ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

THE USE OF DREDGED MATERIALS FOR ROAD FILL AND THE CHARACTERISTICAL ANALYSIS OF TREATED MATERIALS

M.Sc. THESIS

Ece BAYRAM

Department of Civil Engineering

Ground Mechanics and Geotechnical Engineering Programme

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Thesis Advisor: Ass. Prof. Dr. Berrak TEYMUR

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DİP TARAMA MALZEMELERİNİN YOL DOLGUSU İÇİN KULLANIMI VE İYİLEŞTİRİLMİŞ MALZEMELERİN ÖZELLİKLERİ

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Ece Bayram, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 501141304, successfully defended the thesis/dissertation entitled “THE USE OF DREDGED MATERIALS FOR ROAD FILL AND THE CHARACTERISTICAL ANALYSIS OF TREATED MATERIALS”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 05 May 2017
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To my grandfather Ibrahim and mother,

FOREWORD

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May 2017 Ece BAYRAM

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ABBREVIATIONS

ASSHTO : American Association of State Highway nad Transportation Officials
CBR : California bearing ratio
EPA : Environmental Protection Agency
EuDA : European Dredging Association
IADC : International Association of Dredging Companies
IMO : International Maritime Organization
OSPAR : Oslo and Paris Commissions
PIANC : The World Association for Waterborne Transport Infrastructure
SedNet : European Sediment Network
UCS : Unconfined compression stress/strength
UNEP : United Nations Environment Program
USACE : United States Army Corps of Engineers
WODA : The World Organization of Dredging Associations

SYMBOLS

c_u : Undrained cohession
LL : Liquid Limit
PI : Plasticity index
PL : Plastic limit
q_u : Unconfined compression strength/stress
$q_u(7)$: Unconfined compression strength/stress after 7 days of curing time
W : Weight
w : Water content
V_m : Volume of mold
γ : Moist unit weight
γ_d : Dry unit weight
τ : Shear strength
φ : Angle of internal friction
σ_n : Normall stress

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THE USE OF DREDGED MATERIALS FOR ROAD FILL AND THE CHARACTERISTICAL ANALYSIS OF TREATED MATERIALS

SUMMARY

Each year huge quantities of material are dredged from seas, rivers and lakes for different purposes. Navigation, material winning, and land reclamation and environmental dredging are the four main reasons of dredging operations. Disposal of dredged material can be achieved by two methods; disposal at sea and disposal at land. However, the disposal of dredged materials is complex, expensive and hazardous for environment. Moreover, the disposal activities of dredged material are restricted by national and international legistilations such as London Convention, Barcelona Convention and Bucharest Convention. Therefore, dredged material must be recycled to contribute to the economy and environment. Several options for the beneficial uses of dredged materials have been identified such as land remediation, beach nourishment, habitat creation, enhancement and restoration, agriculture, forestry and aquaculture, building materials and capping. One of the main area of beneficial use of dredged material is the road construction, which consumes large quantities of natural aggregates. This thesis focuses on investigating the mechanical properties of dredged materials, examining the impacts of lime and cement treatment on the engineering properties of dredged material and evaluating the suitability of treated dredged materials for beneficial use in different layers of road construction. Two different non-contaminated fine grained dredged material is used for the experimental studies. They were obtained from different regions of Tuzla, İstanbul. Thet are called as Dtm-1 and Dttm-10. Due to the poor mechanical properties of dredged materials, hydraulic binders were used to enhance mechanical properties of samples. Lime and cement were selected for to enhance the engineering properties of dredged material. Mixtures were preapered at three different contents of hydraulic binders to find optimum content for beneficial use in road construction. The percentages of lime mixed with fine dredged material was fixed at 2%,4% and 6% of the dry weight of raw dredged material. The percentage of cement was fixed at 5%,10% and 15% % of the dry weight of raw dredged material. Atterberg limit tests, miniature compaction test and unconfined compression test were performed on raw dredged material and and dredged materialmixed with various percentages of lime or cement to evaluate the impacts on the engineering properties and the potential use of dredged materials in road construction. The variation of Atterberg limits and the development of unconfined compression strength were discussed at different binder types and contents. The Atterberg test results shows that the plastic limit of treated samples increases with addition of lime or cement when their liquid limit and plasticity index decreases. The unconfined compression strength of dredged material treated with lime or cement is significantly improved by increase in binder content and curing time. Based on the laboratory tests and national and international guidelines, Dtm-1 and Dtm-10 can be used as road fill material. From the point of view of mechanics and applicability in road construction, the optimum lime content of Dtm-1 is 4%, which can be used for embankment. The optimum lime content of Dtm-10 is 6%, which can be used for embankment. According to the USACE guideline, Dtm-1 mixed with 4% lime can be used as sub-base (rigid pavement/floor slab/foundation/flexible pavement) material.

Moreover, Dtm-10 mixed with 6% lime can bu used for sub-base layer of road. For the cemen treatment results, Dtm-1 and Dtm- 10 could be used as subbase and subgrade layer material of rigid pavement and the optimum cement is 15% Dtm-1 and Dtm-10 according to the USACE guideline.

DİP TARAMA MALZEMELERİNİN YOL DOLGUSU İÇİN KULLANIMI VE İYİLEŞTİRİLMİŞ MAZEMELERİN ÖZELLİKLERİ

ÖZET

Her yıl, denizlerin, nehirlerin ve göllerin taranması sonucu büyük miktarlarda malzeme açığa çıkmaktadır. Derinleştirme çalışmaları ve yeni deniz yapılarının inşaatı, deniz tabanından malzeme çıkarmak, arazi kazanımı, deniz dibindeki istilacı bitkilerin ve kirleticilerin temizlenmesi için iç ve dış sularda tarama işlemi gerçekleştirilir. Tarama işleminin gerçekleştirildiği tarama araçları mekanik ve hidrolik tarama araçları olarak ikiye ayrılır. Projenin gereklilikleri, taranacak bölgenin ve malzemenin özelliklerine göre tarama ekipmanı seçilir. Tarama işlemi elde edilen malzemelerin bertarafı denizde ve karada bu işlem için özel alanlarda gerçekleştirilmektedir. Denizde bertaraf uygulama kolaylığı açısından ve ekonomik olmasından dolayı en çok tercih edilen bertaraf yöntemidir. Karada bertaraf işleminde, bu işlem için özel bir alan ayrılarak, malzemenin buraya boşaltıması gerekmektedir. Karada bertaraf uygulanması zor bir yöntemdir ve ekonomik değildir. Ayrıca, her iki bertaraf yönteminin de çevreye fiziksel, kimyasal ve biyolojik olarak zararlı etkileri bulunmaktadır. Bunun yanında, bölgesel ve ulusal bazda kabul edilen anlaşmalar ile tarama malzemelerinin denizde ve karada bertaraf edilmesi sonucunda çevreye vereceği zararlı etkilerinin azaltılması amaçlanmış ve bu nedenle bertaraf yöntemlerinin uygulanmasında bazı kısıtlamalar getirilmiştir. Bu nedenle, tarama malzemelerinin yeniden kullanılarak ekonomiye kazandırılması ve bu yolla çevreye olan etkileri azaltılması giderek önem kazanmış ve bir çok alanda faydalı kullanıma başlanmıştır. Tarama malzemesinin faydalı kullanım alanları arazi oluşturma ve iyileştirme, kumsal besleme, habitat oluşturma ve iyileştirme, tarım, ormancılık ve balık yetiştiriciliği alanlarının oluşturması, inşaat malzemesi ve başlık geçirmedir. Tarama malzemesinin yol dolgusunda kullanımı önemli faydalı kullanım alanlarından biridir. Tarama işlemi sonucu çıkan malzeme, zayıf mühendislik özellikleri çeşitli katkılar ile iyileştirilerek yol çalışmalarının çeşitli aşamalarında kullanılabilir.

