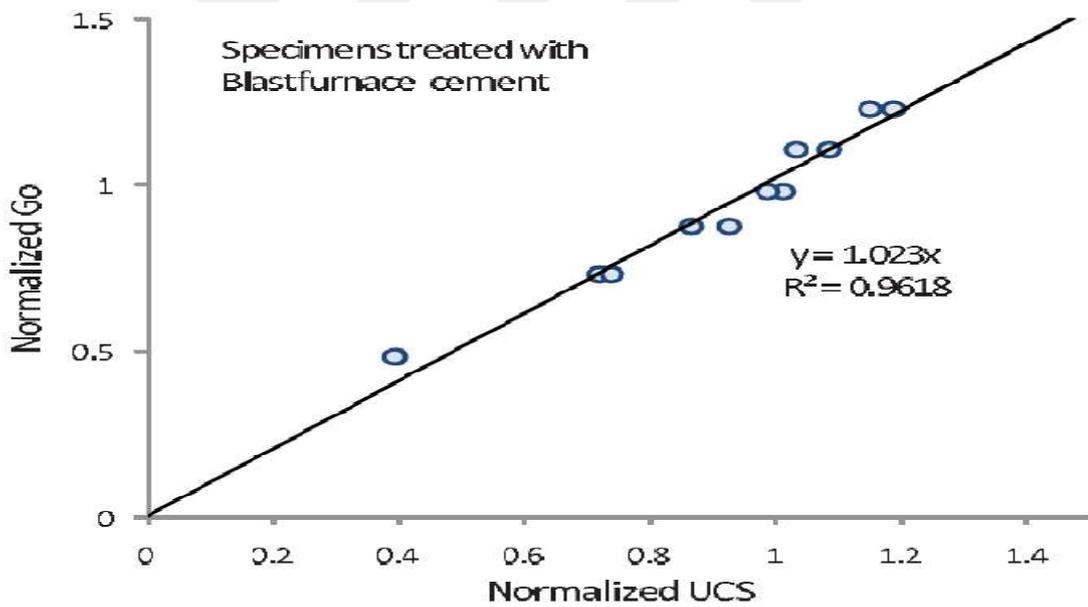


Figure 2.11. Normalized ( $G_0$ ) in function of normalized UCS for BSC treated soil [28]

### **2.2.6. The use of blastfurnace slag cement in soft soils**

Verástegui Flores [33] studied the suitability of deep dry mixing technology for common soft soils encountered in Flanders. Specifically, silty clay and organic silty clay (peat) were examined both in the laboratory and in the field. Based on laboratory research, it can be determined that blastfurnace slag cement can be used to stabilize the silty clay and peat. An improvement ratio of about 40.00 for the stabilized silty clay (after a curing time of about 60 days) was reached with a binder (150.00 kg/m<sup>3</sup>) consisting of 20.00% lime and 80.00% cement. This improvement ratio ranged from 2.00 to 3.00 after 90 days for peat.

The plasticity of the soil decreases by using lime and it facilitates the mixing process which leads to more homogeneous and strong soil-binder columns. In this case, only cement is mixed with soil and it hardly spreads uniformly. Therefore, a combination of lime and cement gives more effective results in plastic soils. However, the use of lime in organic soils does not play an important role [33].

### **2.2.7. Factors affecting the DSM material strength**

Terashi [34] specified the factors affecting the strength increment with time of stabilized soil using lime or cement as a binder. The reason is that the basic strength increment mechanism is correlated with chemical reactions between the soil and stabilizing agent. The weight ratio of water/binder has a significant influence on the mechanical and durability characteristics of the material [5, 34, 35].

Table 2.3 presents an overview of the different factors divided into four categories: Characteristics of the stabilizing agents, characteristics and condition of the soil, mixing conditions and curing conditions.

**Table 2.3.** *Factors affecting the strength increment of stabilized soil [34]*

|   |   |
|---|---|
| I. Characteristics of stabilizing agents                                    | 1. Type of stabilizing agent                              |
|   | 2. Quality  |
|   | 3. Mixing water and additives                             |
| II. Characteristics and conditions of soil (especially important for clays) | 1. Physical chemical and mineralogical properties of soil |
|   | 2. Organic content  |
|   | 3. pH of pore water                                       |
|   | 4. Water content  |
| III. Mixing conditions  | 1. Degree of mixing                                       |
|   | 2. Time of mixing/re-mixing                               |
|   | 3. Quantity of stabilizing agent                          |
| IV. Curing conditions   | 1. Temperature  |
|   | 2. Curing time  |
|   | 3. Humidity   |
|   | 4. Wetting and drying/freezing and thawing, etc.          |

It should be noted that the categories are given below;

- Category I strongly affect the strength increment of soil;
- Category II are usually impossible to change on site since these are inherent characteristics of the soil and the way it has been deposited;
- Category III are easily altered and controlled on site during the DSM;
- Category IV are easy to control in the laboratory but not on site [34, 35].

Regarding the characteristics of the soil, its nature has a large influence on the strength and uniformity of the DSM material. More specifically, soil inclusions can occur in the DSM material of which the amount depends on the soil conditions as a result of the mixing process [5]. Based on in situ created DSM piles, Denies and Van Lysebetten reported the following amounts of soil inclusions:

- Less than 3.50% in quaternary or tertiary sands
- Between 3.00 and 10.00% in silty soils and alluvial clays
- Up to 35.00% and higher in clayey soil with high organic content (peat) or in tertiary stiff clays (overconsolidated) [5].

In addition to the factors denoted by Terashi [34] demonstrated that the strength of a stabilized soil (soft peat and clay) also strongly depends on the magnitude of the initial load shortly after mixing. Because of this preloading, compression occurs such that the distance between the binder grains and the soil particles will reduce and facilitate the bonding of the hydration products.

### **3. MATERIAL**

#### **3.1. In-Situ Soft Soil**

Considering the objective of this study, soft peat and clayey soil were studied shown in Figures 3.1 and 3.2, respectively. Based on observations, it was found that the clayey soil has a dark grey colour, soft and sticky and has water content ranging between 55.00% and 86.00%. The peat has a black colour, a slight odour and a water content ranging between 100.00% and 428.00%. The clayey soil and peat were located at a depth ranging from 6.00 to 8.00 m and 4.50 to 6.50 m, respectively. In addition, the organic content of the peat and clayey soil were determined as a  $\pm 81.00\%$  and  $\pm 19.00\%$ , respectively.



**Figure 3.1.** *Sample of peat*



**Figure 3.2.** *Sample of clayey soil*

Localisation of the project site regarding the soft soil originated in Baanhofstraat, Ostend, Belgium is shown in Figure 3.3. Table 3.1 presents an overview of the clayey soil and peat used in this study from different borings.



**Figure 3.3.** Localisation of the project site regarding the soft soil origin

**Table 3.1.** Overview clayey soil and peat

|      | Depth(m) | Wet Density(g/cm <sup>3</sup> ) | Water Content (%) |
|------|----------|---------------------------------|-------------------|
| PEAT | 4.80     | 1.01                            | 428.77            |
|      | 4.80     | 1.44                            | 343.23            |
|      | 5.30     | 0.98                            | 385.55            |
|      | 5.30     | 1.02                            | 374.29            |
| CLAY | 6.30     | 1.57                            | 89.00             |
|      | 6.30     | 1.59                            | 66.84             |
|      | 7.00     | 1.58                            | 80.47             |
|      | 7.30     | 1.58                            | 73.25             |
|      | 7.80     | 1.72                            | 55.86             |
|      | 7.80     | 1.84                            | 65.92             |

### 3.2. Recycled Materials (RM)

The recycled material (RM) used in this study was provided by SLW Foundation Group shown in Figure 3.4. The RM originated from demolitions composed of mainly a mixture of crushed concrete, crushed mortar, crushed bricks and sand.



Figure 3.4. Sample of recycled material used in this study

The water content of RM was calculated to be 14.80 %, as the mean of three measurements. The particle size distribution of the RM measured on previous research is illustrated in Figure 3.5 and determined in accordance with ASTM D 422 – 63 [36]. Regarding the soil composition, RM contains 39.90% of gravel (> 2.00 mm), 49.90% of sand, 7.10% of silt and 3.10% of clay. The particle sizes of RM are given in Table 3.2.

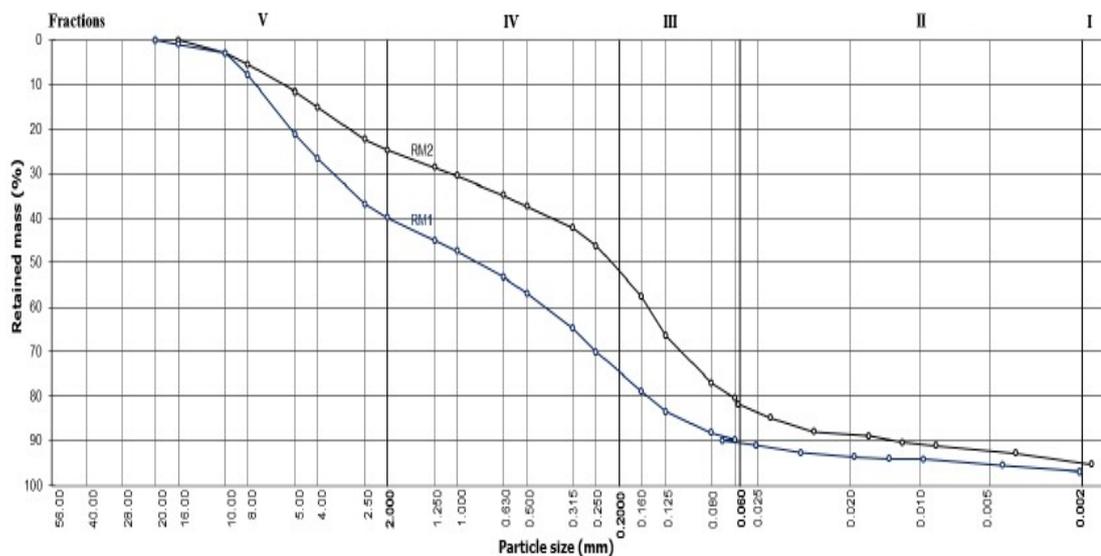


Figure 3.5. Particle size distribution of the recycled materials

**Table 3.2.** *Classification of RM constituents*

| Constituents       | RM (%) |
|--------------------|--------|
| Gravel (> 2.00 mm) | 39.90  |
| Sand               | 49.90  |
| Silt               | 7.10   |
| Clay               | 3.10   |

### 3.3. Blastfurnace Slag Cement (BSC)

BSC type CEM III/A 42.5 N LA was used in this study to strengthen the in-situ soft soil. BSC was preferred due to its intensely increasing strength after the first 28 days in this study. BSC consists of an intimate mixture of Portland cement and ground granulated blastfurnace slag. Chemically, slag composed of a mixture of lime, silica, and alumina. The amount of blastfurnace slag is ranging from 36 to 65%. Chemical compositions of the BSC used in this study are given in Table 3.3 as provided by the supplier. Additionally, the sample of BSC used in this study is given in Figure 3.6.

**Table 3.3.** *Chemical composition of BSC*

|                                |       |
|--------------------------------|-------|
| CaO                            | 52.20 |
| SiO <sub>2</sub>               | 25.80 |
| Al <sub>2</sub> O <sub>3</sub> | 8.10  |
| Fe <sub>2</sub> O <sub>3</sub> | 2.30  |
| MgO                            | 4.40  |
| Na <sub>2</sub> O              | 0.36  |
| K <sub>2</sub> O               | 0.60  |
| Na <sub>2</sub> O-eq           | 0.75  |
| SO <sub>3</sub>                | 3.10  |
| Cl <sup>-</sup>                | 0.08  |
| Other                          | 1.60  |



**Figure 3.6.** *Sample of BSC*

### **3.4. Distilled Water (DW)**

In this part of the study, DW was used to prepare mixtures and to clean all tools and instruments. DW was used to keep RM pumpable to the soil and adding of BSC according to the wet deep mixing method. The electrical conductivity and pH of the DW determined at a temperature of 21°C using the InoLab 720 device from WTW, and a pH-Meter CG840 from Schott, respectively. The electrical conductivity ( $\mu\text{S}/\text{cm}$ ) and pH for DW is measured 6.30 and 7.69, respectively.



**Figure 3.7.** *InoLab 720 device from WTW*

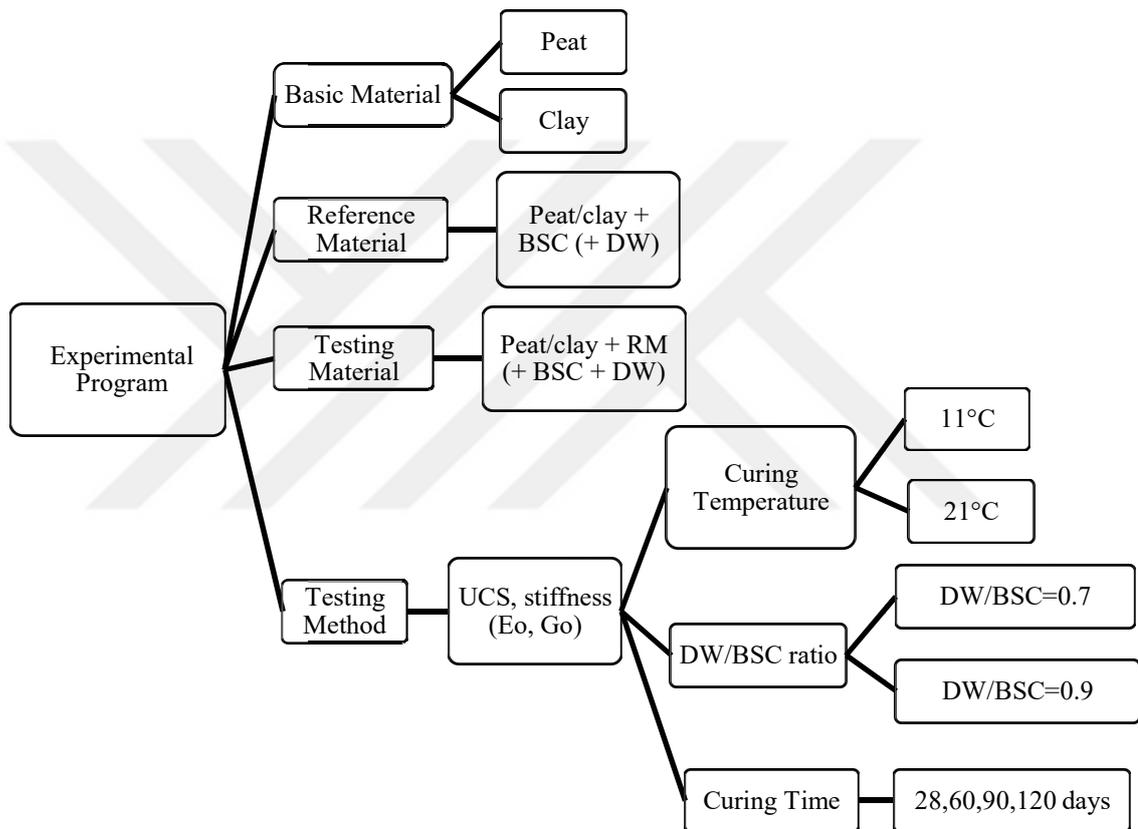


**Figure 3.8.** *pH Meter CGS40 from Schott*

## 4. EXPERIMENTAL PROGRAM AND METHODS

### 4.1. Introduction

In this chapter, RM in soft soil (peat and clayey soil) as an alternative for BSC were studied. Peat and clayey soil was chosen as a basic material. BSC and DW was added to the basic material. Obtained mixtures were compared with the basic materials strengthened with RM. The methodology of the experimental program of this study is given in Figure 4.1.



**Figure 4.1.** Overview of the experimental program

The effect of different parameters on the strength of stabilized soft soil with RM and BSC was investigated by using:

- The curing time,
- The curing temperature,
- Additional DW/BSC ratios of 0.7 and 0.9.

## 4.2. Experimental Program

The experimental procedure of the study is mainly focuses on the soft soils (peat and clayey soil) treated with crushed granular RM as an alternative for BSC. Tables 4.1 and 4.2 summarize the experimental program related with peat and clayey soil, respectively. Basically, the experimental program consists of two parts, for which the DW/BSC ratios of 0.7 and 0.9. It should be noted that required amount of DW given in Tables 4.1 and 4.2 is added to soft soils regardless with natural water content to obtain the DW/BSC ratios of 0.7 and 0.9. Moreover, the amounts of RM are the required quantities of laboratory mixing for the preparation of samples. Sample preparation method will be discussed in Chapter 4.

**Table 4.1.** *Experimental program for peat considering stiffness ( $G_0$  and  $E_0$ ) and UCS*

| Curing Degree | DW/BSC Ratio | Mixture Type | RM Amount (kg/m <sup>3</sup> ) | BSC Amount (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) | Curing Days | Number of Specimen |           |    |
|---------------|--------------|--------------|--------------------------------|---------------------------------|-------------------------|-------------|--------------------|-----------|----|
| Peat          | 0.0          | Dry Mixture  | 0                              | 300                             | 0                       | 7,14,28,    | 18                 |           |    |
|               |              |              | 0                              | 500                             | 0                       | 60,90,120   | 18                 |           |    |
|               | 0.7          | Wet Mixture  | 0                              | 300                             | 210                     | 28,60,90,   | 12                 |           |    |
|               |              |              | 0                              | 500                             | 350                     | 120         | 12                 |           |    |
|               | 10°C         | 0.7          | Wet Mixture&RM                 | 300                             | 300                     | 210         | 7,14,28,           | 18        |    |
|               |              |              |                                | 300                             | 500                     | 350         | 60,90,120          | 12        |    |
|               |              | 0.9          | Wet Mixture&RM                 | 500                             | 300                     | 210         |                    | 12        |    |
|               |              |              |                                | 500                             | 500                     | 350         |                    | 12        |    |
|               |              |              |                                | 900                             | 300                     | 210         | 28,60,90,          | 12        |    |
|               |              |              |                                | 900                             | 500                     | 350         | 120                | 12        |    |
|               |              |              |                                | 1200                            | 300                     | 210         |                    | 12        |    |
|               |              |              |                                | 1200                            | 500                     | 350         |                    | 12        |    |
|               |              | 20°C         | 0.7                            | Wet Mixture                     | 0                       | 300         | 270                | 28,60,90, | 12 |
|               |              |              |                                |                                 | 0                       | 500         | 450                | 120       | 12 |
|               | 0.9          |              | Wet Mixture&RM                 | 300                             | 300                     | 270         | 7,14,28,           | 18        |    |
|               |              |              |                                | 300                             | 500                     | 450         | 60,90,120          | 12        |    |
|               |              |              |                                | 900                             | 300                     | 270         | 28,60,90,          | 12        |    |
|               |              |              |                                | 900                             | 500                     | 450         | 120                | 12        |    |
|               |              |              |                                | 900                             | 300                     | 210         |                    | 12        |    |
|               |              |              |                                | 900                             | 500                     | 350         |                    | 12        |    |

**Table 4.2.** Experimental program for clayey soil considering stiffness ( $G_0$  and  $E_0$ ) and UCS

|      | Curing Degree    | DW/BSC Ratio | Mixture Type     | RM Amount (kg/m <sup>3</sup> ) | BSC Amount (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) | Curing Days           | Number of Specimen    |    |
|------|------------------|--------------|------------------|--------------------------------|---------------------------------|-------------------------|-----------------------|-----------------------|----|
| Clay | 10°C             | 0.0          | Dry Mixture      | 0                              | 100                             | 0                       | 7,14,28,<br>60,90,120 | 18                    |    |
|      |                  |              |                  | 0                              | 300                             | 0                       |                       | 18                    |    |
|      |                  |              |                  | 0                              | 500                             | 0                       |                       | 18                    |    |
|      |                  | 0.7          | Wet Mixture      | 0                              | 100                             | 70                      | 28,60,90,<br>120      | 12                    |    |
|      |                  |              |                  | 0                              | 300                             | 210                     |                       | 12                    |    |
|      |                  |              |                  | 0                              | 500                             | 350                     |                       | 12                    |    |
|      |                  |              | Wet Mixture & RM | 100                            | 100                             | 70                      | 28,60,90,<br>120      | 12                    |    |
|      |                  |              |                  | 100                            | 300                             | 210                     |                       | 12                    |    |
|      |                  |              |                  | 100                            | 500                             | 350                     |                       | 12                    |    |
|      |                  |              | Wet Mixture & RM | 300                            | 100                             | 70                      | 28,60,90,<br>120      | 12                    |    |
|      |                  |              |                  | 300                            | 300                             | 210                     |                       | 7,14,28,<br>60,90,120 | 18 |
|      |                  |              |                  | 300                            | 500                             | 350                     |                       | 28,60,90,<br>120      | 12 |
|      |                  |              | Wet Mixture & RM | 500                            | 100                             | 70                      | 28,60,90,<br>120      | 12                    |    |
|      |                  |              |                  | 0                              | 300                             | 270                     |                       | 28,60,90,<br>120      | 12 |
|      |                  |              |                  | 0                              | 500                             | 450                     |                       |                       | 12 |
|      |                  |              | Wet Mixture & RM | 100                            | 300                             | 270                     | 28,60,90,<br>120      |                       | 12 |
|      |                  |              |                  | 300                            | 100                             | 90                      |                       | 12                    |    |
|      |                  |              |                  | 300                            | 300                             | 270                     |                       | 7,14,28,<br>60,90,120 | 18 |
|      | Wet Mixture & RM | 300          | 500              | 450                            | 28,60,90,<br>120                | 12                      |                       |                       |    |
|      |                  | 20°C         | 0.7              | Wet Mixture & RM               | 300                             | 300                     | 210                   | 7,14,28,<br>60,90,120 | 18 |

The dry mixing for peat given in Table 4.1 was used as a reference for both DW/BSC ratios of 0.7 and 0.9. Dry mixing samples were prepared according to the dry deep soil mixing method in which the native soil (peat) was mixed with BSC without additional DW. Two dry mixtures are evaluated by using 300 kg/m<sup>3</sup> and 500 kg/m<sup>3</sup> BSC. The water content of these samples was resulting from the natural water content of the peat. RM of 300 kg/m<sup>3</sup> and 900 kg/m<sup>3</sup> were used for both 0.7 and 0.9 DW/BSC ratios to examine the impact of RM on the peat more clearly. Additionally, 300 kg/m<sup>3</sup> and 500 kg/m<sup>3</sup> BSC were used for these mixtures, respectively. Moreover, 500 kg/m<sup>3</sup> and 1200 kg/m<sup>3</sup> RM were evaluated for DW/BSC ratio of 0.7. On the other hand, the effect of temperature was studied for peat. The samples were prepared using 500 kg/m<sup>3</sup> RM and 300 kg/m<sup>3</sup> BSC with DW/BSC ratio of 0.7 and stored at 20°C.