Bu çalışmada, dip tarama malzemelerinin çeşitli katkılar ile iyileştirilerek yol dolgusunda yeniden kulanım potansiyeli araştırılmıştır. Yapılan deneysel çalışmalarda iki farklı bölgeden temin edilmiş ince daneli dip tarama malzemeleri kullanılmıştır. Dip tarama malzemeleri İstanbul ilinin Tuzla bölgesinin iki farklı konumdan elde edilmiştir. Bu numuneler sırası ile Dtm-1 ve Dtm-10 olarak adlandırılmıştır. Kirlilik barındırmayan dip tarama malzmelerinin temel zemin özellikleri belirlenmiştir. Dip tarama malzemelerinin düşük mühendislik özelliklerinden dolayı, hidrolik katkılar bu özellikleri iyileştirmek için kullanılmıştır. Katkı malzemesi olarak kireç ve çimento seçilmiştir. Yol dolgusunda kullanım için optimum katkı oranınını bulmak için karışımlar her bir katkı malzemesi için 3 farklı yüzde de hazırlanmıştır. Karışımlarda ki kireç ve çimento oranları önceki çalışmalar, ulusal ve uluslaarası yönetmelikler göz önüne alınarak belirlenmiştir Doğal haldeki dip tarama malzemeleri ağırlıkça %2, %4 ve %6 oranında kireç ile karıştırılmıştır. Çimento ise %5, %10 ve %15 oranlarında doğal malzeme ile karıştırılmıştır. Oluşturan karışımlar ve saf haldeki dip tarama malzemeleri üzerinde Atterberg limiti testleri, minyatür kompaksiyon testi ve serbest

basınç deneyi gerçekleştirilerek tarama malzemesinin mühendislik özellikleri üzerinde ki değişimler ve yol inşaatında potansiyel kullanımı değerlendirilmiştir.

Yapılan elek analizleri ve kıvam deneyleri sonucu, birleştirilmiş zemin sınıflandırma sistemine göre her iki deniz tarama malzemesi de düşük plastisiteli killi (CL) zemin olarak belirlenmiştir. Karayolları zemin sınıflandırma sistemine göre Dtm-1'in ve Dtm-10'un zemin sınıfları sırasıyla A7 ve A6 olarak belirlenmiştir. Serbest basınç deneyi sonucu elde edilen verilere göre her iki malzemenin serbest basınç dayanımının oldukça düşük olduğu tespit edilmiştir.

Hazırlanan numuneler üzerinde yapılan kıvam deneyleri neticesinde karışımlardaki kireç ve çimento oranın artması ile birlikte numunelerin plastik limit değerlerinin arttığı ve buna bağlı olarak plastisite indislerinin azaldığı gözlenmiştir. Kireç katkısının Dtm-1 numunesinin likit limit değerlerini azalttığı ve bunun tam tersi olarak Dtm-10'un likit limit değerlerinin artmasına neden olduğu tespit edilmiştir. Çimento katkısı her iki numunenin likit limit değerlerinde önemli bir değişime neden olmamıştır. Dtm-1 numunesi için plastisite indisinin en düşük değerleri %4 kireç ve %5 çimento katkılarının bulunduğu karışımlarda elde edilmişir. Dtm-10 numunesi için plastisite indisinin en düşük değerleri %6 kireç ve %15 çimento katkılarının bulunduğu karışımlarda elde edilmişir.

Saf haldeki deniz tarama malzemelerin ve hazırlanmış karışımların optimum su muhtevalarını ve maksimum birim hacim ağırlıklarını belirlemek amacı ile kompaksiyon deneyi yapılmıştır. Dtm-1'in kireç ile iyileştirilmesi sonucu optimum su muhtevası oranı ve maksimum kuru birim hacim ağırlığı değerleri azalmıştır. Dtm-10 numunesine uygulanan kireç katkısı sonucu ilk olarak optimum su muhtevası ve maksimum birim hacim ağırlığının azaldığı gözlenmiştir. Ancak, %4 çimento katkısından sonra optimum su muhtevası değeri artmıştır. Çimento katkısı ilk olarak Dtm-1'in optimum su muhtevasını artırmış ve maksimum birim hacim ağırlı değerini düşürmüştür. Ancak bu durum %10 çimento katkısı gerçekleştirildiğinde tersine dönmüştür. Çimento katkısı Dtm-10'un optimum su muhtevasını artırmış ve maksimum birim hacim ağırlık değerini azaltmıştır.

Serbest basınç deneyi için numuneler 50 mm çapında, 100 mm yüksekliğinde optimum su muhtevasında hazırlanmıştır. Numuneler streç film ile sıkıca sarılarak 1, 7 ve 28 gün boyunca 20±1°C sıcaklığındaki nemi> %95 olan bir ortamda bekletilmiştir. Kireç ve çimento katkısının ve artan kür süresinin numunelerinin serbest basınç değerlerini artırdığı tespit edilmişitir. Kür süresindeki artış, çimento katkılı numunelerinin serbest basınç dayanımının artırılmasında kireç katkılı numunelere göre daha etkili olmuştur. 28 günlük kür süresi sonunda kireç katkılı karışımlar da, Dtm-1'in serbest basınç dayanımı 37 kPa 'dan 527 kPa'a ve Dtm-10'un serbest basınç dayanımı kPa 'dan 402 kPa'a çıkmıştır. Çimento katkılı karışımlarda en çok dayanım artımı 7 gün kürden sonra gözlenmiş ve 28 günlük kür sonunda dayanımlarında çok az bir artış tespit edilmiştir. Dtm-1'in serbest basınç dayanımı 37 kPa'dan 1430 kPa'a ve Dtm-10'un serbest basınç dayanımı 61 kPa 'dan 1594 kPa'a çıkmıştır.

Karayolları Teknik şartnamesine göre Dtm-1'in yol inşaatında dolgular için kullanılabileceği ve bu uygulamalar için optimum kireç yüzdesi olarak %4 kireç oranı seçilmiştir. Ayrıca, Dtm-10 adlı malzemeninde dolgular için kullanıma uygun olguğu ve optimum kireç yüzdesinin %6 olduğuna karar verilmiştir. USACE'nin belirlediği limit değerlere göre de %4 oranında kireç içeren Dtm-1 ve %6 oranında kireç içeren Dtm-10 yol inşaatının alt temel tabakalarında kullanılabilir. Karayolları teknik şartnamesi çimento ile iyileştirme ile herhangi bir kriter belirlemediği için sadece

USACE’nin belirlediği kriterler göz önüne alınmıştır. Bu şartnameye göre ağırlıkça %15 oranında çimento ile iyileştirilmiş Dtm-1 ve Dtm-10 yol inşaatlarında alttemel malzemesi olarak kullanılabilir.

Bu çalışma kireç ve çimento katkı malzemeleri ile Tuzla bölgesinden çıkarılan ince daneli dip tarama malzemelerinin mühendislik özelliklerinin iyileştirilebileceği ve malzemenin yol dolgusu uygulamaları için kullanılabiliceğini gösterilmiştir.

1. INTRODUCTION

Dredging could be defined as excavation of sediments from underwater by different types of dredger for various purposes. Dredging is essential to construct and maintain harbours, water ways, canals and infrastructure system for prosperity of people and economic development. There are four main causes of the dredging operations; navigation, material winning, and land reclamation and environmental dredging. Navigation includes dredging for construction and maintainance of ports, channels and water ways. Material winning includes excavation of coarse material for construction projects. Land reclamation is creation of new land for residential and industrial purposes. The environmental dredging is needed for removal of contaminated material from the seas and rivers.

In parallel with increasing in the world population, the volume of global trade develops each year so the need for new and wider harbours and waterways results in extensive dredging operations. Besides, the volume of contaminated dredged material increases with the dumping of residential and industrial waste to the sea, rivers and lakes which is associated with increase in daily and industrial activities. Disposal of dredged materials can be achieved two methods; disposal at sea and disposal at land. The dredged material is dumped to disposal area in the sea. Unconfined or confined disposal project is carried out depending on the contamination condition of dredged material. When the dredged material is contaminated or fine-grained sediment, it is dumped into the sea depressions or constructed bound and is capped with clean material to isolate from marine environment, which is called as confined disposal method. The designed confined land areas are used to discharge dredged material for disposal at land. Dikes or ponds are used to isolate dredged material from environment. There are detrimental physical and chemical impacts of disposal at sea and land on the environment. Disposal at sea could eradicate fauna and flora of marine environment. The mounded dredged material leads to change in currents, waves by altering topography of seabed. Moreover, the contaminants could be released from disposed dredged material. The contaminants from land disposal of dredged material can easily release with leaching into the groundwater, rainfall surface runoff, release contaminant in the effluent, evaporation of effluent during and after the disposal operation and direct or undirect uptake by plants and animals (USACE,2004). Besides, the design and construction of land disposal area is not economical method for management of dredged material. Due to harmful impacts of dredged material disposal, there are many important organizations, conventions which aim to regulate dredging operations, to restrict and control disposal actions of dredged material and to assess environmental impacts of dredging operations and dredging material disposal.

As a result of impacts of dredged material disposal on environment, restriction of disposal at sea by regulations and conventions, dredged material has begun to be considered as a new material source for different types of projects which consume large quantities of material. Dredged material could be use beneficial for land remediation, beach nourishment, habitat creation, enhancement and restoration, agriculture, forestry and aquaculture, building materials, capping and road construction purposes.

There are various studies about the potential usage of dredged material as a road construction material and impacts of hydraulic binders on the engineering properties of dredged material. Because of weak engineering properties of dredged material, they are generally treated with hydraulic binders such as lime, cement and flay ash. The tests results indicate that hydraulic binders enhance the mechanic properties of dredged material to desired limits.

In this study, two different clayey dredged materials were used to investigate the impacts of hydraulic binders and to evaluate the potential use of dredged materials for road construction projects. Dredged materials were treated with lime and cement. The lime and cement contents were determined based on the previous studies, national and international guidelines. Lime was added to dredged materials in ratios of 2%, 4% and 6% of the dry weight of dredged material. Cement was added to dredged material in ratios of 5%, 10% and 15% of the dry weight of dredged material. The Atterberg limits tests, the miniature compaction test and the unconfined compression strength test were conducted on the untreated and treated materials. These tests were applied for each ratio of lime and cement treated material. The unconfined compressive strength test was conducted on lime and cement treated materials after 1, 7 and 28 days to observe strength development. Besides, sieve analysis and standard Proctor compaction test were conducted on the untreated sediments.

Previous studies which are about the reuse of dredged material and the effects of hydraulic binder on the mechanical properties of dredged material, are covered in Chapter 2. Chapter 3 provides information about the reasons of dredging operations, dredging equipment and environmental impacts of dredging activities, sea and land disposal of dredged material and international and regional environmental conventions and guidelines. This is followed by the explanation of beneficial usage methods of dredged material in Chapter 4. In Chapter 5, the characteristic of dredged materials, lime and cement and mix design method is explained. Conducted laboratory test is explained in Chapter 6. The tests results of each mixes are examined in Chapter 7. Finally, Chapter 8 includes the comparison of test results between each other and previous studies and the assessment of suitability of treated dredge material as a road construction material.

2. PREVIOUS STUDIES

Previous studies have evaluated the effects of different types of binders to stabilize dredged materials for reuse purposes. Particularly, geotechnical evaluation of cement, lime and another binder types treated dredged material for road construction have been studied by several authors. Reviewed researches have shown that stabilization of dredged materials with hydraulic binders ensures the needed geotechnical characteristics for road construction.

2.1 Effects of Lime on Characteristics of Dredged Materials

Siham et al. (2008) studied stabilization dredged material from Dunkirk harbour of France for the construction of foundation and base layers of roads. The significant reduction of water content is observed when 4% of lime is used by wet weight (Figure 2.1).

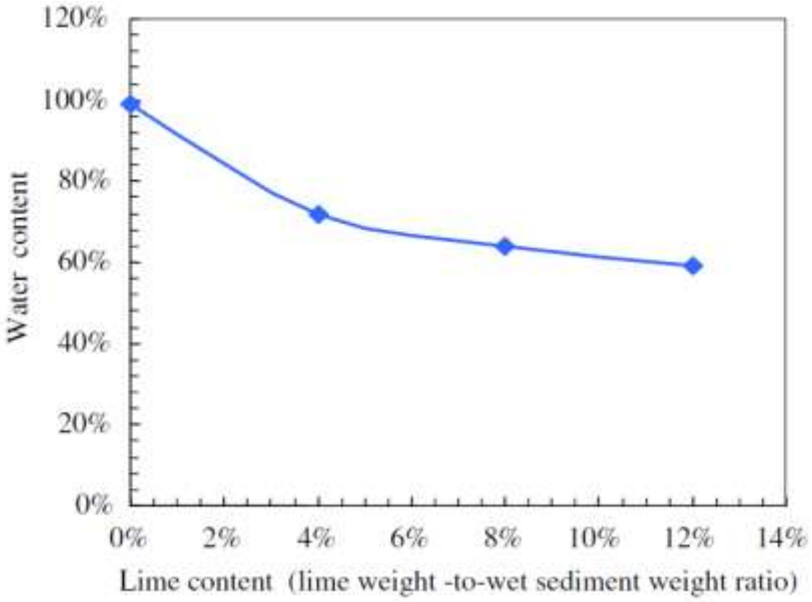


Figure 2.1 : Effect of lime addition on water content (Siham et al, 2008).

In order to be more economical and improve workability of material, Mixtures “A”, “B” and “C” were prepared with addition of dredged sand, cement and lime. The composition of mixtures represented in Table 2.1. The test results indicate that dredged materials could be used successfully for the road construction.

Table 2.1 : Composition of mixtures “A”, “B” and “C” (Siham et al, 2008).

	Dry content of mixture “A” (%)	Dry content of mixture “B” (%)	Dry content of mixture “C” (%)
Dewatered sediment	27	27	27
Dredged sand	37	39	39
Boulogne sand	28	28	28
Cem1	8	6	-
Cem2	-	-	6

Silva et al. (2003) noted the effect of binder content and curing time on the sediments of Quonset and Davisville channel. The dredged sediments were treated with lime at weight of percentages of 3%, 5%, 6% by weight. A compaction curve of the sediment with 3% lime plotted from the Harvard miniature compaction test results. As illustrated in Figure 2.2, the optimum moisture content was found to be about 19.5% and the compaction curve was compared with Modified Proctor test results. The test results indicate that when applied Modified Proctor test, the soil has greater maximum dry density and lesser optimum moisture content than the results of Harvard Proctor test, because of increased applied energy.