Dry Mixture samples in Table 4.2 were prepared according to the dry DSM method such that the native soil was mixed with BSC without additional DW. The water content in these samples was resulting from the natural water content of the native soft soil. Additional DW was added to obtain a DW/BSC ratios of 0.7 and 0.9 for these samples containing RM. 300 kg/m<sup>3</sup> and 300 kg/m<sup>3</sup> BSC with 0.7 DW/BSC ratio was used and stored at 20°C storage temperature to evaluate the effect of temperature on clayey soil. All mixtures were evaluated after curing time of 28, 60, 90 and 120 days. Certain mixtures given in Tables 4.1 and 4.2 were also cured at 7 and 14 days for comparison with the previous study.

### 4.3. Material Preparation

Domo DO9070KR Mixer was used to mix the materials shown in Figure 4.2. The mixing was carried out at about 350 rpm such that level 3 for Domo Mixer until a visually material mixed homogeneously. The procedure is given below.

First, native soil was mixed homogeneously for 30 seconds. Then, BSC added to the soil and then mixed for 2 minutes. Finally, DW and/or RM added to the final mixture and mixed for 3 minutes.

Note that a spatula was used to dislodge any soil sticking to the edges of the mixing bowl. Dry mixture, contains neither DW nor RM, was prepared and the mixing time of soil and BSC was about 3 minutes. The mixing time was kept to a minimum to avoid excessive stiffening of the mixture during material preparation as a result of cement hydration. The Euro Soil Stab [22] also reports the limit of mixing time to prevent destruction of peat fibres.



**Figure 4.2.** *Domo DO9070KR Mixer*

### 4.3.1. Material composition

The required amounts for material preparation were described for each mixture type in Tables 4.1 and 4.2. However, it was already noted that these amounts were expressed relatively to the amount of soil. The latter was determined for a reference volume of 196.35 cm<sup>3</sup>, equal to the optimal dimensions of a cylindrical test specimen. Using the sample preparation, the final composition of the samples depend on the compactability of the mixture. An overview of the material composition of all peat and clayey test samples is presented in Tables 4.3, 4.4, 4.5, 4.6 and 4.7.

Table 4.3. Material composition of peat samples for BSC content: 300 kg/m<sup>3</sup>

| Mixture Type | BSC content (kg/m <sup>3</sup> ) | RM Content (kg/m <sup>3</sup> ) | DW/ BSC Ratio |           | Soil (kg/m <sup>3</sup> ) | RM (kg/m <sup>3</sup> ) | BSC (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) |
|--------------|----------------------------------|---------------------------------|---------------|-----------|---------------------------|-------------------------|--------------------------|-------------------------|
| Dry Mixture  | 300                              | 0                               | 0.0           | Mean      | 1066.55                   | 0.00                    | 278.17                   | 0.00                    |
|              |                                  |                                 |               | % by mass | 79.31                     | 0.00                    | 20.69                    | 0.00                    |
| Wet Mixture  | 300                              | 0                               | 0.7           | Mean      | 899.43                    | 0.00                    | 234.58                   | 164.21                  |
|              |                                  |                                 |               | % by mass | 69.28                     | 0.00                    | 18.07                    | 12.65                   |
|              |                                  | 300                             | 0.7           | Mean      | 800.36                    | 208.74                  | 208.76                   | 146.12                  |
|              |                                  |                                 |               | % by mass | 58.68                     | 15.30                   | 15.31                    | 10.71                   |
|              |                                  | 500                             | 0.7           | Mean      | 764.56                    | 332.35                  | 199.41                   | 139.58                  |
|              |                                  |                                 |               | % by mass | 53.24                     | 23.15                   | 13.89                    | 9.72                    |
|              |                                  | 900                             | 0.7           | Mean      | 720.46                    | 563.71                  | 187.90                   | 131.53                  |
|              |                                  |                                 |               | % by mass | 44.93                     | 35.15                   | 11.72                    | 8.20                    |
|              |                                  | 1200                            | 0.7           | Mean      | 678.76                    | 704.50                  | 176.12                   | 123.29                  |
|              |                                  |                                 |               | % by mass | 40.34                     | 41.87                   | 10.47                    | 7.33                    |
|              |                                  | 0                               | 0.9           | Mean      | 840.53                    | 0.00                    | 219.22                   | 197.30                  |
|              |                                  |                                 |               | % by mass | 66.87                     | 0.00                    | 17.44                    | 15.70                   |
|              |                                  | 300                             | 0.9           | Mean      | 780.96                    | 203.68                  | 203.69                   | 183.32                  |
|              |                                  |                                 |               | % by mass | 56.94                     | 14.85                   | 14.85                    | 13.36                   |
|              |                                  | 900                             | 0.9           | Mean      | 683.12                    | 534.49                  | 178.50                   | 160.35                  |
|              |                                  |                                 |               | % by mass | 44.89                     | 34.34                   | 11.47                    | 10.30                   |

Note that the amounts are expressed in terms of mass of material per unit volume of test specimen. Also remark that these amounts were determined based on the wet mass and volume before testing. Homogeneous mixtures were also obtained after the material preparation.

**Table 4.4.** Material composition of peat samples for BSC content: 500 kg/m<sup>3</sup>

| Mixture Type | BSC content (kg/m <sup>3</sup> ) | RM Content (kg/m <sup>3</sup> ) | DW/ BSC Ratio |           | Soil (kg/m <sup>3</sup> ) | RM (kg/m <sup>3</sup> ) | BSC (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) |
|--------------|----------------------------------|---------------------------------|---------------|-----------|---------------------------|-------------------------|--------------------------|-------------------------|
| Dry Mixture  | 500                              | 0                               | 0.0           | Mean      | 1009.4                    | 0.00                    | 439.01                   | 0.00                    |
|              |                                  |                                 |               | % by mass | 69.69                     | 0.00                    | 30.31                    | 0.00                    |
| Wet Mixture  | 500                              | 0                               | 0.7           | Mean      | 765.68                    | 0.00                    | 332.83                   | 232.98                  |
|              |                                  |                                 |               | % by mass | 57.51                     | 0.00                    | 25.00                    | 17.49                   |
|              |                                  | 300                             | 0.7           | Mean      | 699.30                    | 182.38                  | 303.97                   | 212.44                  |
|              |                                  |                                 |               | % by mass | 50.02                     | 13.04                   | 21.74                    | 15.20                   |
|              |                                  | 500                             | 0.7           | Mean      | 669.91                    | 290.12                  | 291.20                   | 203.84                  |
|              |                                  |                                 |               | % by mass | 46.04                     | 19.94                   | 20.01                    | 14.01                   |
|              |                                  | 900                             | 0.7           | Mean      | 658.15                    | 514.41                  | 286.09                   | 200.05                  |
|              |                                  |                                 |               | % by mass | 39.68                     | 31.01                   | 17.25                    | 12.06                   |
|              |                                  | 1200                            | 0.7           | Mean      | 564.67                    | 589.09                  | 245.45                   | 171.82                  |
|              |                                  |                                 |               | % by mass | 35.94                     | 37.50                   | 15.62                    | 10.94                   |
|              |                                  | 0                               | 0.9           | Mean      | 710.20                    | 0.00                    | 308.72                   | 277.84                  |
|              |                                  |                                 |               | % by mass | 54.77                     | 0.00                    | 23.81                    | 21.43                   |
| 300          | 0.9                              | Mean                            | 664.26        | 173.25    | 288.75                    | 259.87                  |                          |                         |
|              |                                  | % by mass                       | 47.92         | 12.50     | 20.83                     | 18.75                   |                          |                         |
| 900          | 0.9                              | Mean                            | 582.21        | 455.54    | 253.08                    | 227.77                  |                          |                         |
|              |                                  | % by mass                       | 38.34         | 30.00     | 16.66                     | 15.00                   |                          |                         |

**Table 4.5.** Material composition of clayey samples for BSC content: 100 kg/m<sup>3</sup>

| Mixture Type | BSC content (kg/m <sup>3</sup> ) | RM Content (kg/m <sup>3</sup> ) | DW/ BSC Ratio |           | Soil (kg/m <sup>3</sup> ) | RM (kg/m <sup>3</sup> ) | BSC (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) |
|--------------|----------------------------------|---------------------------------|---------------|-----------|---------------------------|-------------------------|--------------------------|-------------------------|
| Dry Mixture  | 100                              | 0                               | 0.0           | Mean      | 1487.12                   | 0.00                    | 90.31                    | 0.00                    |
|              |                                  |                                 |               | % by mass | 94.27                     | 0.00                    | 5.73                     | 0.00                    |
| Wet Mixture  | 100                              | 0                               | 0.7           | Mean      | 1438.22                   | 0.00                    | 87.34                    | 61.14                   |
|              |                                  |                                 |               | % by mass | 90.64                     | 0.00                    | 5.51                     | 3.85                    |
|              |                                  | 100                             | 0.7           | Mean      | 1366.45                   | 82.98                   | 82.98                    | 58.09                   |
|              |                                  |                                 |               | % by mass | 85.91                     | 5.22                    | 5.22                     | 3.65                    |
|              |                                  | 300                             | 0.7           | Mean      | 1285.54                   | 234.21                  | 78.07                    | 54.65                   |
|              |                                  |                                 |               | % by mass | 77.80                     | 14.17                   | 4.72                     | 3.31                    |
|              |                                  | 500                             | 0.7           | Mean      | 1210.38                   | 367.52                  | 73.50                    | 51.45                   |
|              |                                  |                                 |               | % by mass | 71.08                     | 21.58                   | 4.32                     | 3.02                    |
|              |                                  | 300                             | 0.9           | Mean      | 1343.98                   | 244.85                  | 81.62                    | 73.46                   |
|              |                                  |                                 |               | % by mass | 77.07                     | 14.04                   | 4.68                     | 4.21                    |

**Table 4.6.** Material composition of clayey samples for BSC content: 500 kg/m<sup>3</sup>

| Mixture Type | BSC content (kg/m <sup>3</sup> ) | RM Content (kg/m <sup>3</sup> ) | DW/ BSC Ratio |           | Soil (kg/m <sup>3</sup> ) | RM (kg/m <sup>3</sup> ) | BSC (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) |
|--------------|----------------------------------|---------------------------------|---------------|-----------|---------------------------|-------------------------|--------------------------|-------------------------|
| Dry Mixture  | 500                              | 0                               | 0.0           | Mean      | 1263.93                   | 0.00                    | 383.78                   | 0.00                    |
|              |                                  |                                 |               | % by mass | 76.71                     | 0.00                    | 23.29                    | 0.00                    |
| Wet Mixture  | 500                              | 0                               | 0.7           | Mean      | 1030.62                   | 0.00                    | 312.94                   | 219.06                  |
|              |                                  |                                 |               | % by mass | 65.96                     | 0.00                    | 20.03                    | 14.02                   |
|              |                                  | 100                             | 0.7           | Mean      | 1036.95                   | 62.97                   | 314.86                   | 220.40                  |
|              |                                  |                                 |               | % by mass | 63.42                     | 3.85                    | 19.25                    | 13.48                   |
|              |                                  | 300                             | 0.7           | Mean      | 968.65                    | 176.48                  | 294.13                   | 205.89                  |
|              |                                  |                                 |               | % by mass | 58.88                     | 10.73                   | 17.88                    | 12.51                   |
|              |                                  | 0                               | 0.9           | Mean      | 979.29                    | 0.00                    | 297.35                   | 267.62                  |
|              |                                  |                                 |               | % by mass | 63.41                     | 0.00                    | 19.25                    | 17.33                   |
|              |                                  | 300                             | 0.9           | Mean      | 958.53                    | 174.63                  | 291.05                   | 261.95                  |
|              |                                  |                                 |               | % by mass | 56.85                     | 10.36                   | 17.26                    | 15.53                   |

**Table 4.7.** Material composition of clayey samples for BSC content: 300 kg/m<sup>3</sup>

| Mixture Type | BSC content (kg/m <sup>3</sup> ) | RM Content (kg/m <sup>3</sup> ) | DW/ BSC Ratio |           | Soil (kg/m <sup>3</sup> ) | RM (kg/m <sup>3</sup> ) | BSC (kg/m <sup>3</sup> ) | DW (kg/m <sup>3</sup> ) |
|--------------|----------------------------------|---------------------------------|---------------|-----------|---------------------------|-------------------------|--------------------------|-------------------------|
| Dry Mixture  | 300                              | 0                               | 0.0           | Mean      | 1386.63                   | 0.00                    | 252.63                   | 0.00                    |
|              |                                  |                                 |               | % by mass | 84.59                     | 0.00                    | 15.41                    | 0.00                    |
| Wet Mixture  | 300                              | 0                               | 0.7           | Mean      | 1196.55                   | 0.00                    | 217.99                   | 152.60                  |
|              |                                  |                                 |               | % by mass | 76.35                     | 0.00                    | 13.91                    | 9.73                    |
|              |                                  | 100                             | 0.7           | Mean      | 1180.59                   | 71.70                   | 215.09                   | 150.56                  |
|              |                                  |                                 |               | % by mass | 72.97                     | 4.43                    | 13.29                    | 9.31                    |
|              |                                  | 300                             | 0.7           | Mean      | 1086.48                   | 197.94                  | 197.94                   | 138.56                  |
|              |                                  |                                 |               | % by mass | 67.03                     | 12.21                   | 12.21                    | 8.55                    |
|              |                                  | 0                               | 0.9           | Mean      | 1130.11                   | 0.00                    | 205.89                   | 185.30                  |
|              |                                  |                                 |               | % by mass | 74.29                     | 0.00                    | 13.53                    | 12.18                   |
|              |                                  | 100                             | 0.9           | Mean      | 1128.40                   | 68.53                   | 205.58                   | 185.02                  |
|              |                                  |                                 |               | % by mass | 71.08                     | 4.32                    | 12.95                    | 11.65                   |
| 300          | 0.9                              | Mean                            | 1032.83       | 188.17    | 188.17                    | 169.35                  |                          |                         |
|              |                                  | % by mass                       | 65.43         | 11.92     | 11.92                     | 10.73                   |                          |                         |

#### 4.4. Sample Preparation

This section describes the preparation method of cylindrical test specimens with a height of 100.00 mm and a diameter of 50.00 mm. Samples were prepared according to the following method. After sample preparation, all samples were tightly sealed in plastic wrap and stored in a humid box and conditioned at a room temperature of  $10\pm 1^\circ\text{C}$  and/or a room temperature of  $20\pm 1^\circ\text{C}$ . It is noted that each batch of prepared soil was formed into a sample within 30 minutes after mixing according to the procedure given in the Euro Soil Stab [22].

##### 4.4.1. Method

The sample preparation method used in this study is based on the compaction method as proposed in the Euro Soil Stab [22]. The compaction mould and tools are shown in Figure 4.3.



**Figure 4.3.** *The compaction mould and tools*

The set-up of the compaction method used in this study is presented in Figure 4.4, in which a cylindrical steel mould with a height of 100.00 mm and a diameter of 50.00 mm was clamped to a steel base plate. A cling wrap was placed at the bottom of the steel mould and compressed by rubber ring to avoid losses of soil and water during compaction. In this method, compaction was done using a steel massive cylinder that

perfectly fits into the mould. In this method the test specimens were made of 10 layers having a thickness of approximately 10.00 mm.

Full compaction method started with placing of an amount of material in the mould using a spoon and poured it into the mold to obtain 10.00 mm compacted layer after compaction. Next, the steel cylinder was positioned into the mould and an additional mass was loaded on it for 3 seconds, resulting into a mass of 98.00 kPa in total. Then, the loads were removed and the material was unloaded for 5 seconds. This cycle of loading-unloading was executed five times for each compacted layer. Then, a scratch was used on the compressed layer with a depth of approximately 2.00 mm, to ensure a sufficient bonding with the next layer. This procedure was repeated until the mould was filled. Then the bottom and top plane of the cylindrical specimen were levelled and the sample wrapped by cling wrap to minimize contact with air and to prevent water loss.



**Figure 4.4.** *The set-up of compaction*

Then, the specimen hardened during 60 min at a temperature of  $20\pm 2^{\circ}\text{C}$ . Afterwards, the sample was extruded using a Hydraulic Extruder HS 16.06 of HEICO.

The procedure is given below;

- Material placed into the mould.

- 98.00 kPa mass was loaded on the material for 3 seconds and the material was unloaded for 5 seconds. This cycle repeated 5 times for each layer.
- A cross was cutted in the compacted layer.
- This first 3 steps followed until the mould is filled.
- The specimen wrapped by cling wrap and hardened 60 minutes at a room temperature of  $20\pm 2^{\circ}\text{C}$ .
- The sample extruded using Hydraulic Extruder machine.

## 4.5. Testing Method

### 4.5.1. Free-free resonance

The small-strain stiffness is a significant parameter for a variety of geotechnical design applications that may also be used as an indirect indication of other soil parameters. In this study, small-strain stiffness modulus in longitudinal ( $E_0$ ) and transversal direction ( $G_0$ ) were determined using the free-free resonant frequency method. Free-free resonant frequency method is a good alternative of bender/extender element testing method due to its simplicity.

In this method, the test specimen are laid down horizontally on top of a soft foam layer to approach fully free boundary conditions. A light hammer used to actuate the test specimens. Then, the vibrational response of the specimen was captured with an accelerometer or an acoustic meter placed against one end of the sample, while the other end is impacted with a light hammer. Figures 4.5 and 4.6 illustrate the set-up for measuring the fundamental frequency of vibration in the longitudinal (axial) and transversal directions as a result of an impact. Following this method, the small-strain modulus can be calculated as:

$$E_0 = \rho \cdot v_p^2 = \rho \cdot (2 \cdot L \cdot f_L)^2 \quad (4.1)$$

$$G_0 = \rho \cdot v_s^2 = \rho \cdot (2 \cdot L \cdot f_T)^2 \quad (4.2)$$

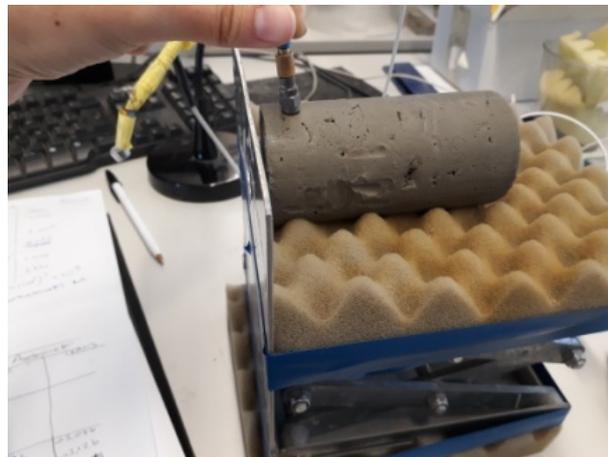
where  $\rho$  is the bulk density,  $L$  is the length of specimen,  $f_L$  is the longitudinal resonant frequency,  $f_T$  is the transversal resonant frequency,  $v_p$  is the compressive wave velocity and  $v_s$  is the shear wave velocity. It is marked that both formulas evaluated by assuming the wavelength ( $\lambda$ ) of the vibrating specimen is equal to twice the length of

the sample for which is only valid for the free–free resonant testing specimens having  $D/L \leq 0.5$  (Diameter / Length  $\leq 0.5$ ).