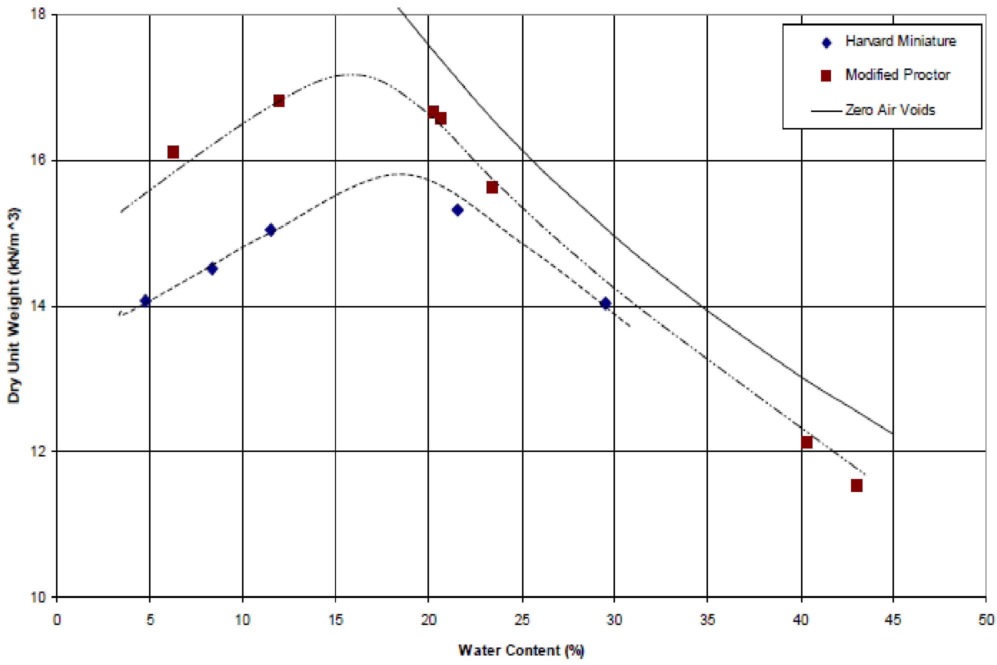


Figure 2.2 : Compaction curves of sediment mixed with 3% lime (Silva et al, 2003).

Unconfined compressions tests results of the sediment with 3%, 5%, and 7% lime at the optimum water content of 19.5% are showed in Figure 2.3, Figure 2.4 and Figure 2.5. Most of the compressive strength increase in the lime stabilized soil has occurred during the first 7 days of curing time. There is a modest increase in the compressive strength as a result of the increase in lime content.

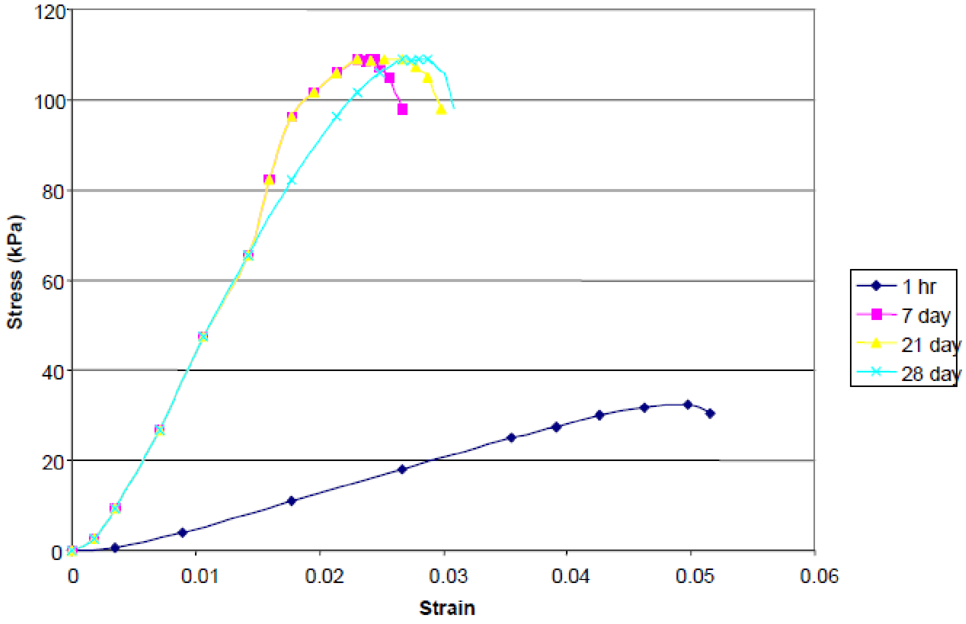


Figure 2.3 : Effects of 3% lime addition and curing time stress-strain curve of dredged sediments (Silva et al, 2003).

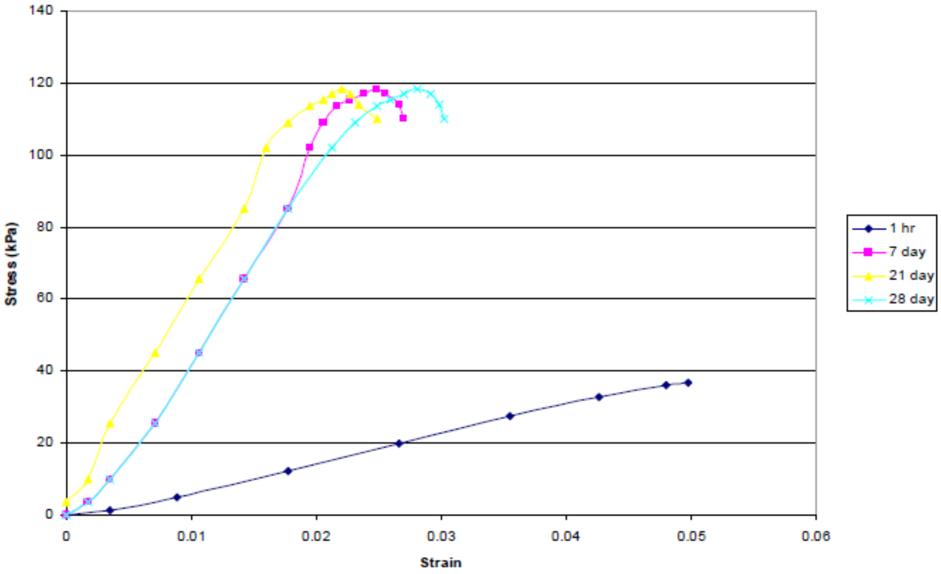


Figure 2.4 : Effects of 5% lime addition and curing time on stress-strain curve of dredged sediments (Silva et al, 2003).

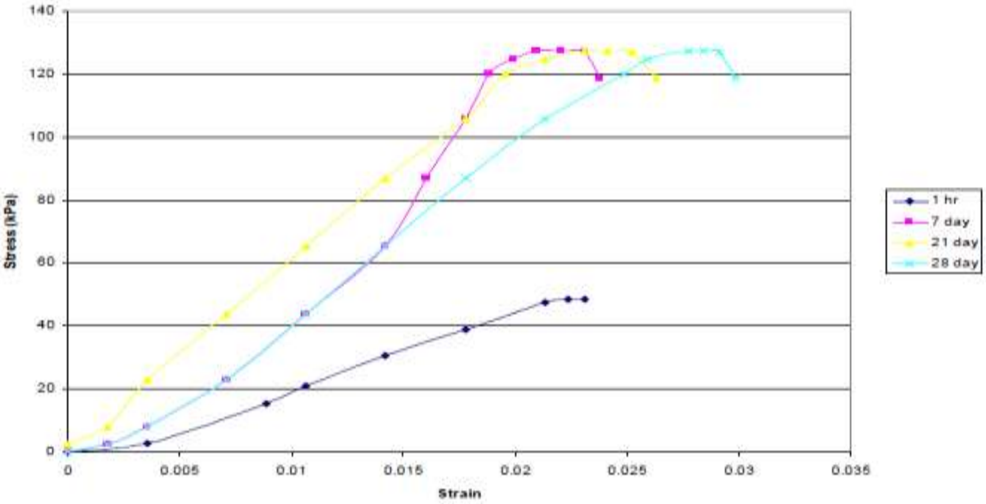


Figure 2.5 : Effects of 3% lime addition and curing time on stress-strain curve of dredged sediments (Silva et al, 2003).

Mir (2015) conducted some experimental tests to assess the impacts of lime stabilization on the engineering behaviour of dredged sediment from Tailbal Basin of Dal Lake. The mixes were prepared in the dry state and the lime percentages varies from 0% to 9% of dry weight.

The plastic limit of treated sediments increases while the liquid limit and plasticity index of treated sediments with addition of lime until 6% of dry weight of samples. The addition of 6% of lime has changed the classification of dredged sediment from CL to ML. After the addition of 9% lime, the plasticity index increases with the decrease in plastic limit (Figure 2.6).

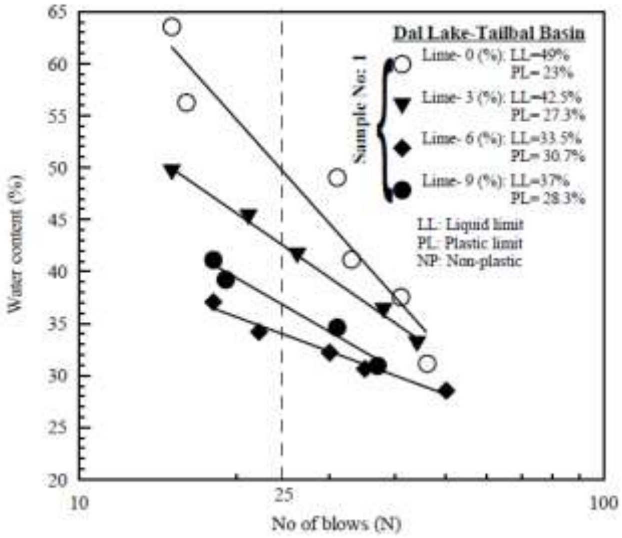


Figure 2.6 : Effect of lime addition on Atterberg limits (Mir, 2015).

Figure 2.7 indicates that addition of lime flattens compaction curve of dredged material thus the desirable dry density is provided over a much wider range of moisture content.

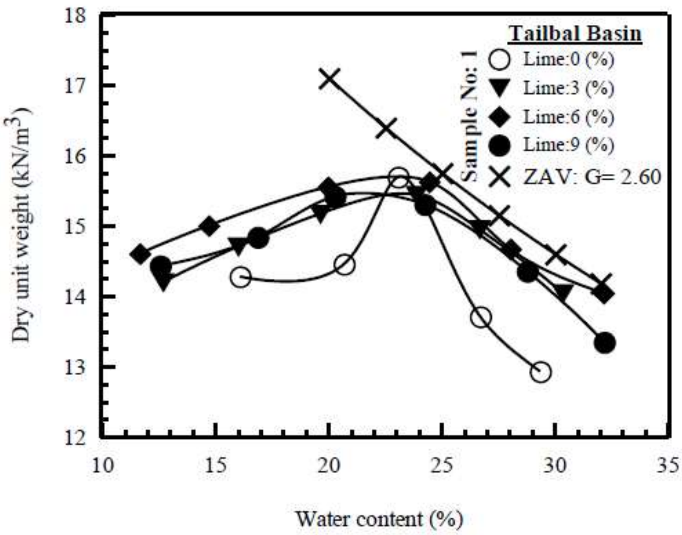


Figure 2.7 : Effect of lime addition on compaction curves (Mir, 2015).

The unconfined compression strength results of untreated and lime treated dredged sediment is shown in Figure 2.8. The strength of dredged sediment reaches peak value at 6% lime addition. The direct shear test results indicate that lime improves shear strength parameters (c_u and ϕ) of dredged soil significantly by pozzolanic reactions between soil and lime (Figure 2.9).

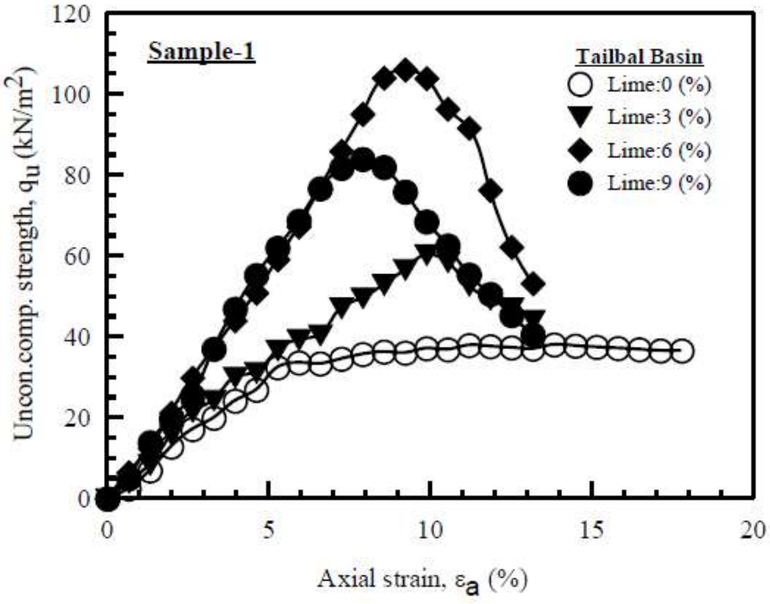


Figure 2.8 : Effect of lime addition on the unconfined compressive strength (Mir, 2015).

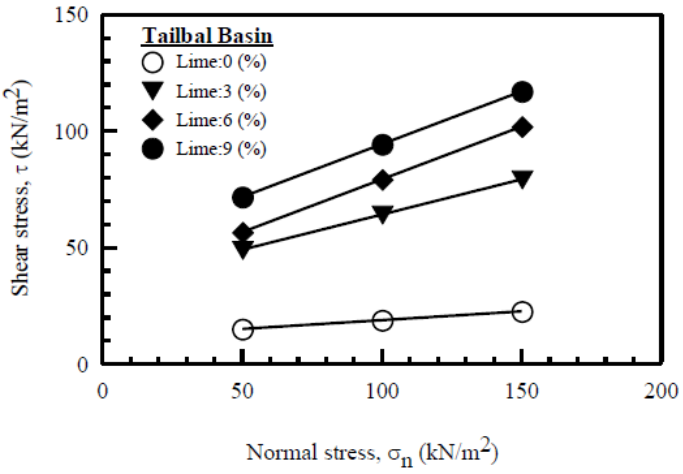


Figure 2.9 : Effect of lime addition on shear strength parameters (Mir, 2015).

2.2 Effects of Cement on Characteristics of Dredged Materials

Dermatas et al. (2003) investigated the effects of different amount of cement treatment and sediment water content on the engineering behaviour of the treated sediments as construction fill materials. The mixtures were prepared with 9 %, 11 % and 13 % by wet weight cement content and they were tested at 90 % (Low), 130% (High) and 170%(Very high) water content. The compaction test results show that an increase in cement addition resulted in decreased dry density values and that a higher initial water content will result in a lower maximum dry density value as seen in Figure 2.10. Also, the test results show that the strength of sediment increase with increasing cement content and lower water content. The increment of strength with curing time is more apparent at 9% and 11% of cement addition at low water content.