Figures 4.5 and 4.6 show an example of the determination of the frequency of a specimen using an accelerometer. In this study, the resonant frequency in longitudinal and transversal directions was evaluated using both an accelerometer and an acoustic meter.



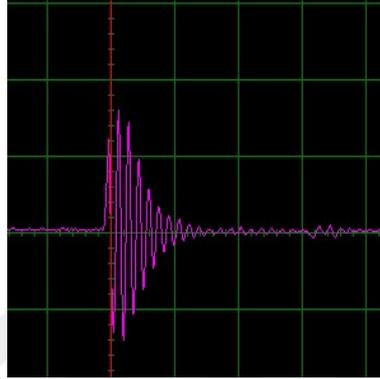
**Figure 4.5.** *Laboratory set-up in longitudinal direction*



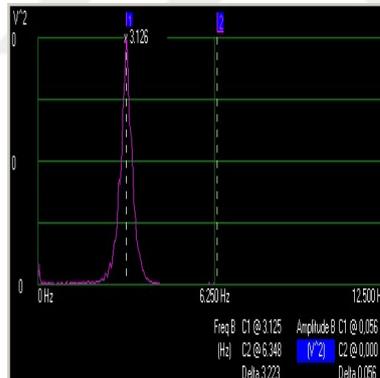
**Figure 4.6.** *Laboratory set-up in transversal direction*

Figure 4.7 shows an example of a measured impact, which decays in time, in longitudinal direction. The specimen used on this example is a clay wet mixture without RM having DW/BSC ratio of 0.7 with BSC content of  $100 \text{ kg/m}^3$ . Samples are measured in longitudinal direction using acoustic meter after 60 days curing time. Fourier transform performed on this signal in the frequency domain and presented in

Figure 4.8. This result indicates that the longitudinal mode shape is relevant with a frequency of 3.126 kHz. The accelerometer used in this study to determine the vibrational response of the specimen is a type of PCB A353B68 with a frequency range up to 10 kHz. The selected foam has a density of 21 kg/m<sup>3</sup> and an approximate Young's modulus of 20 kPa in this study.



**Figure 4.7.** Example of a measured impact signal with decay using an acoustimeter (Wet Mixture - DW/BSC: 0.7- BSC: 100kg/m<sup>3</sup> - RM:0 kg/m<sup>3</sup> clay after 60 days) in time domain



**Figure 4.8.** Example of a Fourier transformed measured impact signal using an acoustimeter (Wet Mixture - DW/BSC: 0.7- BSC: 100kg/m<sup>3</sup> - RM:0 kg/m<sup>3</sup> clay after 60 days) in frequency domain

$E_0$  (small-strain stiffness modulus in longitudinal direction) and  $G_0$  (small-strain stiffness modulus in transversal direction) can be calculated for the example given in Figures 4.7 and 4.8 by using the equation 4.1 and 4.2 , respectively.  $E_0$  and  $G_0$  was calculated 0.75 GPa and 0.27 GPa as a mean value of three measurement, respectively.

#### 4.5.2. Unconfined compressive strength (UCS)

The unconfined compressive strength test was conducted according to the ASTM D 2166 – 00 [37] and the UCS of the specimens were measured. A constant axial strain for the UCS test was fixed at 0.50 mm/min. Wykeham Farrance type Tritech 50 compression machine was used in this study. In the compression test, the specimens were taken out to avoid completely breaking maximum load. Figure 4.9 illustrates the set-up of UCS test and the sample used in the figure is an example of dry mixture of clayey soil with 300 kg/m<sup>3</sup> BSC. Three same blocks were used to raise the sample in the experimental set-up shown in Figure 4.9.



**Figure 4.9.** UCS testing device and set-up

## 5. RESULTS AND DISCUSSIONS

In this study, the possible reuse of crushed granular RM as an alternative for BSC in the deep soil mixing method is evaluated.

### 5.1. Preliminary Research

In Chapter 3, the origin of the studied peat and clayey soil was outlined. These soil layers were selected based on a preliminary laboratory study conducted by Meeusen [38] of the subsoil for the considered project site discussed in this section.

#### 5.1.1. Soil investigation

Based on the thesis of Meeusen [38] two continuous borings B1 and B7 were executed by the SLW foundations group considering the laboratory study. The sampled soil from the borings B1 and B7 is given in Figures 5.1 and 5.2, respectively. Note that the ground level is indicated with 'GL' in the left upper corner of both figures. Also remark that the soil layering in Figures 5.1 and 5.2 should be interpreted as follows: starting from the left, the base of each pair of samples follows on the top of the next pair of samples.



**Figure 5.1.** Soil layers resulting from boring B1 [38]



**Figure 5.2.** Soil layers resulting from boring B7 [38]

Besides the continuous borings, undisturbed samples were also taken at specific depths for more in-deep laboratory testing by using thin-walled shelly tubes. Each sample was stored in a steel tube with a length of 0.50 m and a diameter of 0.10 m shown in Figure 5.3. Note that the sampling of the tubes was obtained near the locations of the borings B1 and B7. As a result, a distinction between ‘Tubes B1’ and ‘Tubes B7’ will be made.



**Figure 5.3.** Soil sampling at specified depths [38]

Table 5.1 provides an overview of the depths for which tests were carried out. Note that penetrometer tests were carried out on the top surface of the vane samples.

**Table 5.1.** *Overview of the terrain depth for each test sample [38]*

| Depth (m)          | Location B1 |       |       | Location B7 |       |       |
|--------------------|-------------|-------|-------|-------------|-------|-------|
|                    | SS1-B       | SS2-A | SS3-A | SS4-B       | SS5-A | SS6-A |
| Mean depth of tube | 1.88        | 4.27  | 6.04  | 1.68        | 4.98  | 6.28  |
| Oedometer          | 1.78        | 5.00  | 5.89  | 1.73        | 5.04  | 6.28  |
| Vane               | 1.90        | 5.07  | 5.99  | 1.80        | 5.15  | 6.35  |
| Penetrometer       | 1.90        | 5.07  | 5.99  | 1.80        | 5.15  | 6.35  |
| UCS                | 1.68        | 4.91  | 6.19  | 1.60        | 4.93  | 6.17  |

## 5.1.2. Physical properties

### 5.1.2.1. Organic content and water content

Figures 5.4 and 5.5 show the organic content (muffle furnace) and water content over depth, respectively. The organic content was determined according to ASTM D 4373–96 [39]. The water content was determined after drying the material at 105°C. Note that both parameters were determined using the soil from the continuous borings B1 and B7 shown in Figures 5.1 and 5.2, respectively. Undisturbed samples were also taken to verify the obtained results. It should also be remarked that ‘the depth’ should be considered as the mean depth of the considered soil layer. The mean depth of the samples presented in Table 5.1. As it can be seen from Figure 4.3 that a high organic content was measured at a depth of 5.75 m.

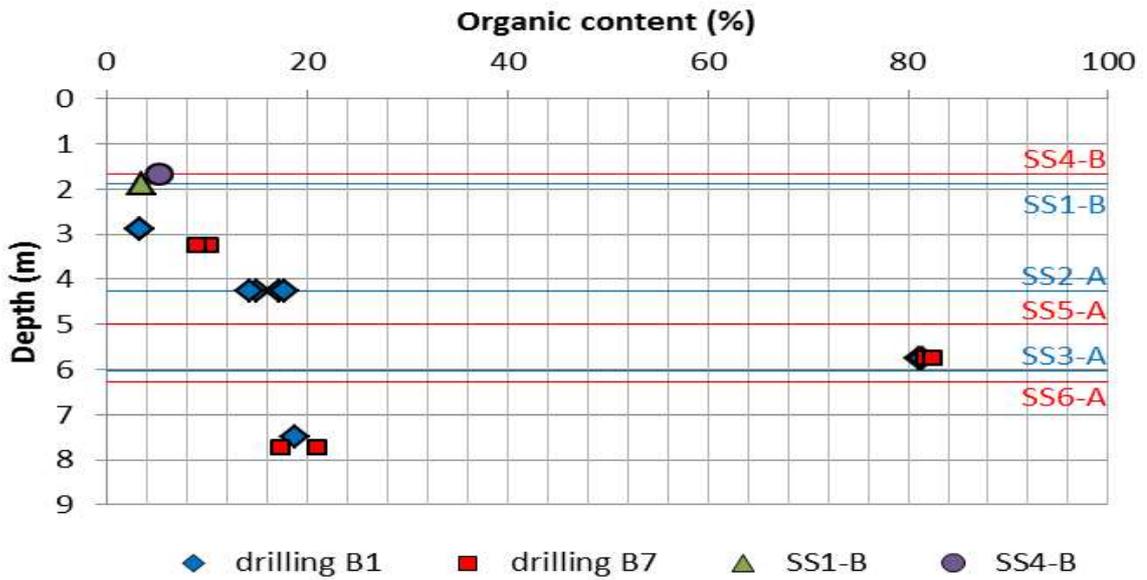


Figure 5.4. Variations of the organic content (muffle furnace) with depth [38]

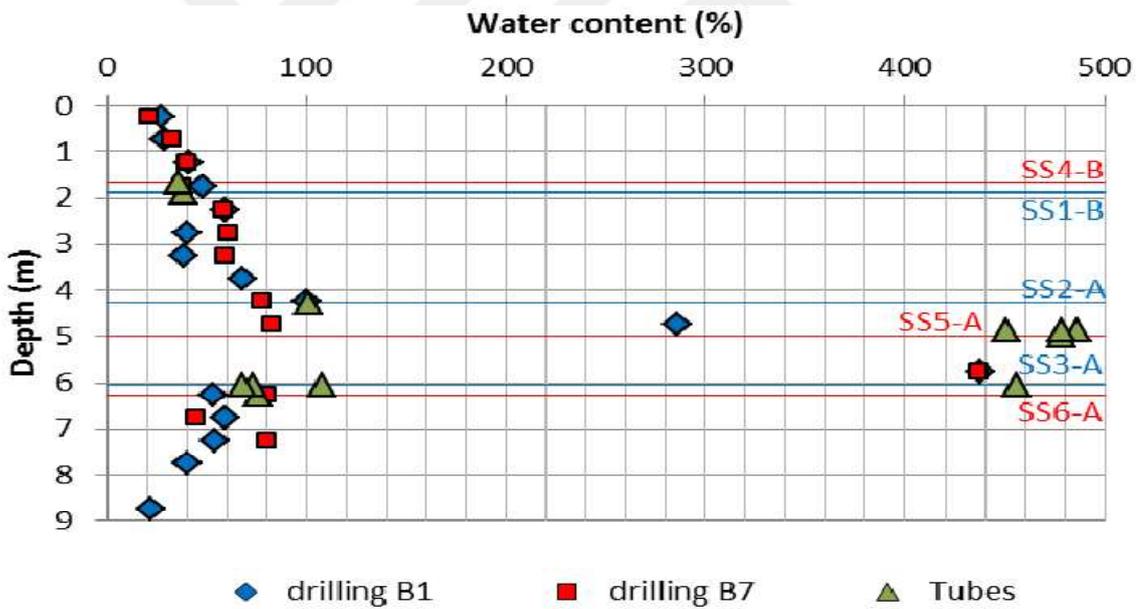


Figure 5.5. Variations of the water content with depth[38]

### 5.1.2.2. Wet and dry density

The wet and dry density with depth are shown in Figures 5.6 and 5.7, respectively. Note that the wet density was calculated from oedometer samples. The dry density was determined using the corresponding wet density and water content. Remark that the dry density corresponds to the state in which the soil is dewatered, but still the total volume remains constant.

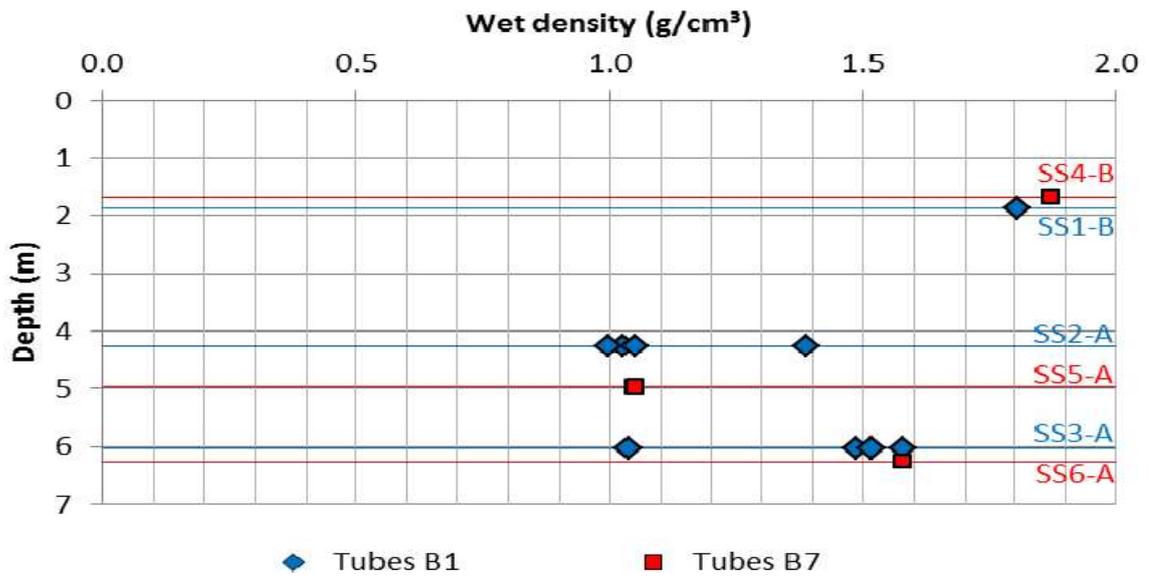


Figure 5.6. Variations of the wet density with depth

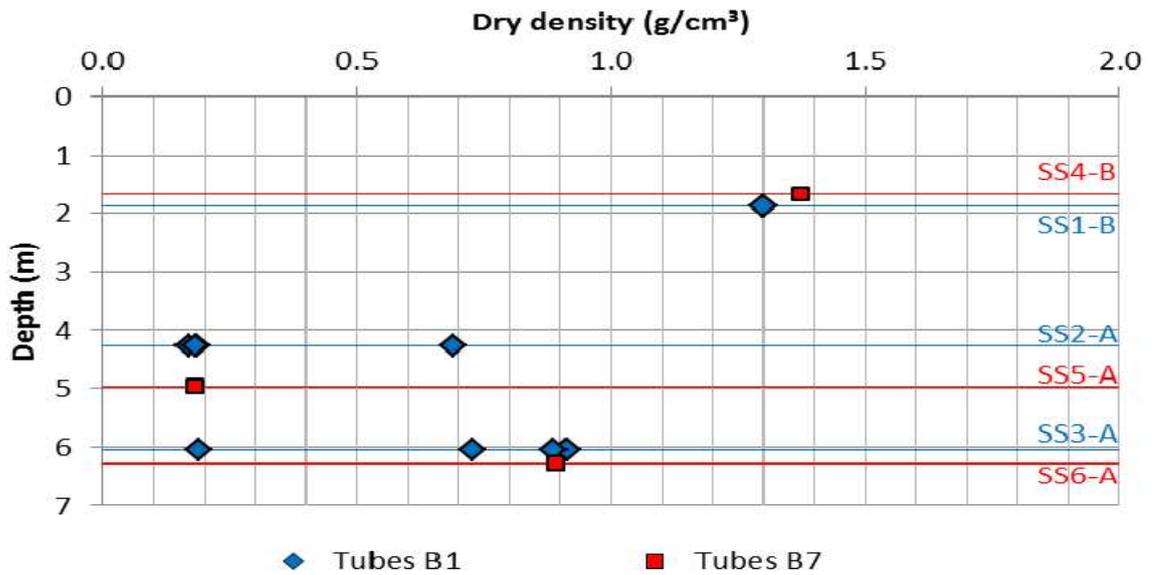


Figure 5.7. Variations of the dry density with depth

### 5.1.2.3. Atterberg limits and soil classification

An overview of the Atterberg limits and organic content determined according to ASTM D 4318 [40] and ASTM D 2974 [41], respectively and the results of the clayey soil at various reference depths is shown in Table 5.2. Based on these properties and the results of executed aerometer tests based on ASTM D 422 – 63 [36], the clayey soil is also classified according to ASTM D 2487 [42] as indicated in Table 5.2.

**Table 5.2.** *Atterberg limits and organic content [38]*

|       | Liquid Limit (%) | Plastic Limit (%) | Plasticity Index (%) | Average organic content (%) | Classification |
|-------|------------------|-------------------|----------------------|-----------------------------|----------------|
| SS1-B | 44.70            | 26.00             | 18.70                | 3.49                        | Lean Clay      |
| SS4-B | 57.30            | 28.90             | 28.40                | 5.18                        | Elastic Silt   |
| SS5-A | 62.10            | 46.90             | 15.20                | 11.8                        | Elastic Silt   |
| SS6-A | 48.80            | 29.60             | 19.20                | 3.38                        | Lean Clay      |

### 5.1.2.4. Visual inspection and organic content of peat samples

An observation was made on peat samples according to ASTM D 2487 [42] before performing oedometer tests. Table 5.3 presents the results of the observations. In addition, the water content and organic content are also shown in Table 5.3. The water content was determined after drying of the material at 105°C and the organic content was determined according to ASTM D 4373–96 [39]. Note that the presented organic content is only indicative and is the mean of the organic content values for the peat shown in Figure 5.4. The wet density was also calculated based on the mass and volume of each test specimen.

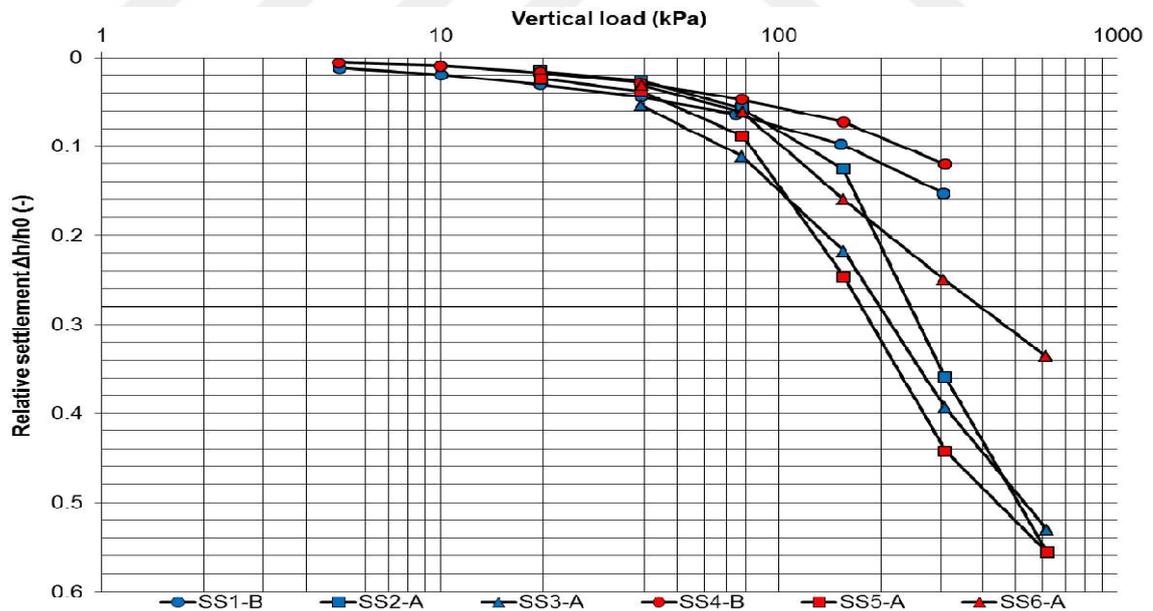
According to ASTM D 2974 [41], peat has higher organic content which is exceeding 75.00% compared to other organic soils. It could be concluded that samples are classified as a full peat based on the test results of the organic content.