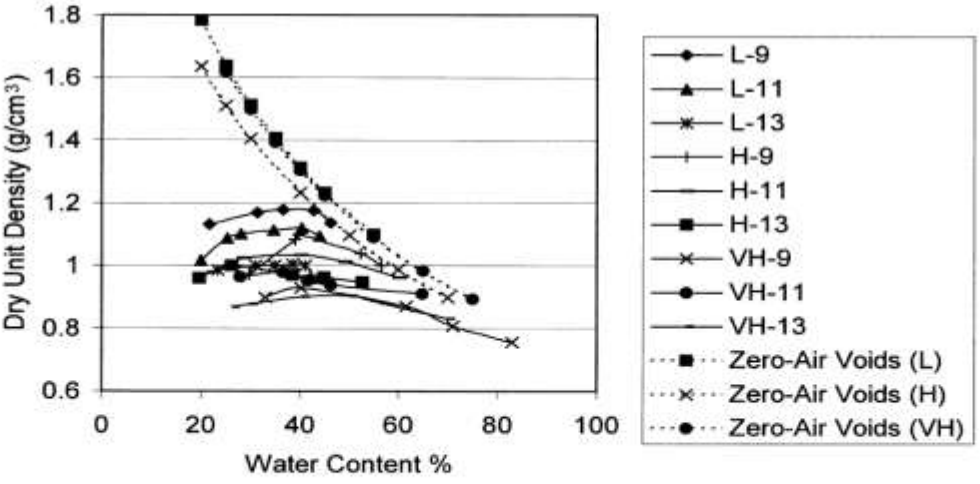


Figure 2.10 : The relationship between water content and dry unit density for different mixtures (Dermatas et al, 2003).

Yun et al. (2006) explored improvement mechanical properties of dredged clay sediments from Korea peninsula after the addition of Portland cement. Figure 2.11 shows the unconfined compression stress increase with curing time. In addition, the strength of cement stabilized soil is improved during the first 14 days of curing time.

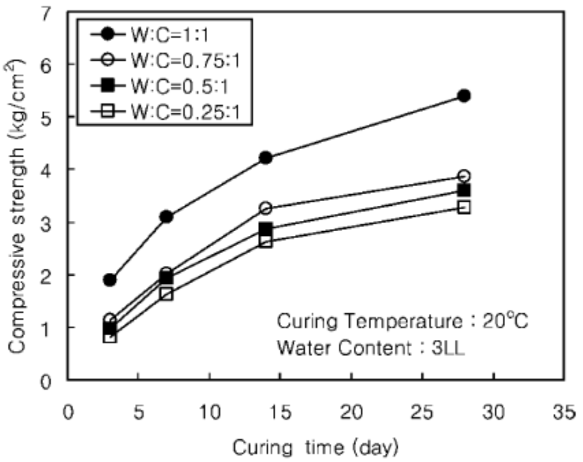


Figure 2.11 : Effect of curing time on the unconfined compressive strength (Yun et al, 2006).

El- Shinawi et al. (2015) reported that Portland cement stabilization can improve the engineering characteristic of dredged sediments from Hurghada coast at different content and curing time. The compaction test results show that there is an increase in optimum moisture content and decrease the maximum dry density with increase in cement content as flocculation of clay particles by cement (Figure 2.12).

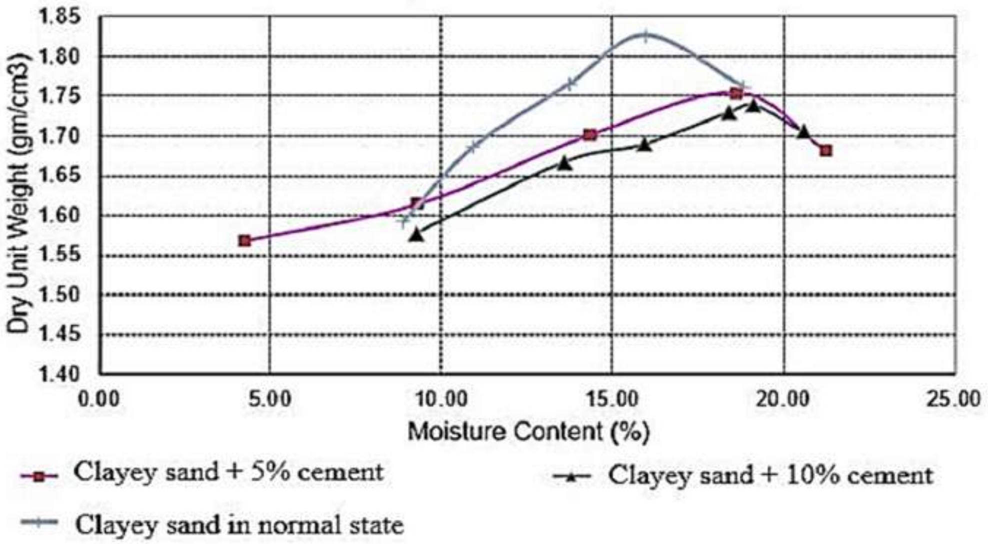


Figure 2.12 : Effect of cement addition on compaction curves of dredged sediments (El- Shinawi et al,2015).

Figure 2.13 and Figure 2.14 summarized the effects of cement content and curing time on the unconfined compression strength of samples. The strength of samples is improved by increase cement content and curing time.

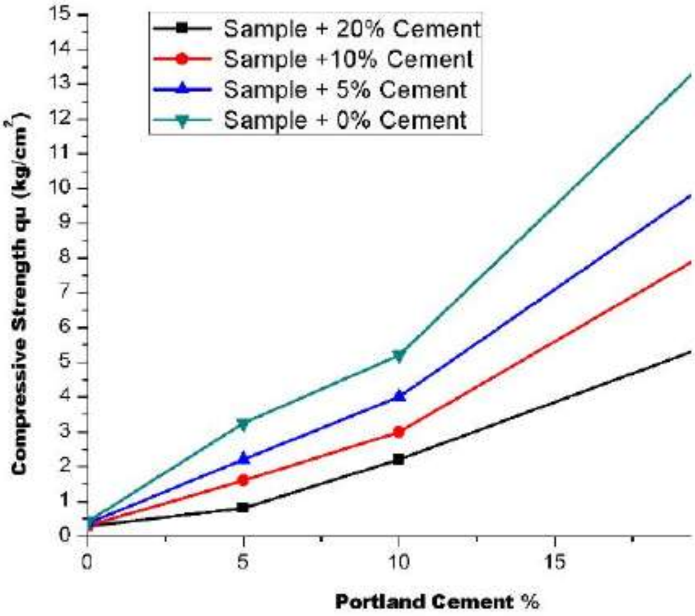


Figure 2.13 : Effect of Portland Cement addition on the unconfined compressive strength (El-Shinawi et al,2015).

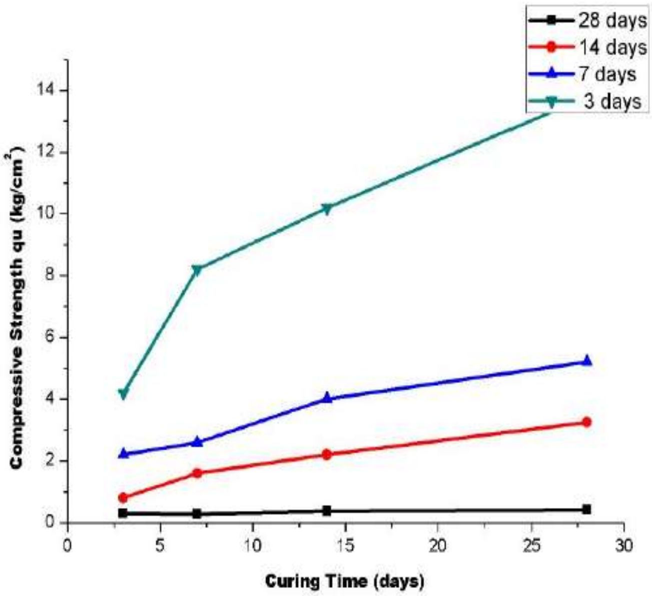


Figure 2.14 : Effect of curing time on the unconfined compressive strength (El-Shinawi et al, 2015).