**Table 5.3.** Observation of peat samples [38]

| Sample | Odour | Colour            | Fibres | Vegetable tissue | Water content(%) | Organic content (%) | Wet density (g/cm <sup>3</sup> ) |
|--------|-------|-------------------|--------|------------------|------------------|---------------------|----------------------------------|
| SS2-A  | light | light/dark brown  | no     | no               | 101.20           | 81.70               | 1.39                             |
| SS3-A  | light | dark brown        | no     | no               | 455.82           | 81.70               | 1.04                             |
| SS5-A  | light | light/dark brown  | no     | no               | 478.43           | 81.70               | 1.05                             |
| SS2-B1 | light | dark brown /black | yes    | yes              | 451.22           | 81.70               | 1.03                             |
| SS2-B2 | light | dark brown /black | yes    | yes              | 486.32           | 81.70               | 1.00                             |
| SS2-B3 | light | dark brown /black | yes    | yes              | 478.31           | 81.70               | 1.05                             |

### 5.1.2.5. Results of regular oedometer tests

The results indicate that mainly the SS2-A and SS5-A samples are very compressible. A relative settlement of more than 50.00% is occurred under the load of 600.00 kPa. These samples were already evaluated to be a peat with a high water content (up to 486.00%) and a low wet density.



**Figure 5.8.** Overview of the regular oedometer test results for borings B1 and B7

However, a relative settlement of 50.00% was recorded for the SS3-A sample. On the contrary, a relative settlement of 35.00% is obtained for the SS6-A sample (located ± 40.00 cm deeper in the subsoil. In this way, the latter is more resistant to the applied

loads in terms of compressibility. The SS3-A sample was also evaluated to be a peat and is in this way as compressible as the SS2-A and SS5-A sample. On the contrary, the SS6-A sample was evaluated to be a clayey soil.

From the above statement, it can be concluded that the peat is much more compressible compared to the clayey soil. On the contrary, it should again be noted that the peat around the SS2-A and SS5-A depth was evaluated to have a higher undrained shear strength by average.

Comparing SS1-B and SS4-B, a similar behaviour is noticed. For these samples, the compressibility is lower than the other tested specimens. The SS1-B and SS4-B samples were evaluated to be a clayey soil without any presence of peat, while the SS6-A was evaluated to be a mixture of clay and peat. Comparing the clayey soil SS6-A with the SS1-B and SS4-B, following conclusions can be drawn;

- A lower organic content (about 15.00% by average, see Figure 5.4) emphasizes that no peat was observed for these samples;
- A lower water content (40.00% compared to 60.00%);
- A higher wet and dry density (Figure 5.6 and Figure 5.7);
- A lower water content (about 20.00% lower by average, see Figure 5.5).

The combination of the above confirms the lower compressibility of the SS1-B and SS4-B clayey soil compared to the peat containing clayey soil (SS6-A).

## **5.2. Research to the Use of Recycled Materials**

In this section, the possible use of the granular RM as an alternative for BSC in the deep soil mixing method will be examined. To use RM in ground improvement projects as an alternative for replacing cement contributes to save money and energy and to reduce the environmental impact of producing new material. In particular, this part of the study focusses on the impact of RM, temperature and the DW/BSC ratio on the original weak soft soil. Strength and stiffness properties are also evaluated.

Based on the preliminary study of the subsoil, it was decided to examine the peat and the clayey soil. Note that basic properties of both soils were already mentioned in Chapter 3. Also remark that sample preparation method was used the same for all samples.

### 5.2.1. Visual inspection

It was found that the clayey mixtures were very difficult to compact when the additional water was added, i.e. mixtures WM<sup>1</sup>, WM-RM-DW/BSC:0.7<sup>2</sup> and WM-RM-DW/BSC:0.9<sup>3</sup>. Although it was found that the clayey mixtures having DW/BSC<sup>4</sup>:0.9 were significantly difficult to compact due to the high water content comparing the mixtures having DW/BSC:0.7. No difficulties regarding compactability were noticed for the peat samples having DW/BSC:0.7. However, it was observed that for peat samples having DW/BSC:0.9 were also difficult to compact. Figures 5.9 and 5.10 present visualisation of clayey samples having DW/BSC:0.7 and DW/BSC:0.9, respectively.



**Figure 5.9.** Example of clayey sample (WM-DW/BSC: 0.7 - BSC: 300 kg/m<sup>3</sup>)



**Figure 5.10.** Example of clayey sample (WM-DW/BSC: 0.9 - BSC: 300 kg/m<sup>3</sup>)

---

<sup>1</sup> WM: Wet mixture.

<sup>2</sup> WM - RM - DW/BSC : 0.7 : Wet mixture with recycled material and distilled water/blastfurnace slag cement ratio is 0.7.

<sup>3</sup> WM - RM - DW/BSC : 0.9 : Wet mixture with recycled material and distilled water/blastfurnace slag cement ratio is 0.9.

<sup>4</sup> DW/BSC: Ratio of distilled water to blastfurnace slag cement.

### 5.2.2. Wet density and water content

Considering the peat mixtures, Figures 5.11 and 5.12 show the water content versus wet density for samples having DW/BSC ratio of 0.7. Figures 5.13 and 5.14 show the water content versus wet density for peat samples having DW/BSC ratio of 0.9. Both parameters were determined from the test specimens. Specifically, the water content was determined after drying at 105°C.

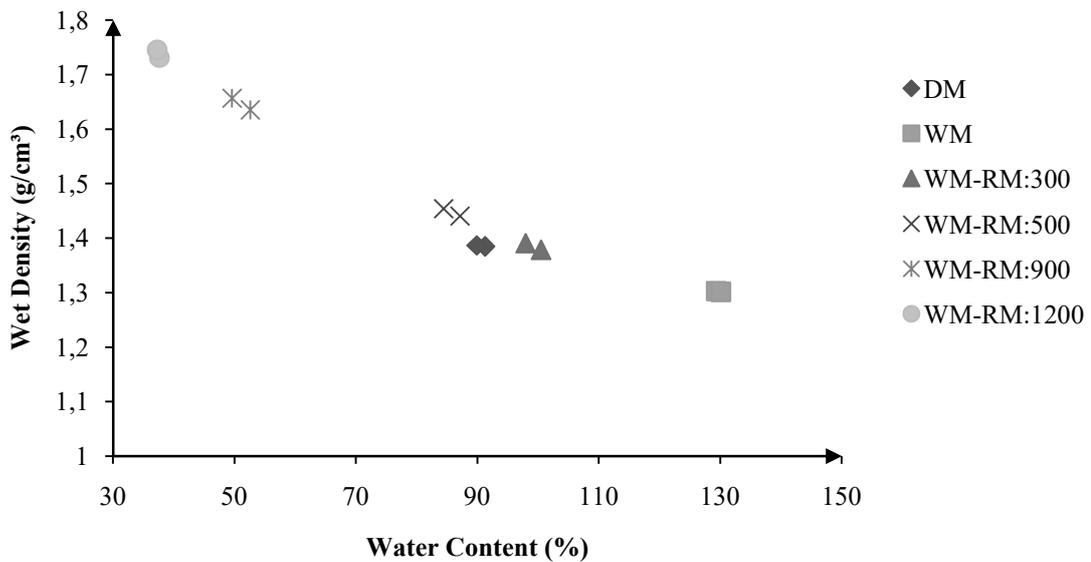


Figure 5.11. Wet density versus water content for peat samples DW/BSC:0.7- BSC:300 kg/m<sup>3</sup>

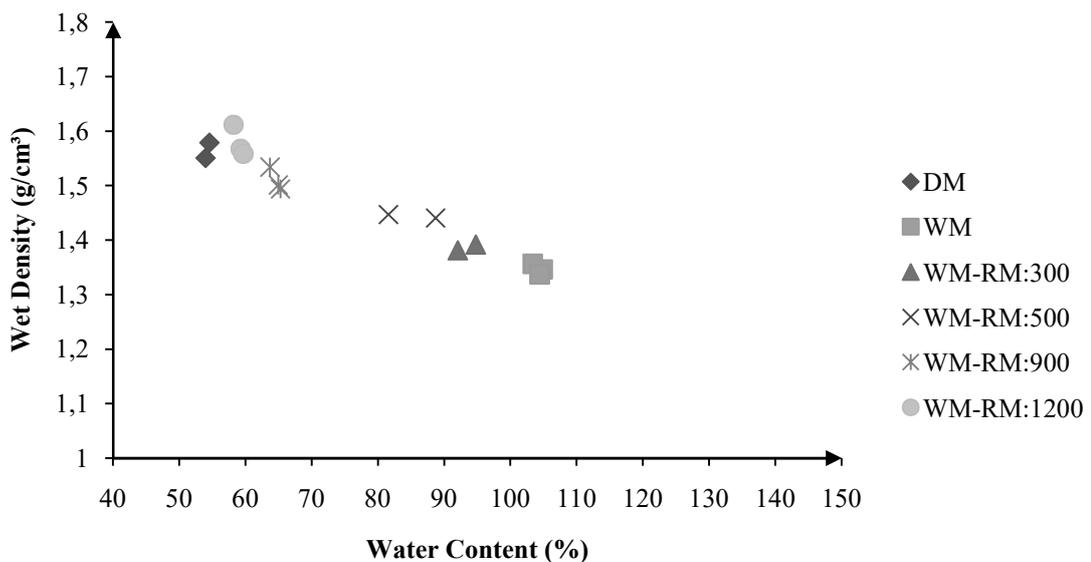


Figure 5.12. Wet density versus water content for peat samples DW/BSC:0.7- BSC:500 kg/m<sup>3</sup>

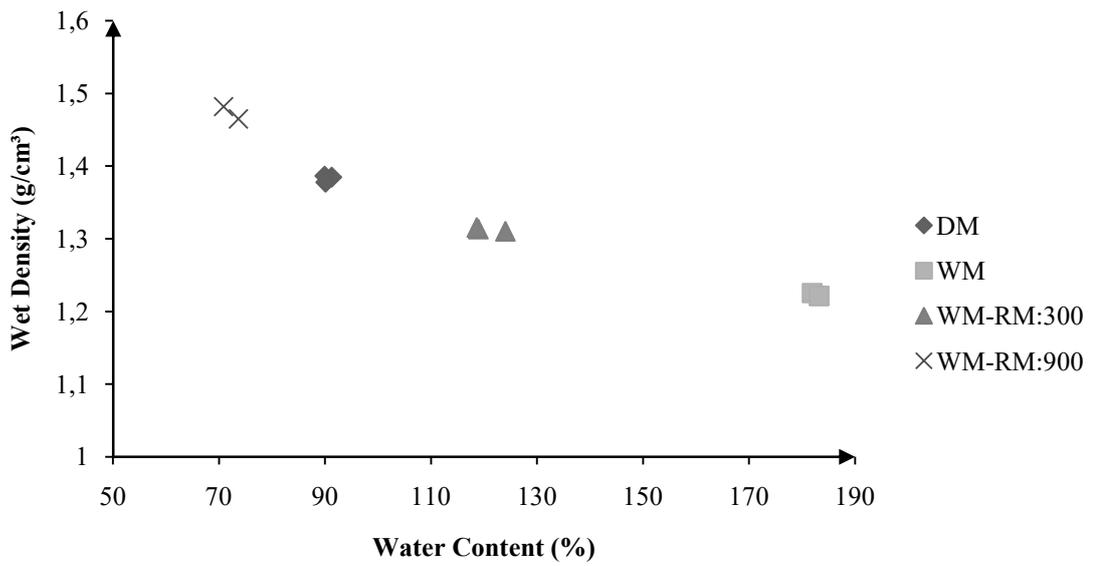


Figure 5.13. Wet density versus water content for peat samples DW/BSC:0.9- BSC:300 kg/m<sup>3</sup>

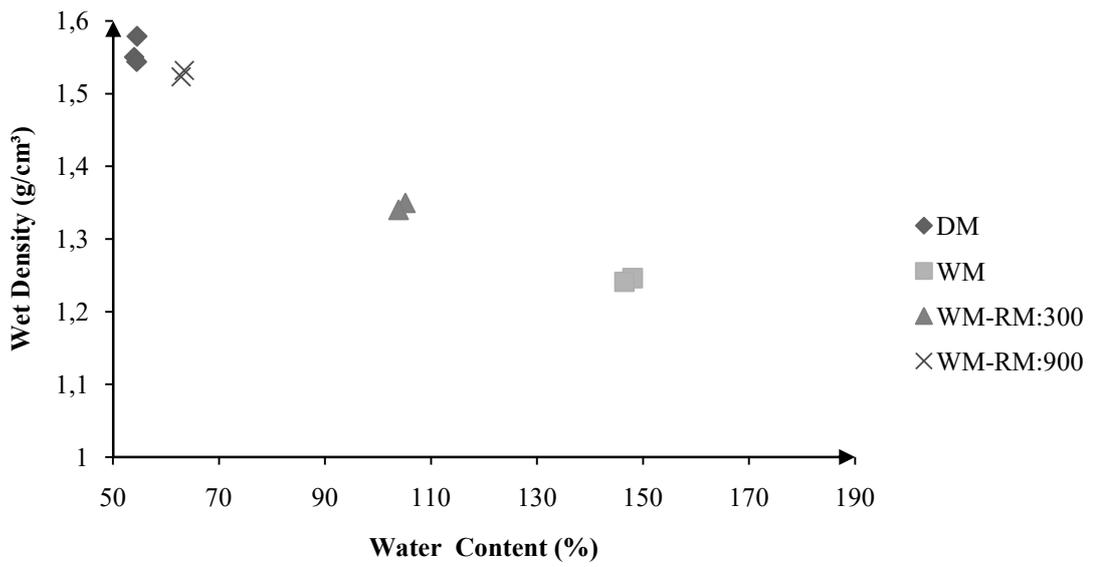
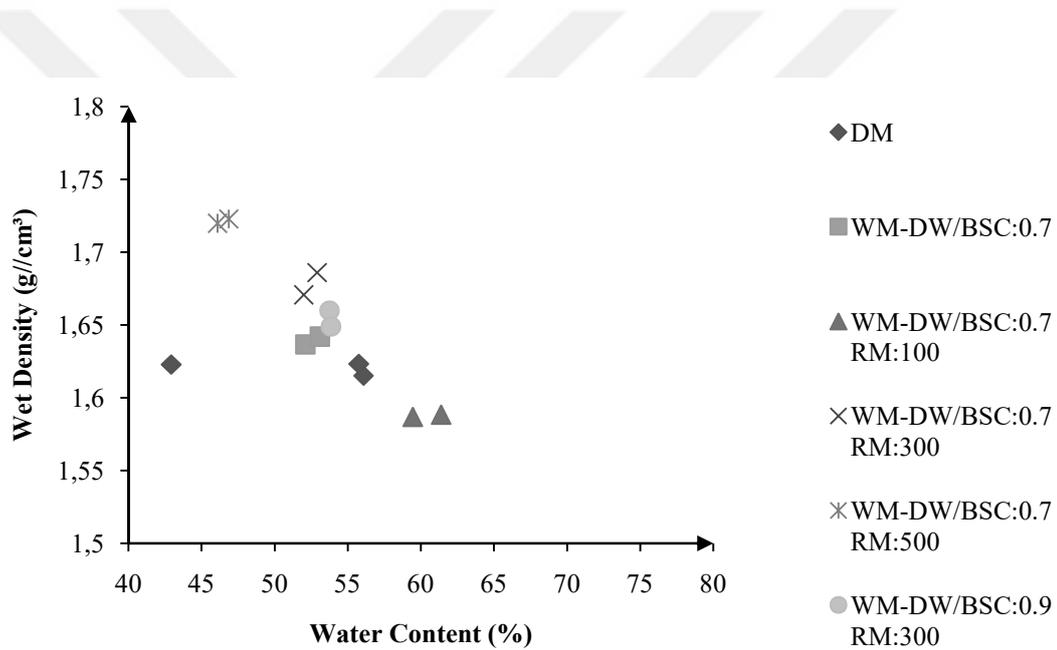


Figure 5.14. Wet density versus water content for peat samples DW/BSC:0.9- BSC:500 kg/m<sup>3</sup>

From these graphs the following conclusions can be drawn;

- It appears that the wet density and water content were quite consistent for different peat samples of each mixture type.
- The water content of the cemented peat ranges from 30.00 to 180.00% which is still quite high values. This illustrates the appearance of quite a high content of unbounded water in the samples which is detrimental with respect to the mechanical behaviour of the soil.
- The highest water content is observed on WM samples.
- Increasing the amount of RM reduces the water content, therefore the lowest water content is measured from RM:1200 kg/m<sup>3</sup> samples.



**Figure 5.15.** Wet density versus water content for clayey samples BSC:100 kg/m<sup>3</sup>

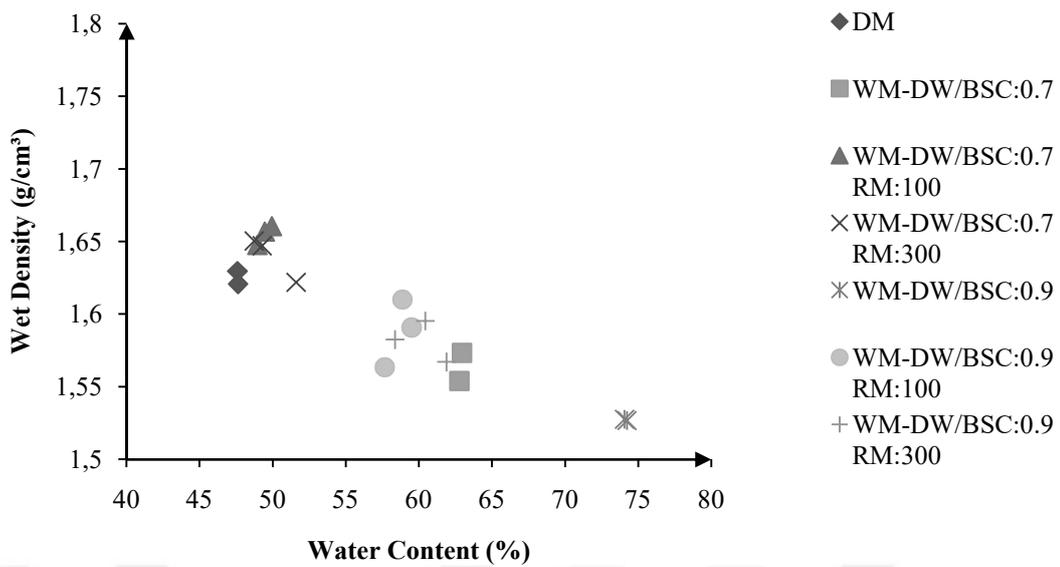


Figure 5.16. Wet density versus water content for clayey samples BSC:300 kg/m<sup>3</sup>

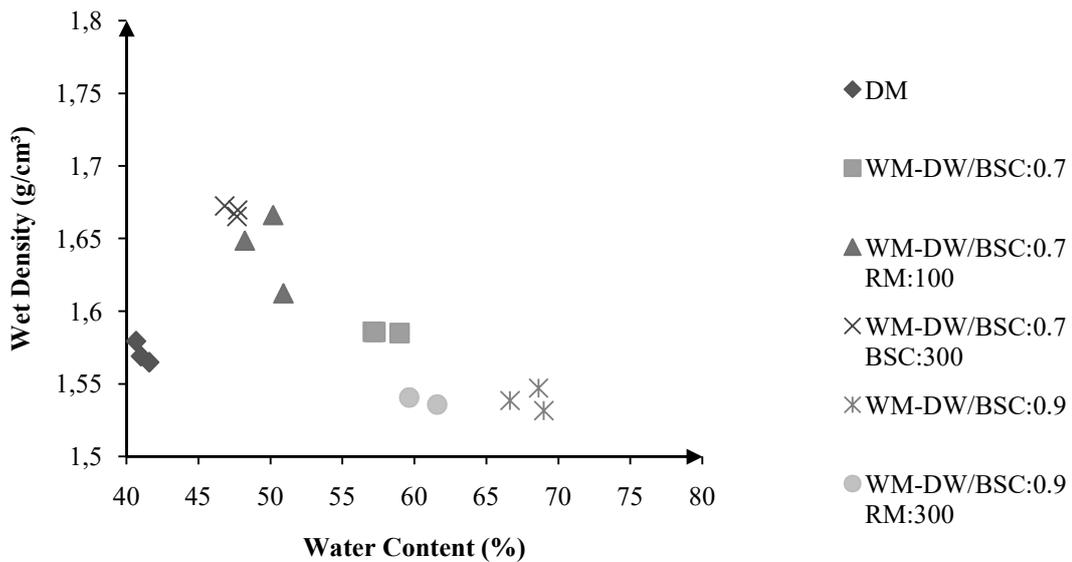


Figure 5.17. Wet density versus water content for clayey samples BSC:500 kg/m<sup>3</sup>

From above graphs, the following conclusions can also be drawn;

- It appears that the wet density and water content were quite consistent for different clayey samples of each mixture type.
- The water content of the cemented clayey soil ranges from 40 to 80%.
- Increasing the amount of RM reduces the water content, therefore the lowest water content is observed from RM:500 kg/m<sup>3</sup> samples.

### 5.2.3. Strength properties

#### 5.2.3.1. Unconfined compressive strength with curing time

The UCS values with curing time is shown in Figures 5.18 and 5.19 for peat and clayey soil samples, respectively.

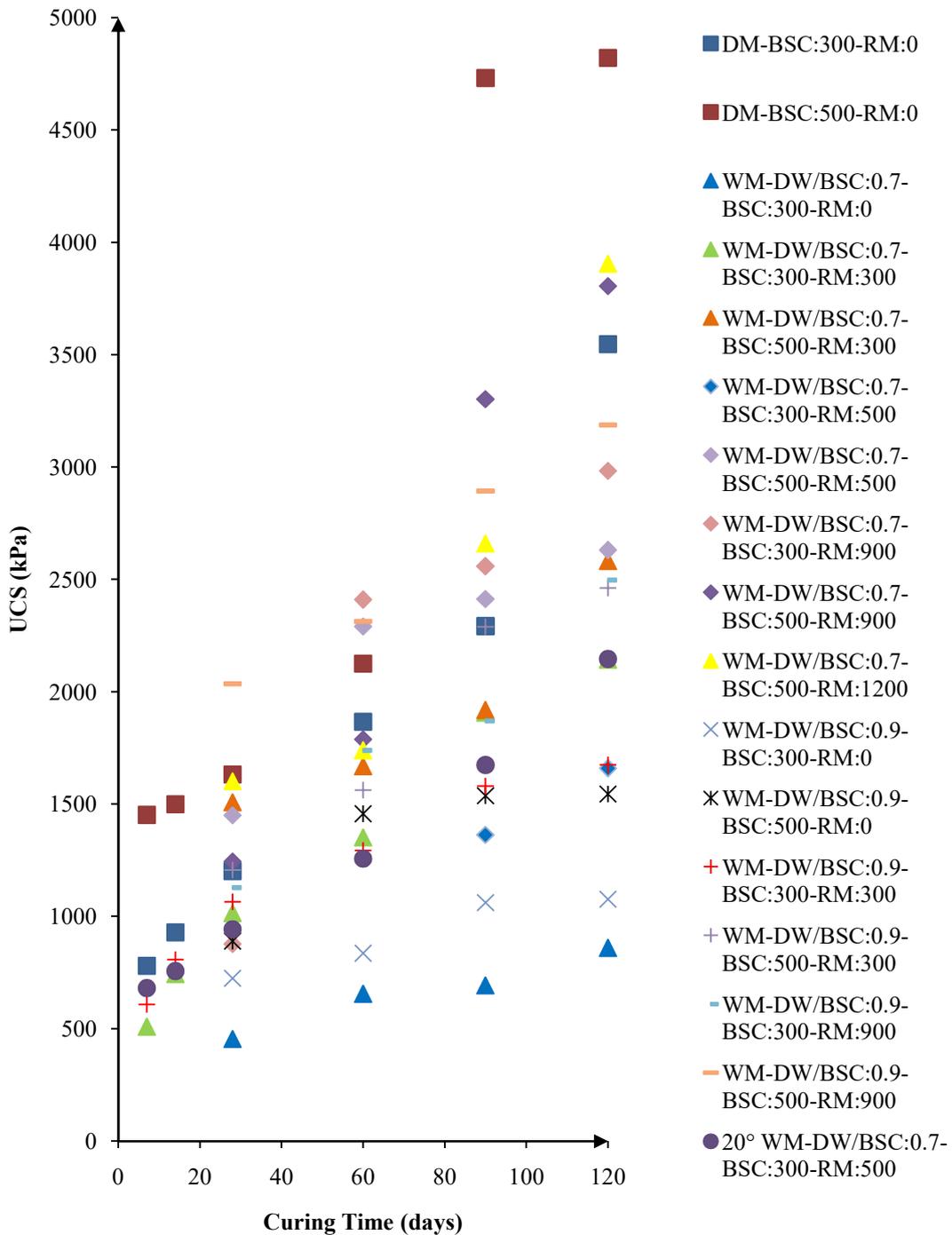


Figure 5.18. UCS versus curing time (peat at 10° storage)

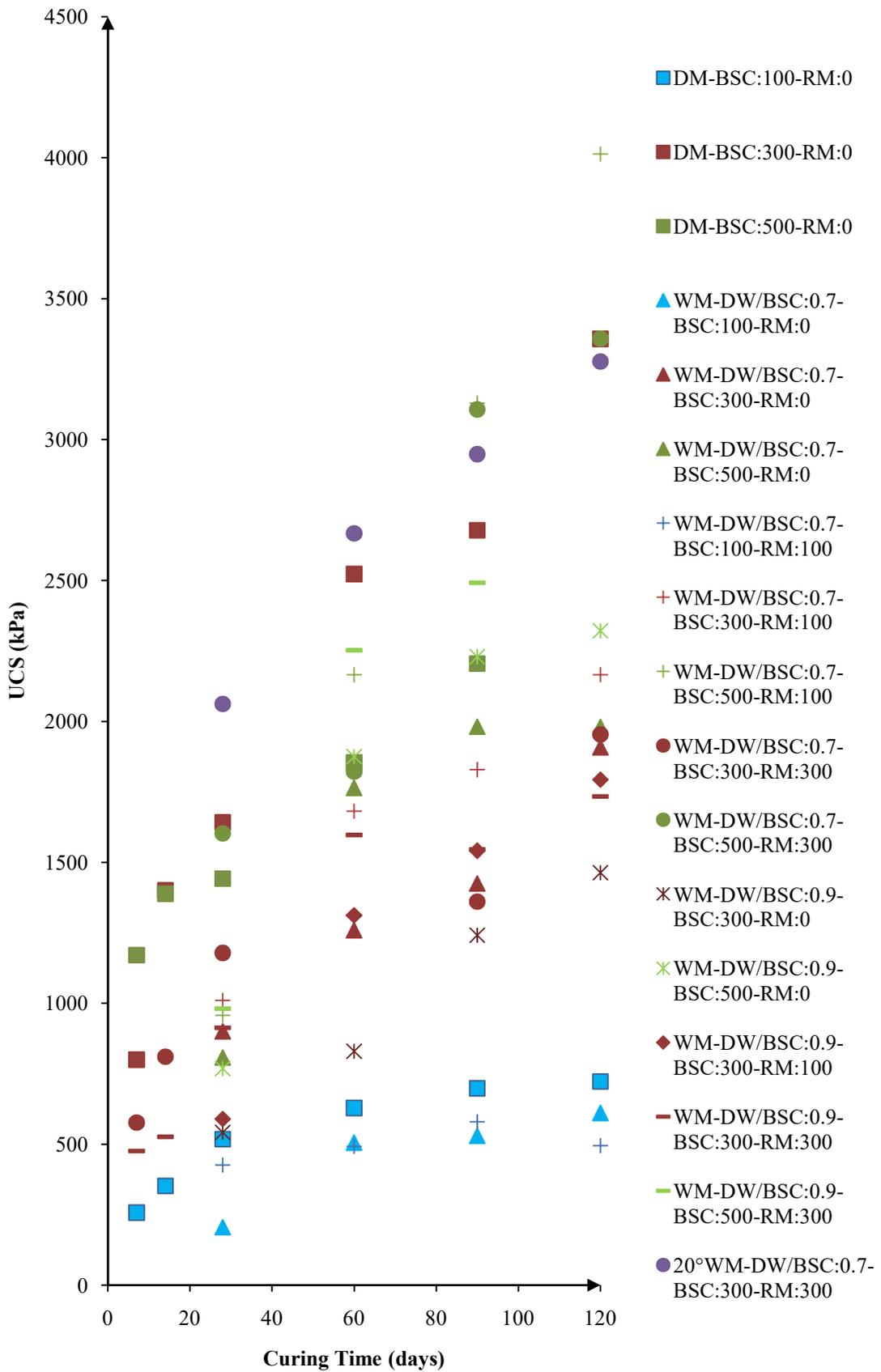


Figure 5.19. UCS with curing time (clay at 10° storage)

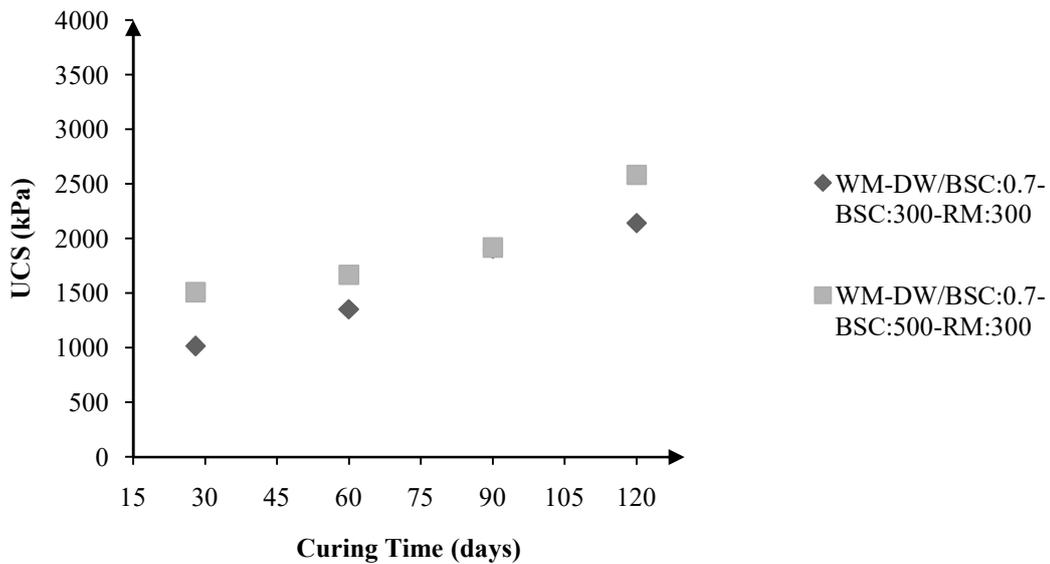
The following conclusions can be drawn for both peat and clayey soil samples:

- The UCS values increase with time as a result of the cement hydration. However, a large scatter for peat samples are obtained after 28 days curing time. A large scatter for the clayey soil samples is also obtained.
- The highest increment of the UCS values are obtained after 120 days curing time for all clayey soil and peat samples.
- For both clayey soil and peat samples having BSC content of  $500 \text{ kg/m}^3$ , DW/BSC ratio of 0.7 are observed the highest strength after 120 days curing time compared to other mixtures having less BSC content.
- Significant higher strength values are obtained for the peat samples compared to the clayey soil samples. Although strength properties of the native clayey soil and peat are quite similar in the field. This could be a result of the higher RM content for the peat samples ( $500 \text{ kg/m}^3$ ) compared to the clayey soil samples ( $300 \text{ kg/m}^3$ ).
- The increase in RM is due to the lower BSC content for the peat samples. It could also be noted that the clayey soil gave react more performant with the BSC (at relatively early strength stages) comparing peat.
- For the WM samples, a lower strength is obtained comparing to the WM-RM samples in general. The former contains a larger amount of soil, BSC and DW compared to the former. Therefore, these results indicate that the partial replacement of BSC by RM can be useful.
- Samples for both clayey soil and peat (DM-BSC: $500 \text{ kg/m}^3$ ) have almost the same strength. However it is observed that peat samples (DM-BSC: $300 \text{ kg/m}^3$ ) have higher strength compared to clayey soil samples (DM-BSC:  $300 \text{ kg/m}^3$ ). It could be due to the BSC properties mentioned in Chapter 2.
- For peat, comparing WM-RM: $1200 \text{ kg/m}^3$  to WM-RM: $300\text{kg/m}^3$  or WM-RM: $100 \text{ kg/m}^3$ , an increase in RM (resulting small decrease in BSC and water content) is evaluated positively for the peat samples.
- It is also observed that the clayey soil mixtures (DM-BSC: $100 \text{ kg/m}^3$ ) have no significant increase on strength.

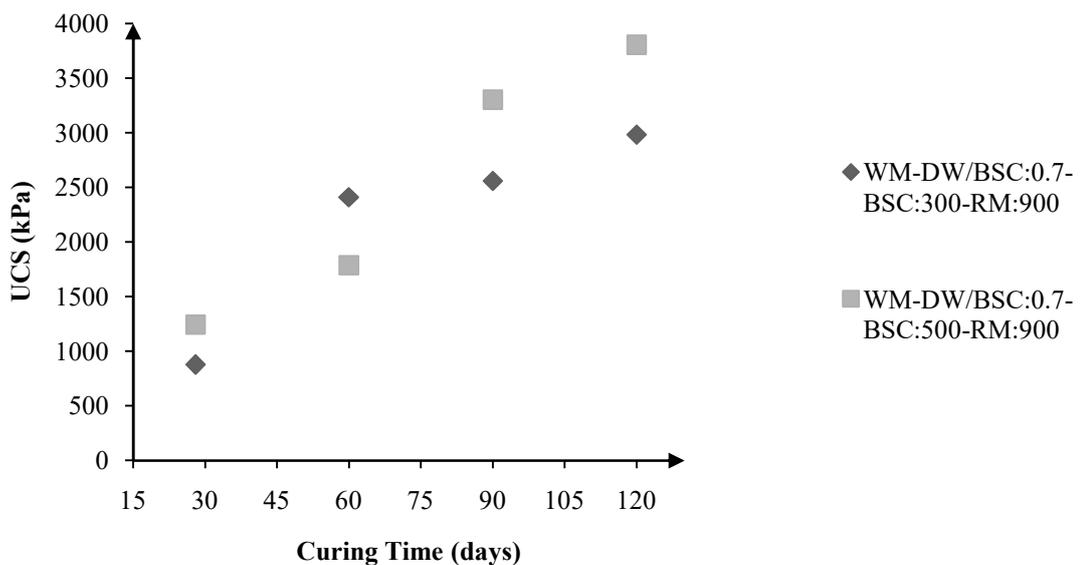
- For both peat and clayey soil have a less increase on mechanical properties observed for DW/BSC ratio of 0.9 compared to DW/BSC ratio of 0.7. Significant lowest results are obtained on clayey soil compared to peat samples. This might be related to the fact that adding DW to the clayey soil caused to obtain a sticky mixture which was hard to compact. As a result of this, samples having a lower quality affected the study of the impact of RM as an alternative for BSC.
- By decreasing the BSC content in the samples WM-RM for clayey soil, the strength is significantly reduced in the field condition. This results indicated that an inadequate bonding for these samples was obtained.
- By increasing the RM content in the samples WM-RM for both clayey and peat, the strength is significantly increased and also soil properties are enhanced. This is proved that RM can be used as replacing material for BSC.
- The results show that the strengthening effect also depends on the storage temperature. The samples prepared with the same mixtures are stored at 20°C and 10°C room temperatures having significantly different strengths. It is observed that, 20°C storage temperature has higher strength than the 10°C storage temperature.
- The determined value of 540 kPa for UCS has already been reached after 28 days of curing time.
- For peat samples, the results show that for DW/BSC ratio of 0.9 has significantly lower strength than the DW/BSC ratio of 0.7. This is due to the higher water content of the native peat samples.

### *The effect of blastfurnace slag cement (BSC)*

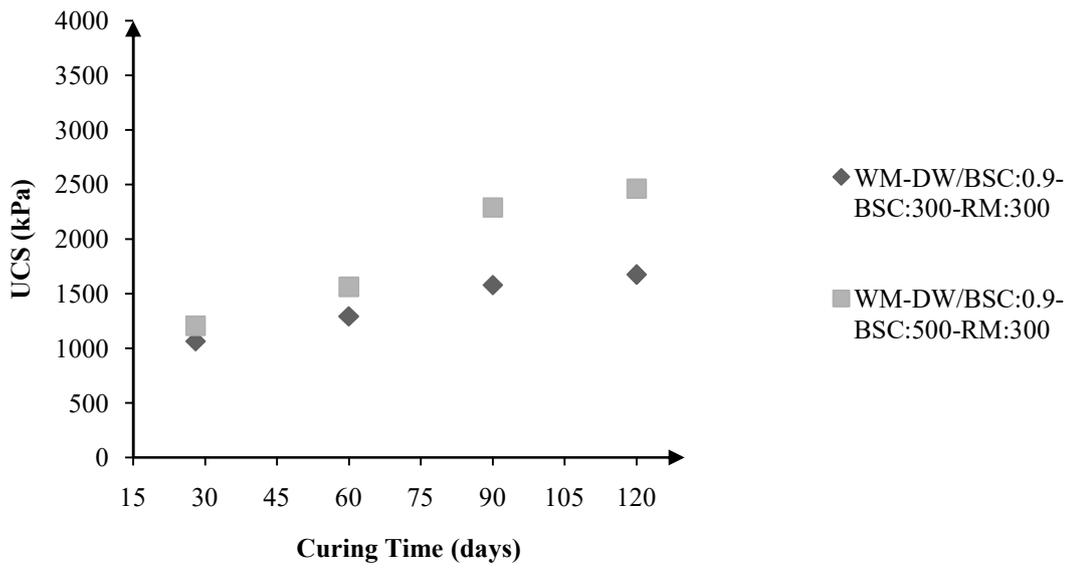
The effect of BSC on peat is presented in Figures 5.20, 5.21, 5.22 and 5.23. UCS with curing time can be given in graphs. The results showed that additional BSC has positive effect on strength of soil. Also, It can be concluded that the strength increases gradually with increasing curing time. The highest value of strength is observed on the samples cured 120 days as a result of cement hydration.



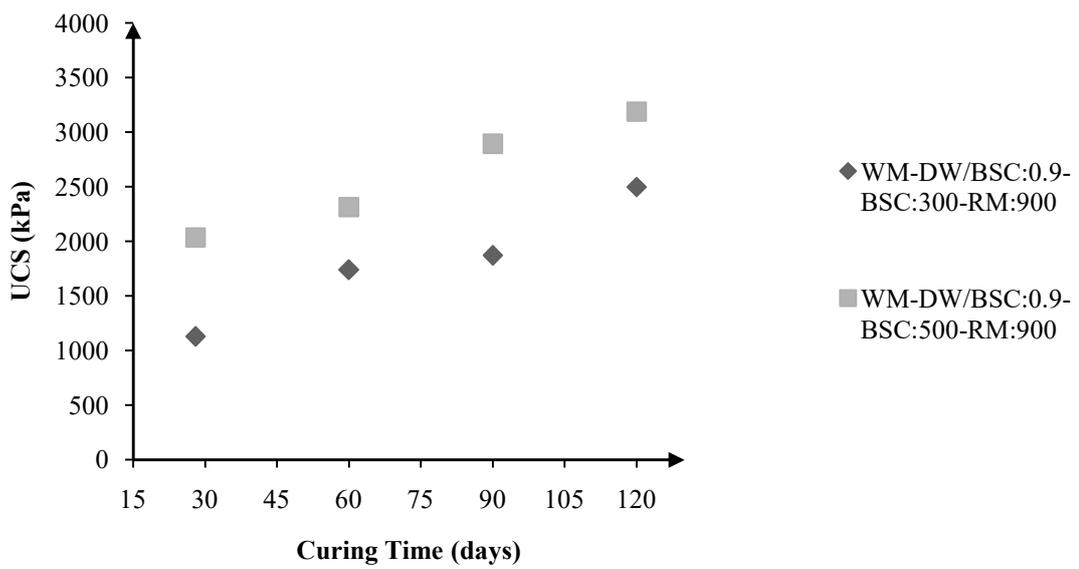
**Figure 5.20.** The effect of additional BSC on peat for DW/BSC ratio is 0.7 and RM content is 300 kg/m<sup>3</sup>



**Figure 5.21.** The effect of additional BSC on peat for DW/BSC ratio is 0.7 and RM content is 900 kg/m<sup>3</sup>

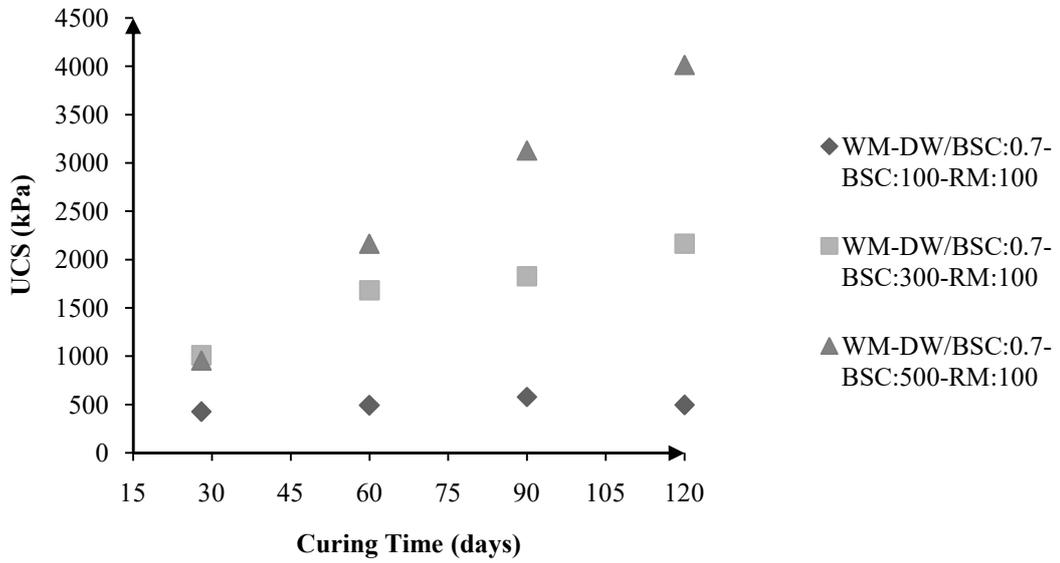


**Figure 5.22.** The effect of additional BSC on peat for DW/BSC ratio is 0.9 and RM content is 300 kg/m<sup>3</sup>

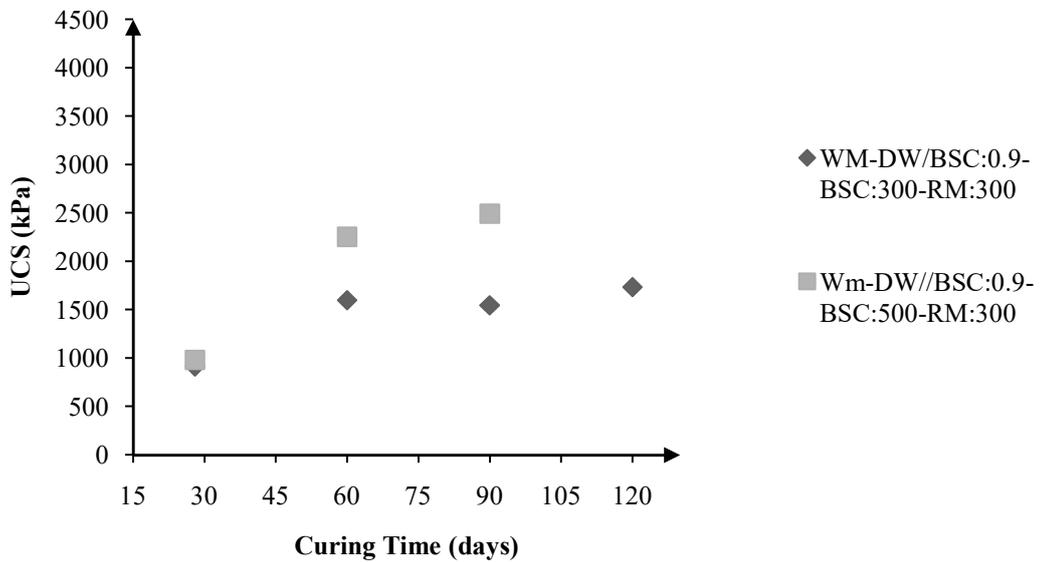


**Figure 5.23.** The effect of additional BSC on peat for DW/BSC ratio is 0.9 and RM content is 900 kg/m<sup>3</sup>

The effect of BSC can also be drawn for clayey soil in Figures 5.24 and 5.25. The same conclusions can be made with the peat samples. BSC has also positive effects on clayey soil.