Yusuf et al. (2012) noted that improved cement stabilized dredged materials could be used for various utilities particularly for subbase construction of roads. The strength of soil increases linearly with addition of cement and curing time as indicated in Figure 2.15 and Figure 2.16. The strength increase range of 1.978 kg/cm^2 (5% cement) and 10.31 kg/cm^2 (20% cement) for 3 days of curing time while for 28 days of curing time, the strength is 5.155 kg/cm^2 (5% of cement) and 22.004 kg/cm2 (20% cement).

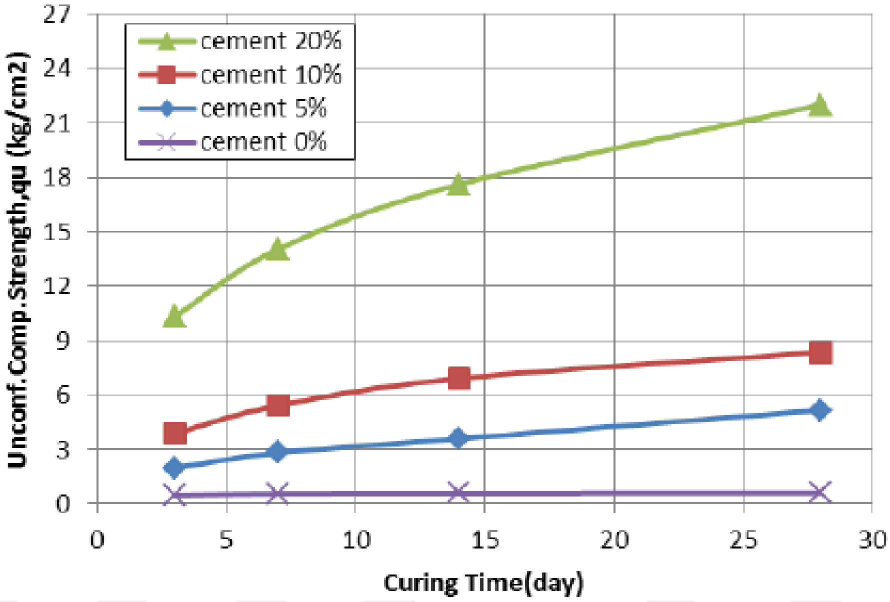


Figure 2.15 : Effect of curing time on the unconfined compressive strength (Yusuf et al, 2012).

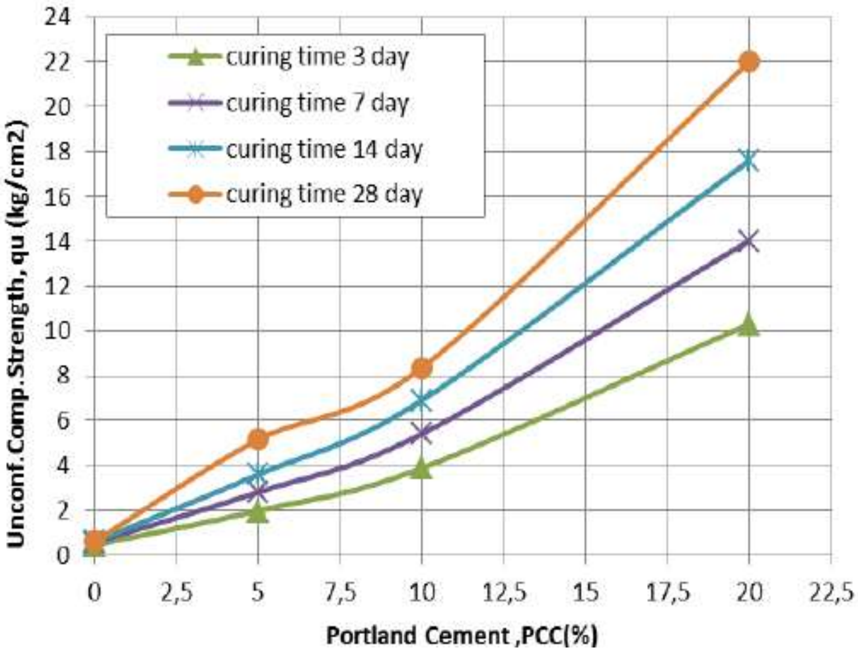


Figure 2.16 : Effect of Portland cement addition on the unconfined compressive strength (Yusuf et al, 2012).

Nontananandh et al. (n.d) investigated the influence of the cement ratio and the initial water content on the unconfined compression strength of seabed dredged material to use as bottom liners for landfill. The seabed dredged materials contained very high-water content. Therefore, their water content reduced by dewatering process to obtain target water content which were within range of approximately 140% and 110%. The mixtures with initial water content before mixing at 108.99% were prepared with 100, 125 and 150 kg/m^3 cement contents (SC108/100, SC108/125 and SC108/150, respectively). Also, the mixtures with initial water content before mixing at 137.87% with 150,200 and 250 kg/m^3 cement contents (SC137/150, SC137/200 and SC137/250, respectively).

The test results show that there is increase in the unconfined compression strength of all mixtures with curing time (Figure 2.17 and Figure 2.18). The most remarkable increase of strength is seen at 14 days of curing time.

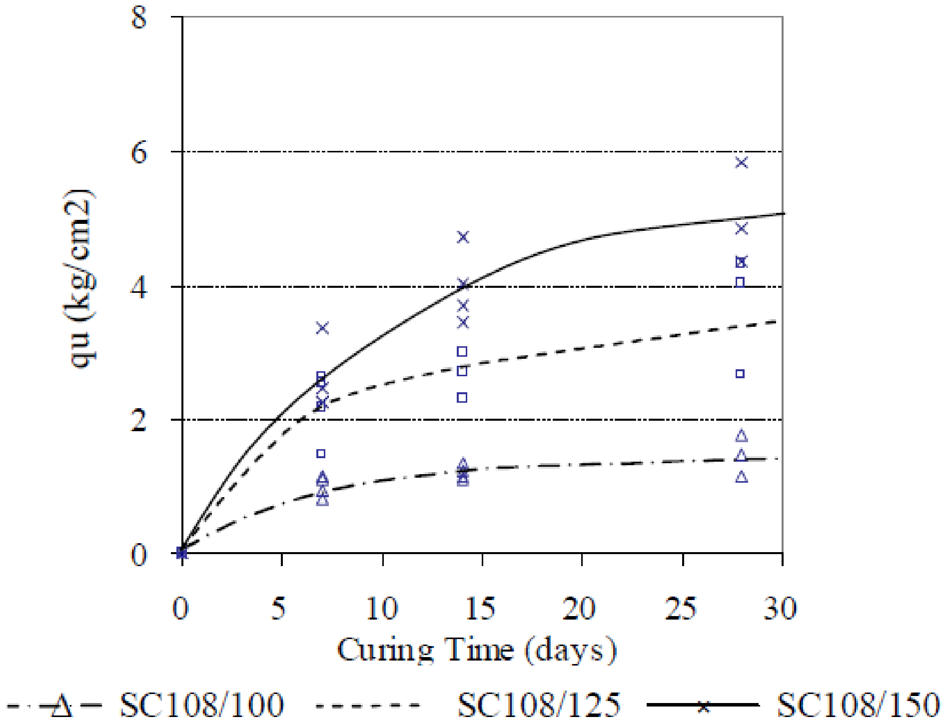


Figure 2.17 : Effect of curing time on the unconfined compressive strength (Initial water content before mixing at 108.99%) (Nontananandh et al, n.d).

As shown in Figure 2.19, there is a linear relationship between increase of strength of mixtures and the cement content for initial water contents before mixing at 108.99 %.