**Figure 5.24.** The effect of additional BSC on clay for DW/BSC ratio is 0.7 and RM content is 100 kg/m<sup>3</sup>



**Figure 5.25.** The effect of additional BSC on clay for DW/BSC ratio is 0.9 and RM content is 300 kg/m<sup>3</sup>

### The effect of recycled material (RM)

The effect of RM for peat is presented in Figures 5.26, 5.27, 5.28, 5.29. From these graphs, a remarkable increase was observed in peat samples as a result of adding recycled material.

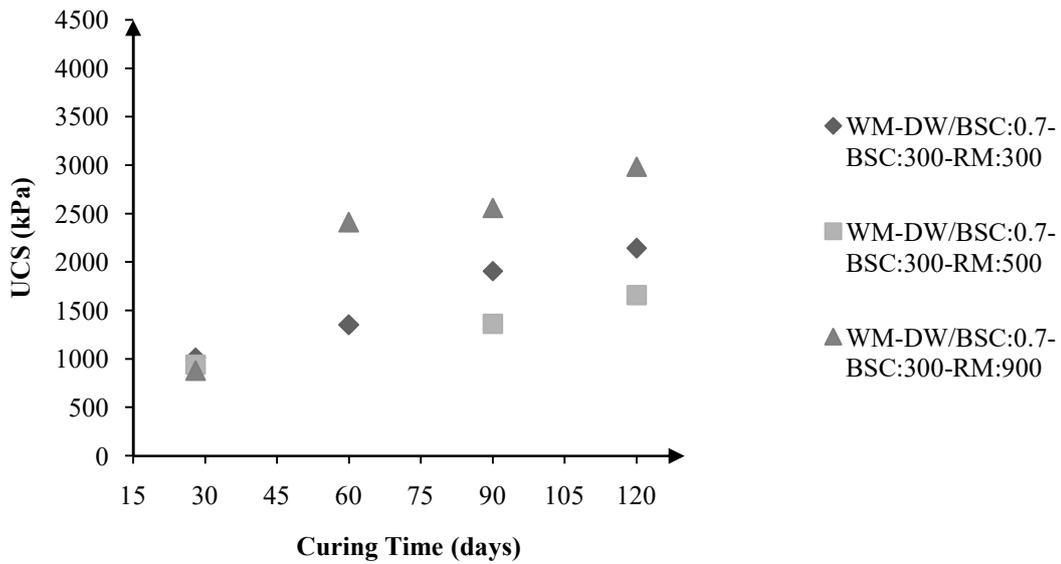


Figure 5.26. The effect of RM on peat for DW/BSC ratio is 0.7 and BSC content is 300 kg/m<sup>3</sup>

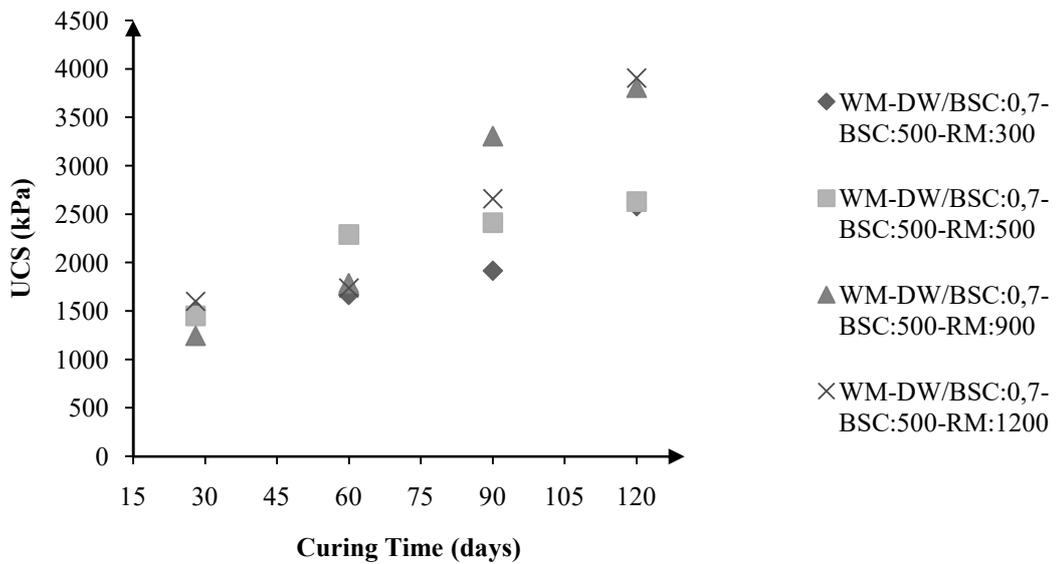
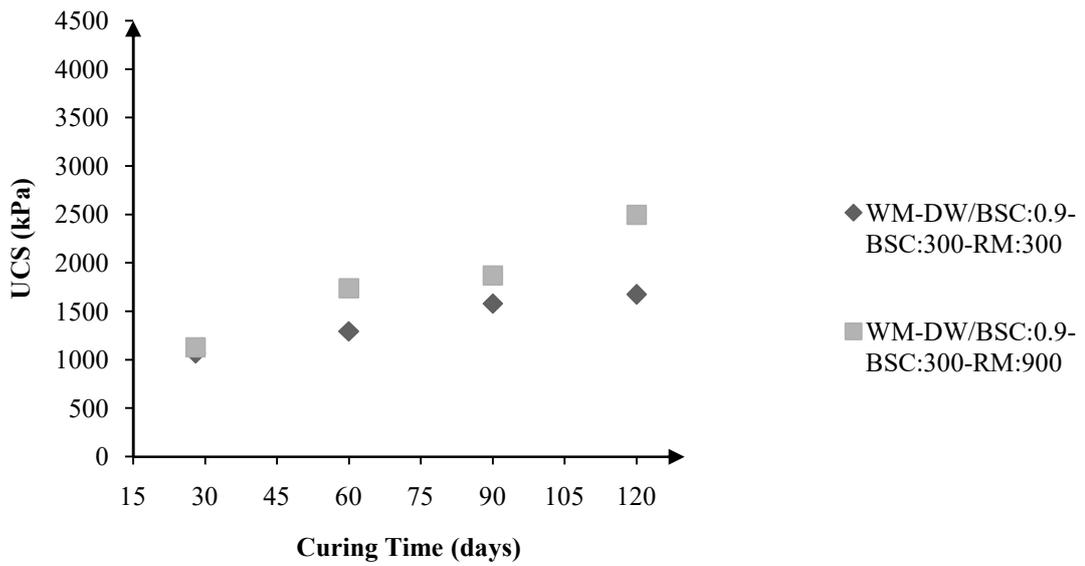
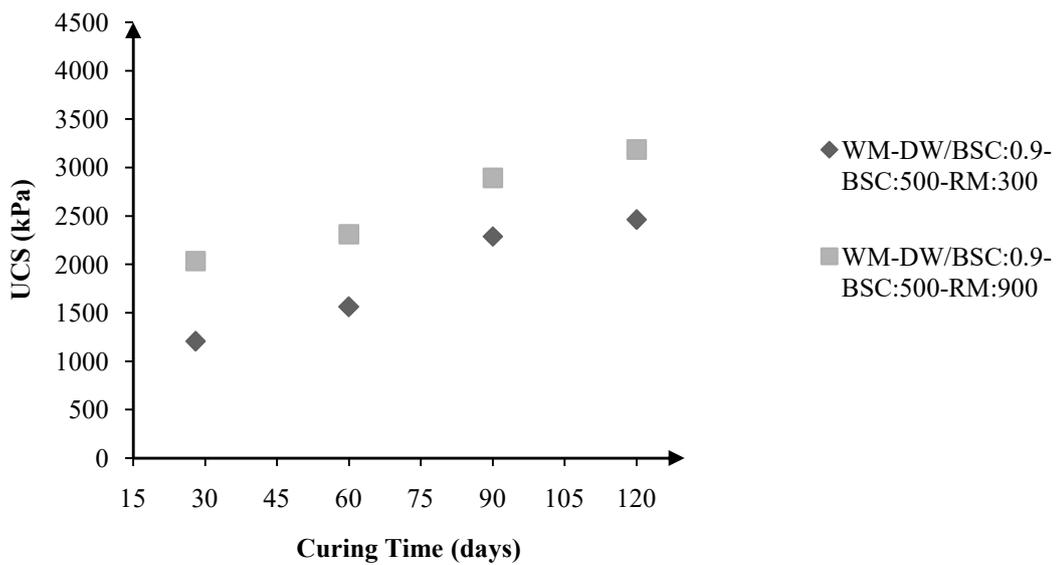


Figure 5.27. The effect of RM on peat for DW/BSC ratio is 0.7 and BSC content is 500 kg/m<sup>3</sup>

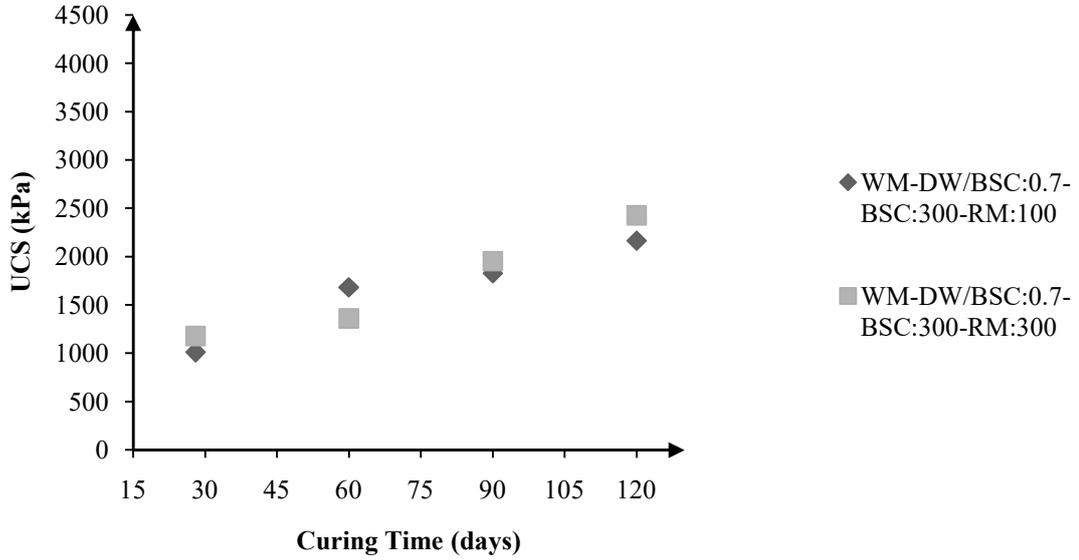


**Figure 5.28.** The effect of RM on peat for DW/BSC ratio is 0.9 and BSC content is 300 kg/m<sup>3</sup>

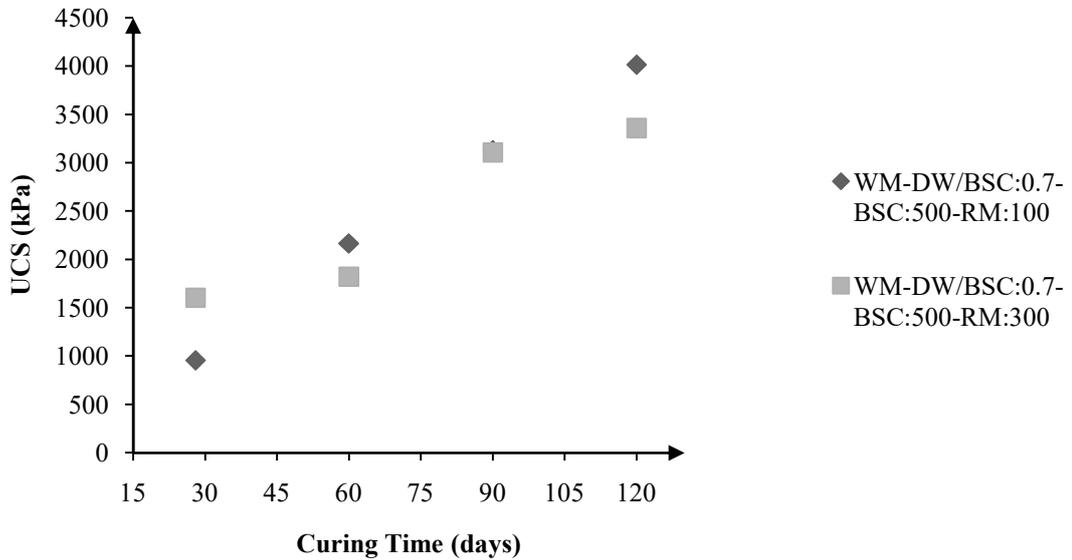


**Figure 5.29.** The effect of RM on peat for DW/BSC ratio is 0.9 and BSC content is 500 kg/m<sup>3</sup>

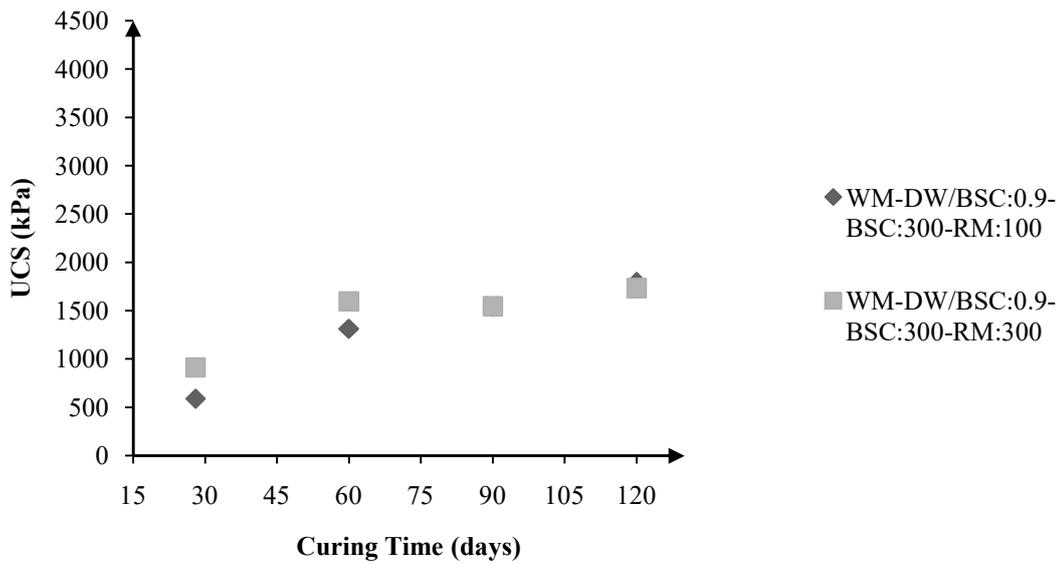
The effect of RM on clayey samples is presented in Figures 5.30, 5.31 and 5.32. It can be found that, there is no significant increase recorded on clayey soil samples. This is due to the using less amount of RM in the clayey samples.



**Figure 5.30.** The effect of RM on clay for DW/BSC: 0.7 and BSC content is 300 kg/m<sup>3</sup>



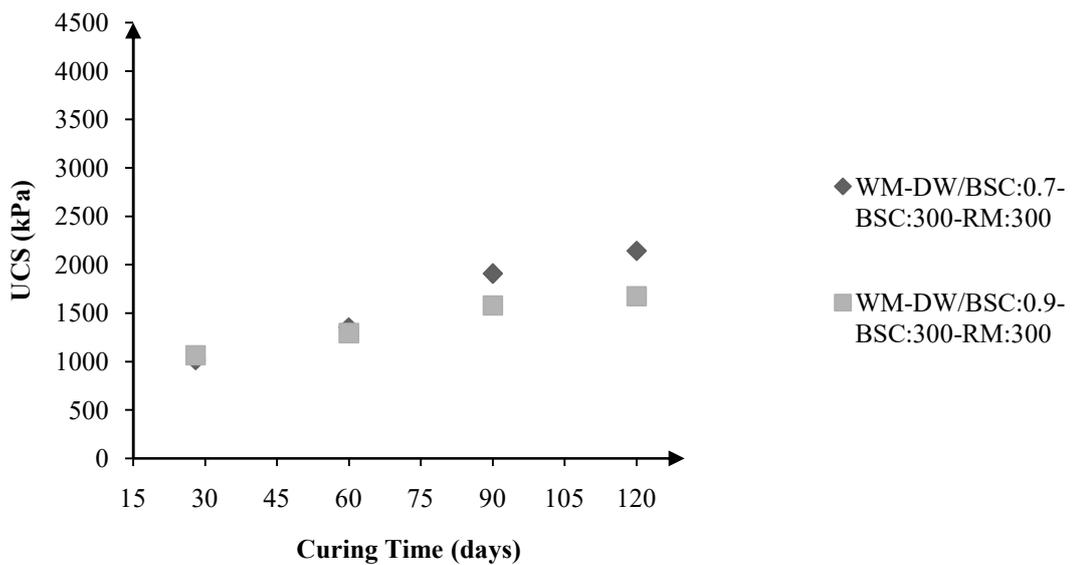
**Figure 5.31.** The effect of RM on clay for DW/BSC: 0.7 and BSC content is 500 kg/m<sup>3</sup>



**Figure 5.32.** The effect of RM on clay for DW/BSC: 0.9 and BSC content is 300 kg/m<sup>3</sup>

***The effect of the ratio of water to blastfurnace slag cement***

Figures 5.33, 5.34 and 5.35 present the DW/BSC ratio for peat samples. Considering the results, increasing water content decreases strength of soil. Also, high water content causes difficulty during compaction. For the samples with DW/BSC ratio of 0.7 has higher strength than the samples with DW/BSC ratio of 0.9. Figures 5.36 and 5.37 present the DW/BSC ratio for clayey samples.



**Figure 5.33.** The effect of DW/BSC on peat for BSC:300 kg/m<sup>3</sup> and RM:300 kg/m<sup>3</sup>

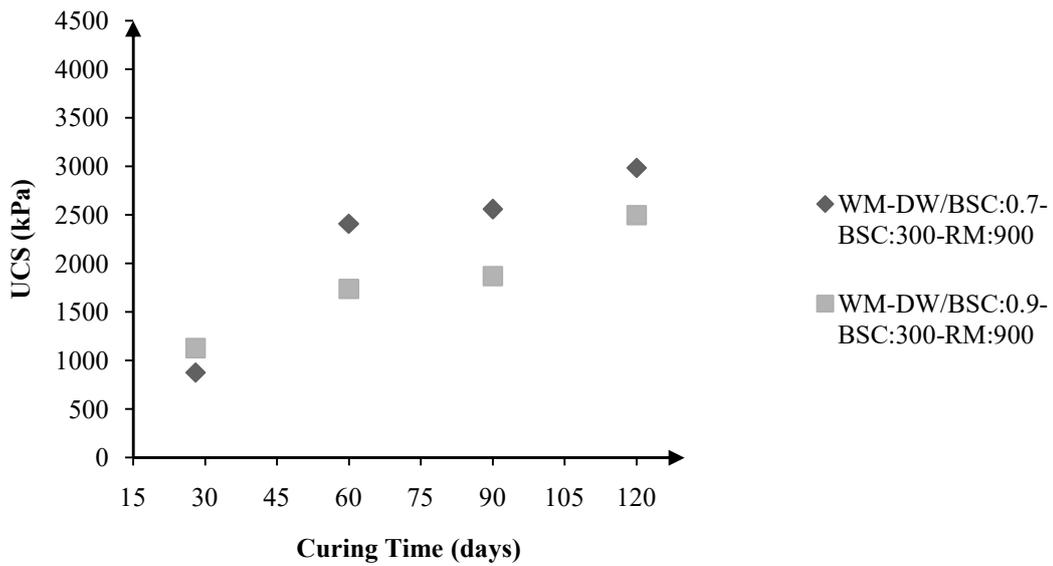


Figure 5.34. The effect of DW/BSC on peat for BSC:300 kg/m<sup>3</sup> and RM:900 kg/m<sup>3</sup>

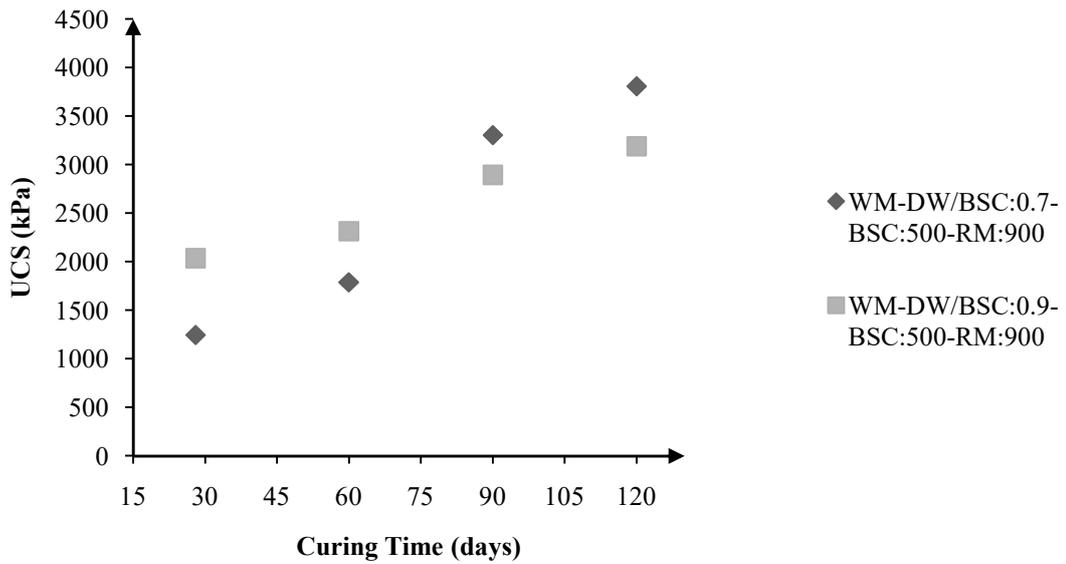
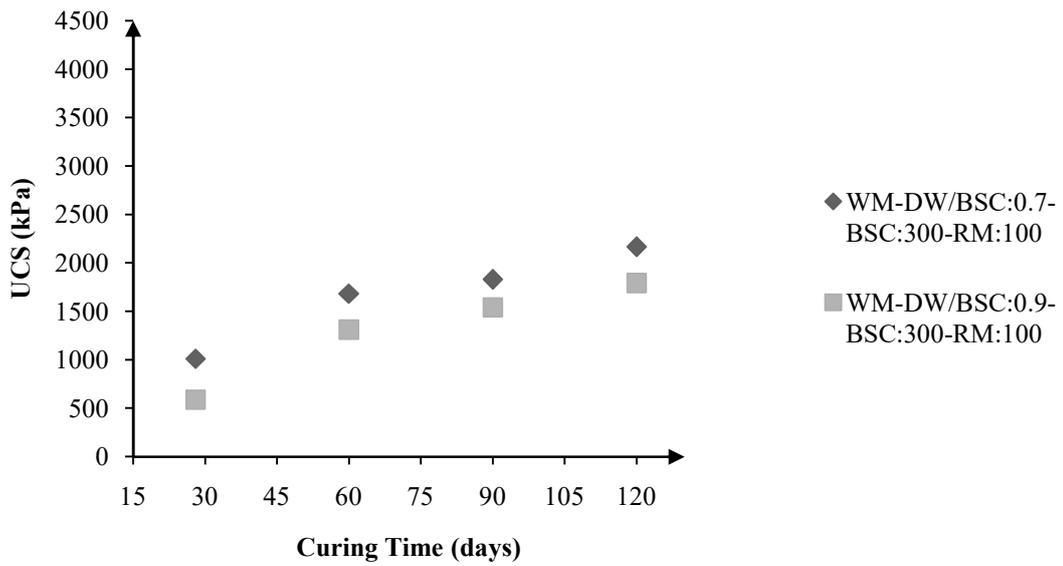
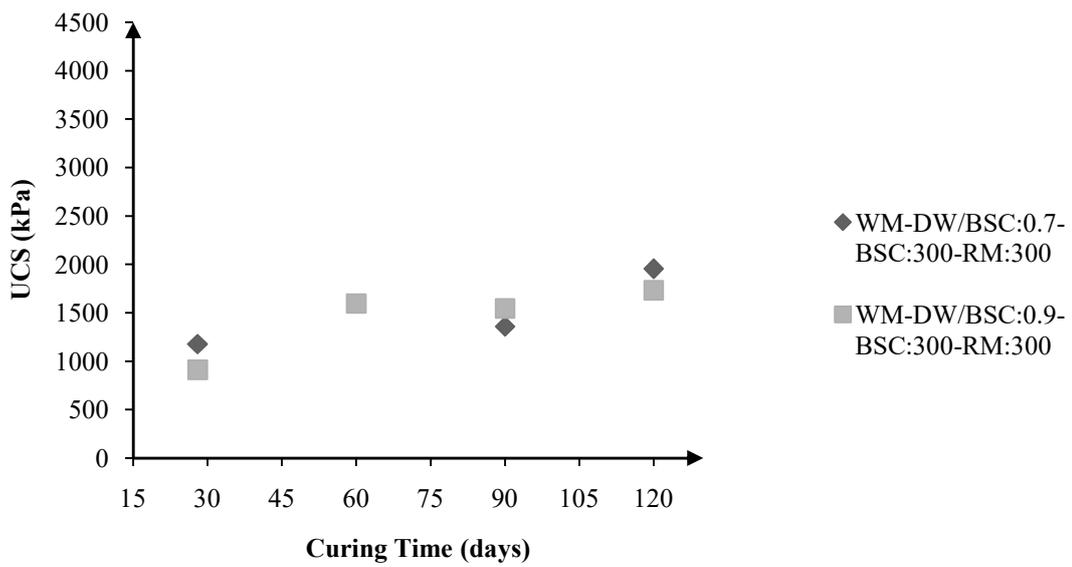


Figure 5.35. The effect of DW/BSC on peat for BSC:500 kg/m<sup>3</sup> and RM:900 kg/m<sup>3</sup>



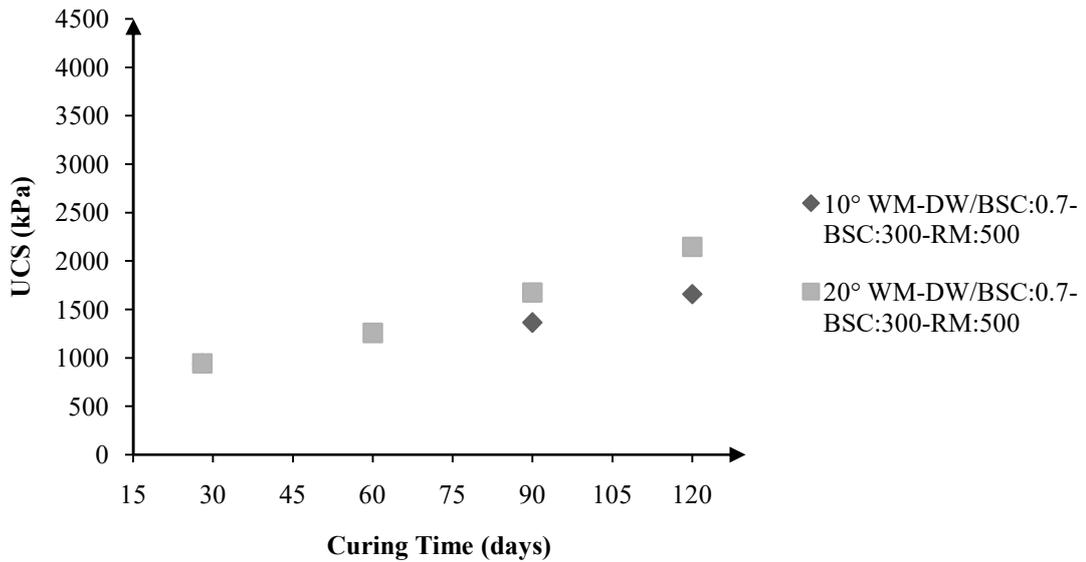
**Figure 5.36.** The effect of DW/BSC on clay for BSC:300 kg/m<sup>3</sup> and RM:100 kg/m<sup>3</sup>



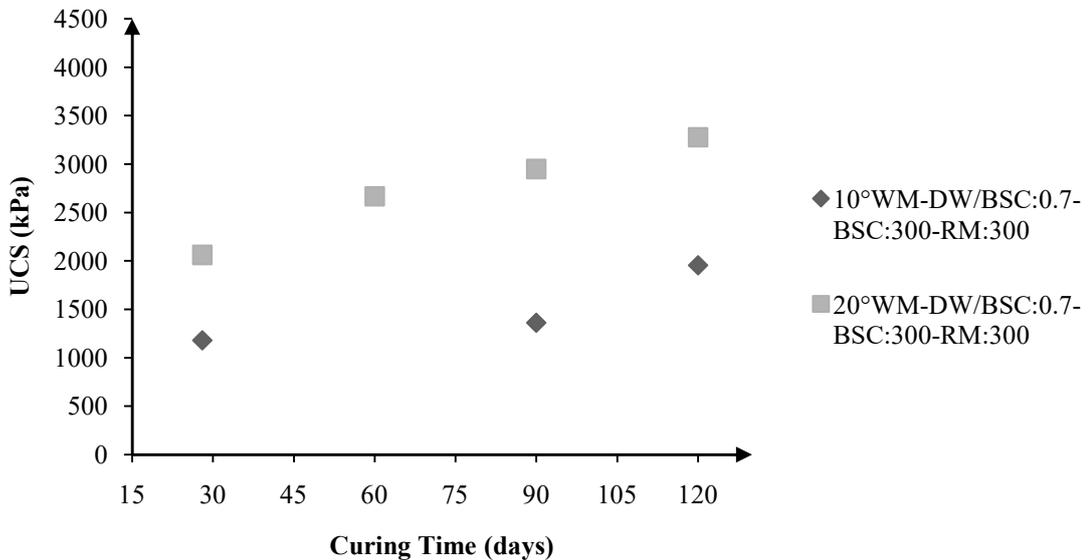
**Figure 5.37.** The effect of DW/BSC on clay for BSC:300 kg/m<sup>3</sup> and RM:300 kg/m<sup>3</sup>

### *The effect of storage temperature*

The effect of storage temperature for peat and clayey soil mixtures can be found in Figures 5.38 and 5.39, respectively. It can be concluded that, higher strength observed for the samples stored at 20°C compared to 10°C for both peat and clayey soil samples.



**Figure 5.38.** *The effect of storage temperature on peat*



**Figure 5.39.** *The effect of storage temperature on clay*

### 5.2.4. Stiffness properties

Longitudinal small strain stiffness modulus ( $E_0$ ) for peat and clayey soil samples is given in Figures 5.40 and 5.41, respectively.

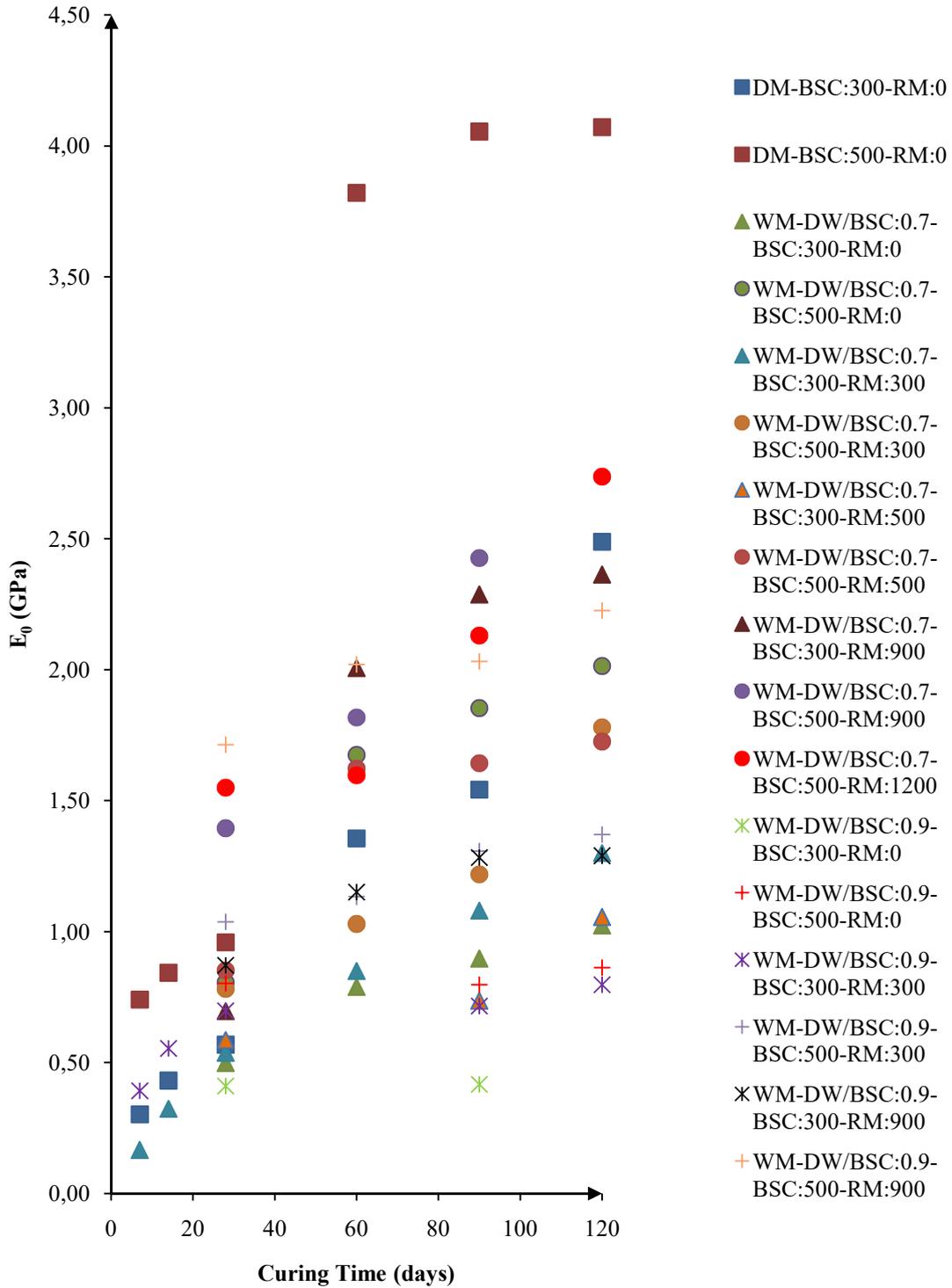


Figure 5.40. Longitudinal small strain stiffness modulus  $E_0$  in function of the curing time (peat)

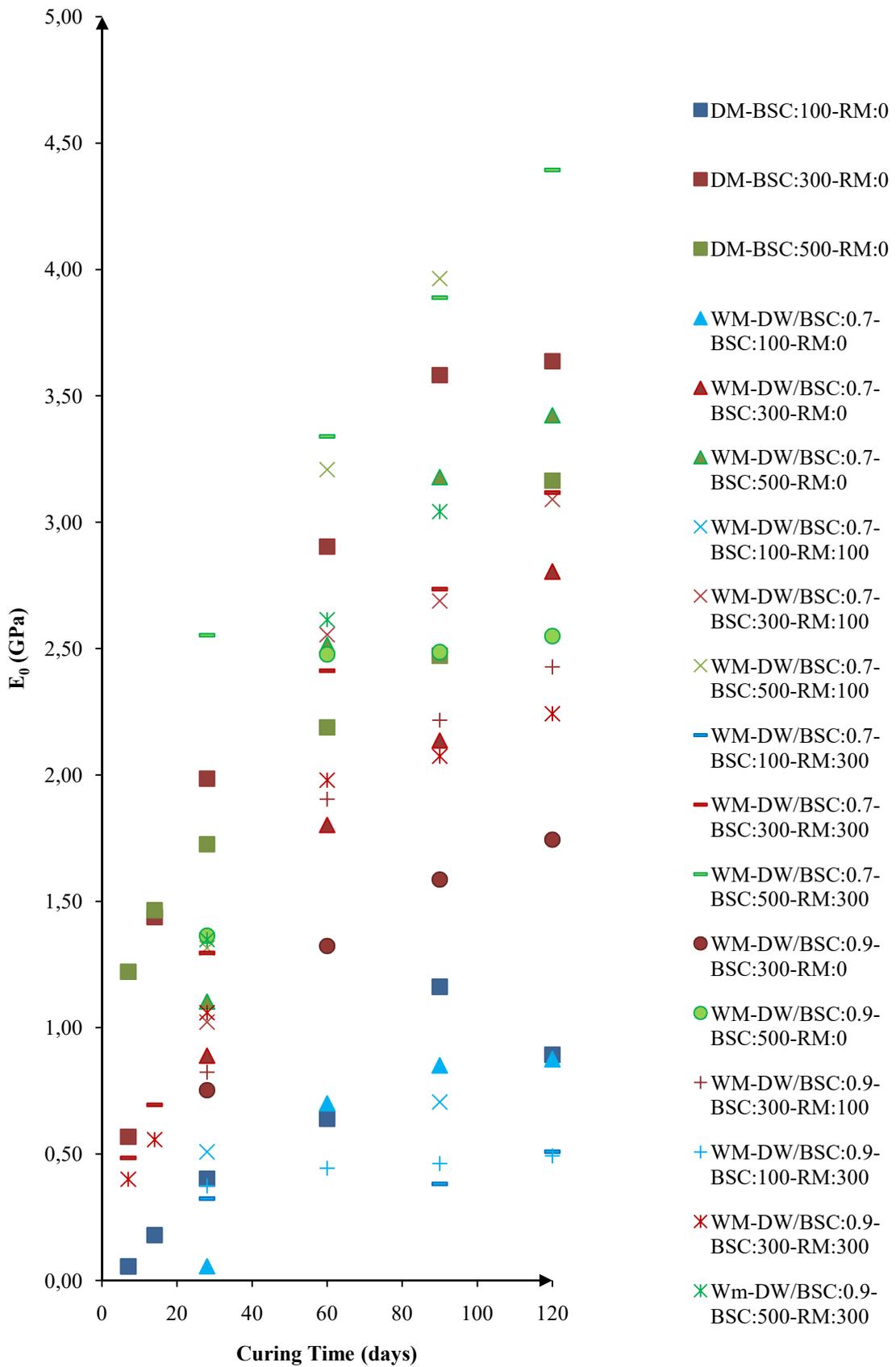


Figure 5.41. Longitudinal small strain stiffness modulus  $E_0$  in function of the curing time (clay)

Transversal small strain stiffness modulus ( $G_0$ ) for the peat mixtures and clayey mixtures is shown in Figures 5.42 and 5.43, respectively.

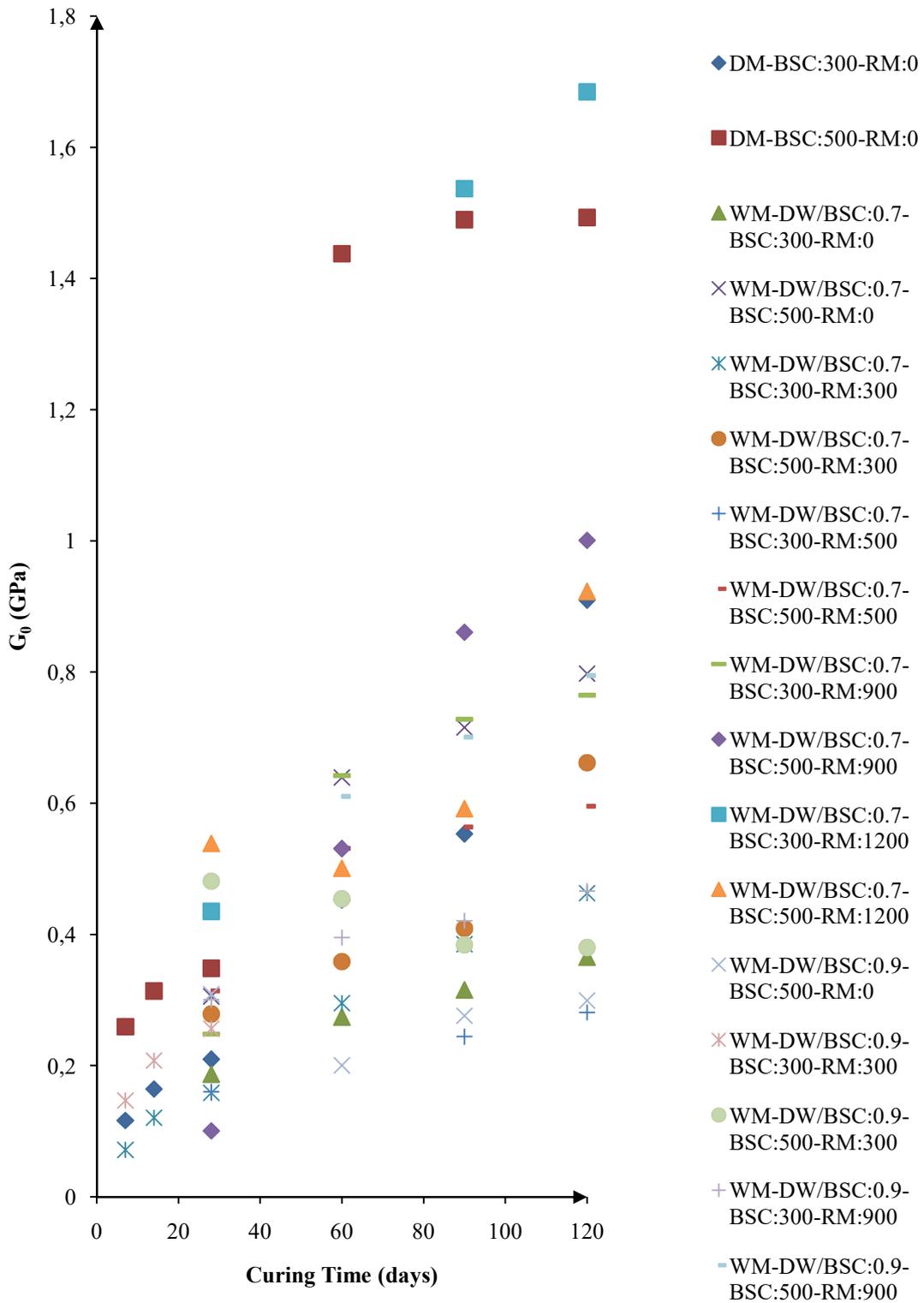


Figure 5.42. Transversal small strain stiffness modulus  $G_0$  in function of the curing time (peat)

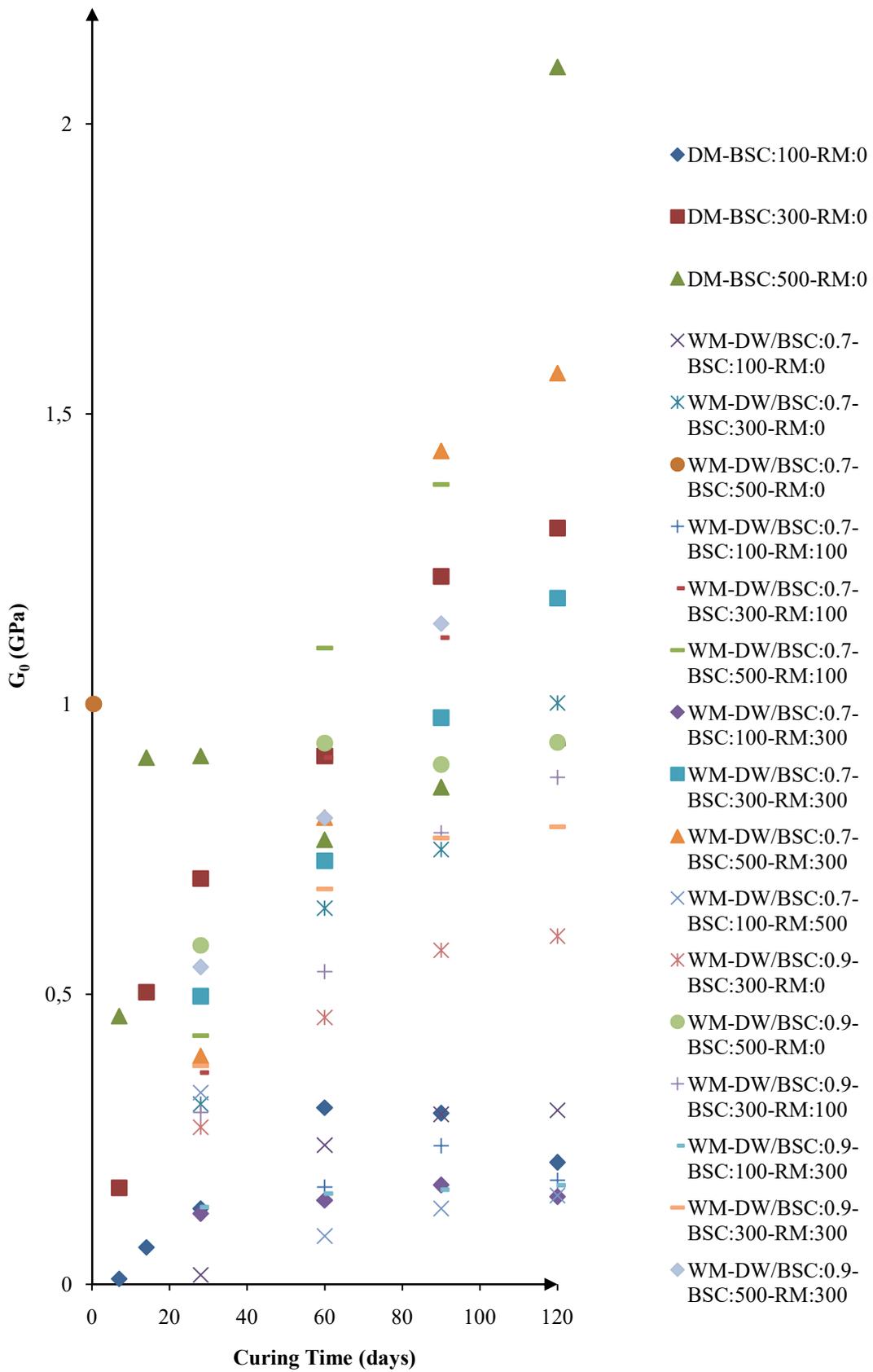


Figure 5.43. Transversal small strain stiffness modulus  $G_0$  in function of the curing time (clay)

From these results the following conclusions can be drawn;

- The small-strain stiffness both in longitudinal and transversal directions indicates the same trends for different mixtures.
- The same trends as the UCS test results were observed for the peat and clayey soil samples .
- The highest  $E_0$  and  $G_0$  are also observed from the mixtures having the highest RM content (RM:1200 kg/m<sup>3</sup>) for the peat.
- It should also be noted that for the mixtures having DW/BSC ratio of 0.9 is difficult to determine frequencies during free-free resonance test. It could be difficult during compaction for samples having lower stiffness values.

#### 5.2.4.1. Relation between unconfined compressive strength (UCS) and small-strain stiffness modulus ( $E_0$ )

In addition, the results for clayey and peat related to UCS values versus ( $E_0$ ) for 90 days curing time are given in Figures 5.44 and 5.45, respectively.

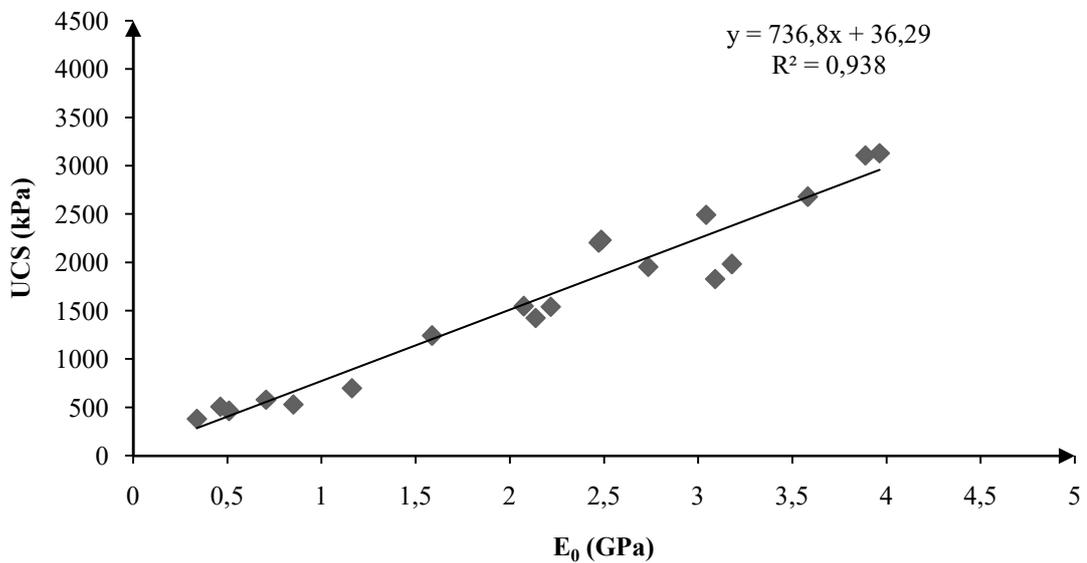
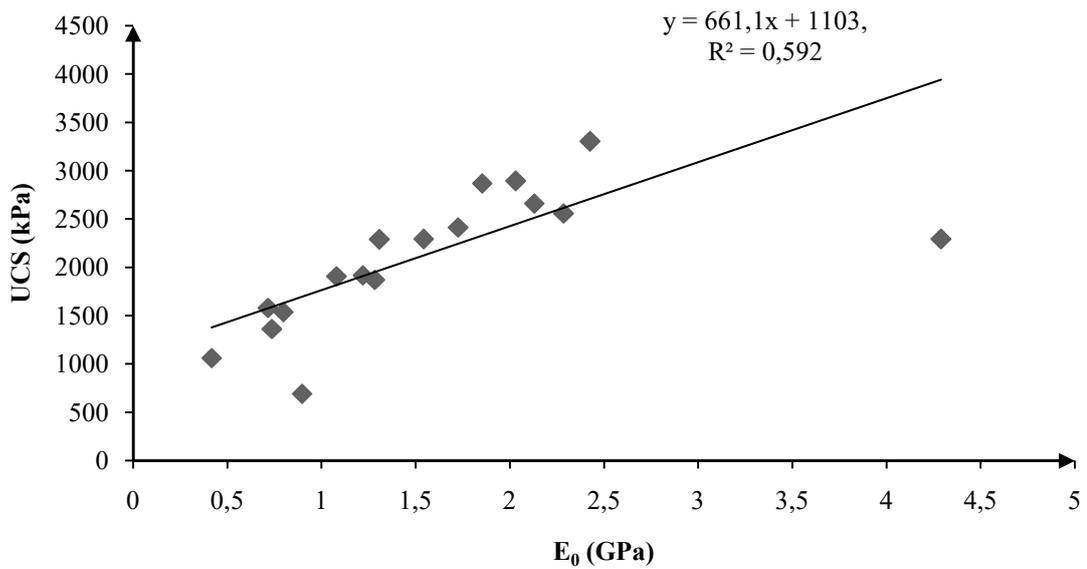


Figure 5.44. Relation between  $E_0$  and UCS(90 days-clay)



**Figure 5.45.** Relation between  $E_0$  and UCS (90 days-peat)

It should be noted that for these trend lines all mixture types were taken into account. Also note that a higher correlation is obtained from the peat samples. The lower correlation of the clayey soil samples could be a result of the difficult compactability of many clayey soil samples, possibly resulting from a larger scatter of the results.

### 5.2.5. Total DW/BSC ratio

The total DW/BSC ratio is studied in this part of the study to get a better understanding of strength. The total amount of DW is calculated as the amount of added water, water in the soil and water in the RM. The wet density versus of the total DW/BSC ratio is shown for the peat and clayey soil samples in Figures 5.46 and 5.47, respectively.

For the same mixture type (WM-DW/BSC:0.9 BSC:300 kg/m<sup>3</sup> RM:300 kg/m<sup>3</sup>), overall the DW/BSC ratio is slightly higher in the peat samples compared to the clayey soil samples. This is due to the higher water content of the peat compared to the clayey soil.

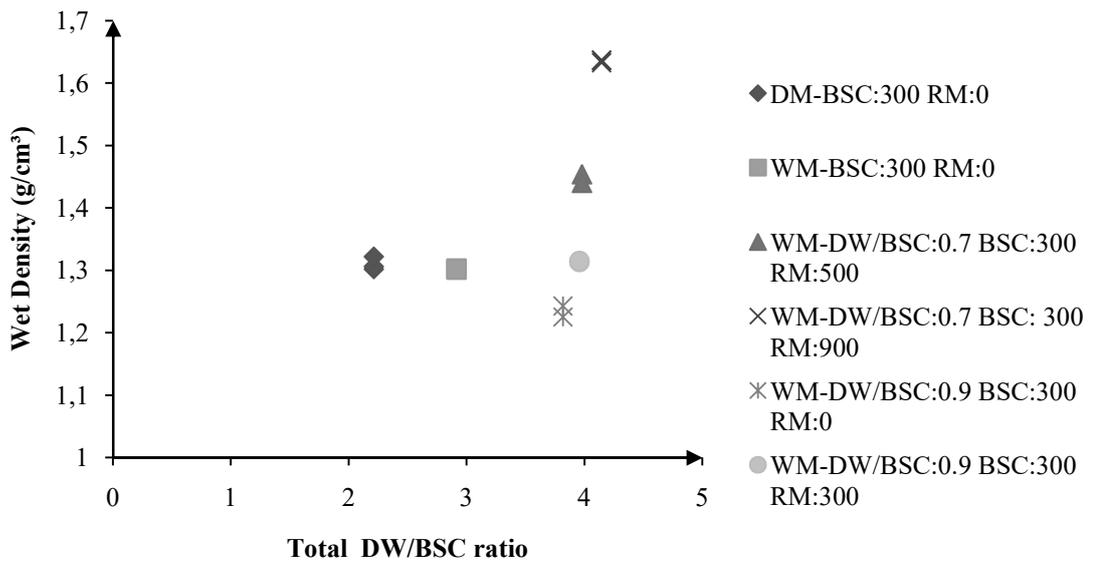


Figure 5.46. Wet density versus total DW/BSC ratio for peat

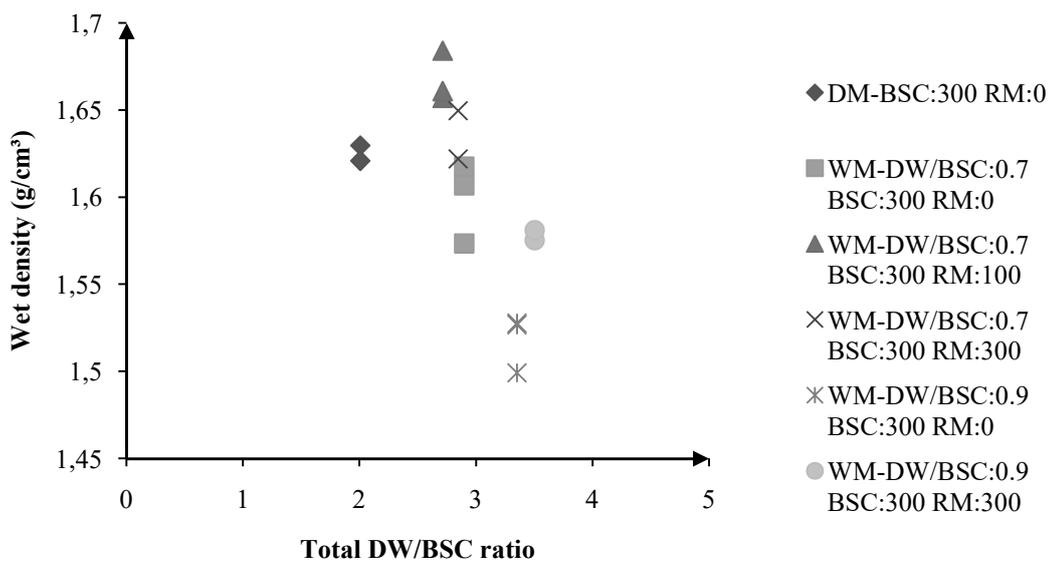


Figure 5.47. Wet density versus total DW/BSC ratio for clayey soil

## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1. Conclusions

The following conclusions can be drawn from this study;

- RM showed good performance in long-term strength development and seemed to be a good material to be concerned in future.
- By adding additional DW to the clayey soil, a very sticky mixture was obtained which was hard to compact. This resulted into samples having a lower quality which affect the study of the impact of RM as an alternative for BSC.
- Still a high water content was observed for the peat samples ranging from 80.00 to 160.00% for the different mixture types. The water content ranged from 30.00 to 65.00% for the clayey soil samples. The water content did not change over the curing period between 28 and 120 days which implies the appearance of quite a high content of unbounded water among the particles. This was deemed to be detrimental regarding the mechanical properties of the treated peat and clayey soil.
- It appeared that the wet density is inversely proportional to the water content for all examined mixtures. The wet density ranged from 1.20 to 1.80 g/cm<sup>3</sup> for the peat samples and from 1.55 to 1.75 g/cm<sup>3</sup> for the clayey soil samples.
- Regarding UCS test results, much larger strengths were observed for the clayey soil samples compared to the peat samples. This could be a result of the higher amount of RM and resulting lower amount of BSC for the peat samples compared to the clayey soil samples.
- For the clayey soil samples results inconsistent results and a relatively large scatter occurred which is probably because of difficulties in the compaction method for sticky clayey soil.
- A more performant mechanical behaviour was found by adding RM to the wet mixing of the native soil for both peat and clayey soil samples.
- The same trends for the small strain stiffness modulus in longitudinal ( $E_0$ ) and transversal direction and ( $G_0$ ) compared to UCS values were found. Quite a clear correlation between these parameters was determined.

- Moreover, studying the effect of the curing time shows an increase in the specimens' ages for all three curing times with increasing the UCS values of the specimens. The rate of increase was significant from 28 days to 120 days. It might be due to the cement hydration during the long term curing times.
- Considering the storage temperature, the highest strength observed for the same mixtures for both clayey and peat samples in 20°C storage compared to 10°C storage.
- This study showed that, DW/BSC ratio has also effect on the samples. Samples having DW/BSC ratio of 0.9 has lower strength than the DW/BSC ratio of 0.7 for both peat and clayey soil.

## **6.2. Recommendations**

- It is advised to study more mixture compositions at a single curing period. By considering a fixed curing time the general trends in changes to the material composition can be studied. To this regard it is advised to change the content of RM to determine a range of optimum contents.
- Studying the type of cement might be an interesting starting point for further research.
- In case practical implications of the DSM method may allow it, a more in-deep laboratory study regarding the dry mixing of cement and RM in the soil is proposed. As a result, this may tackle problems with respect to the compactability of clayey soils.
- The study might conduct on gradually increasing the RM content for clayey soil up to 1200 kg/m<sup>3</sup>. This will allow to compare the obtained results with the peat.

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