However, the strength of mixture improved significantly after the addition 200 kg/cm^3 cement content for initial water contents before mixing at 137.87% (Figure 2.20).

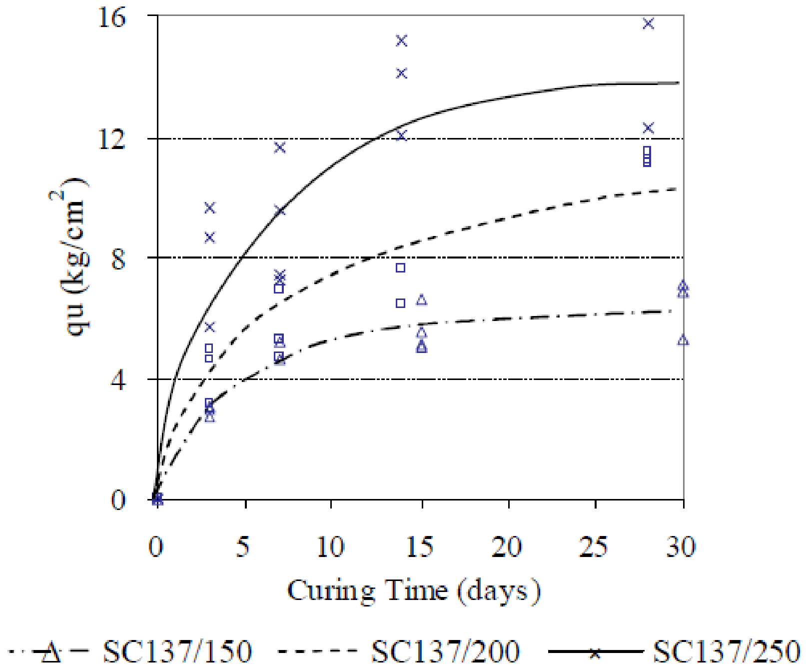


Figure 2.18 : Effect of curing time on the unconfined compressive strength (Initial water content before mixing at 137.87%) (Nontananandh et al, n.d).

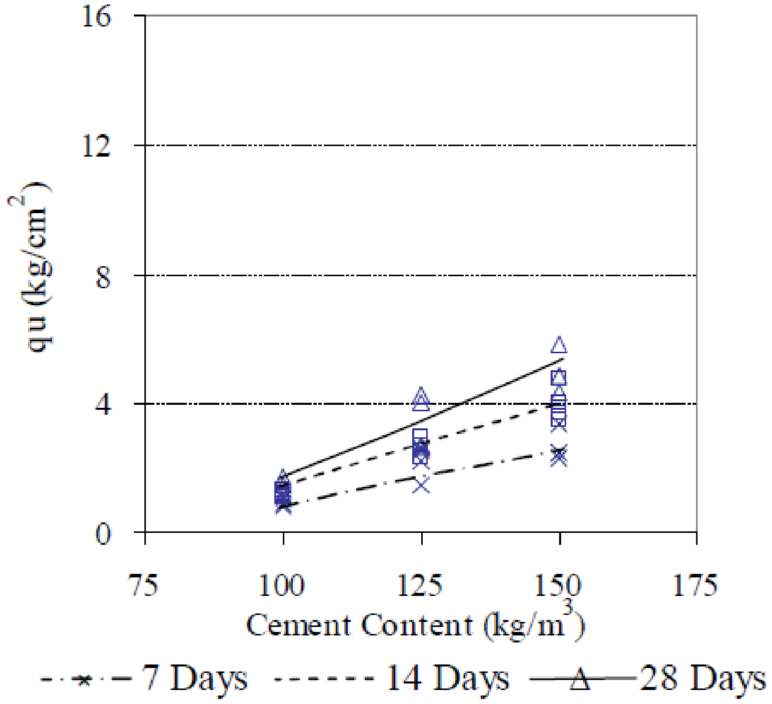


Figure 2.19 : Effect of cement addition on the unconfined compressive strength (Initial water content before mixing at 108.99%) (Nontananandh et al, n.d).

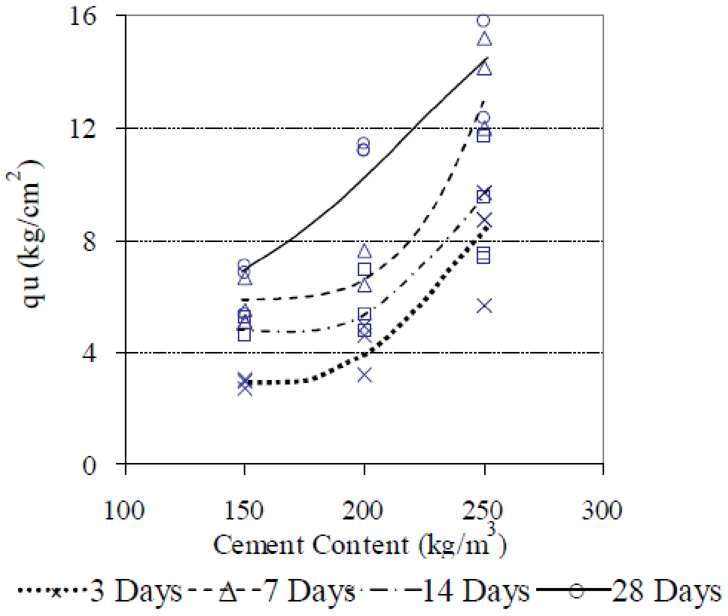


Figure 2.20 : Effect of cement addition on the unconfined compressive strength (Initial water content before mixing at 137.87%) (Nontananandh et al, n.d).

As can be seen in Figure 2.21, the engineering properties of seabed dredged sediment is affected by not only cement content but also initial water content before mixing. Researchers recommended that w/c ratio should be within the range of 5.5 - 6.5 for using as a landfill material.

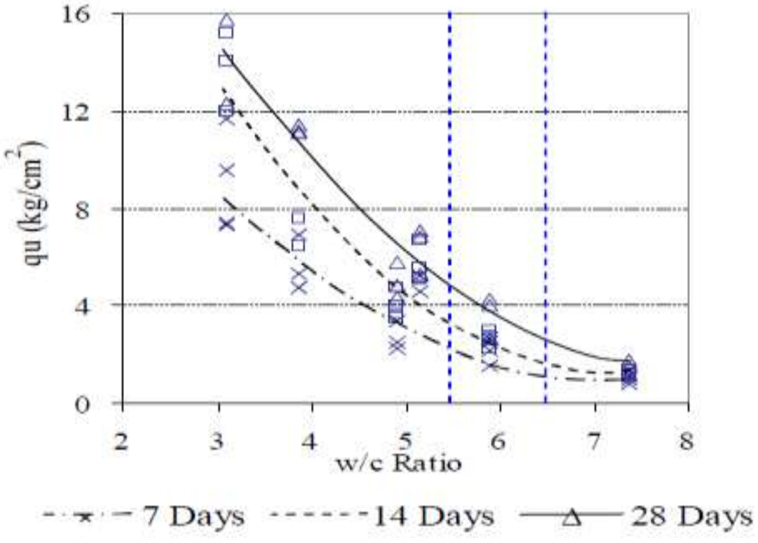


Figure 2.21 : Effect of water cement ratio on the unconfined compressive strength. (Nontananandh et al, n.d).

Rekik et al. (2009) examined effects of cement treatment on the engineering properties of dredged marine sediments at their original water content by using Atterberg limits and unconfined compression test.

As shown in Figure 2.22, the plasticity index decreased while liquid and plastic limit increased because of the increase in cement content. This evolution is more clearly pronounced for 6% and 8% cement content. The relationship between cement content and reduction of plasticity index is explained by an increase in particle size.

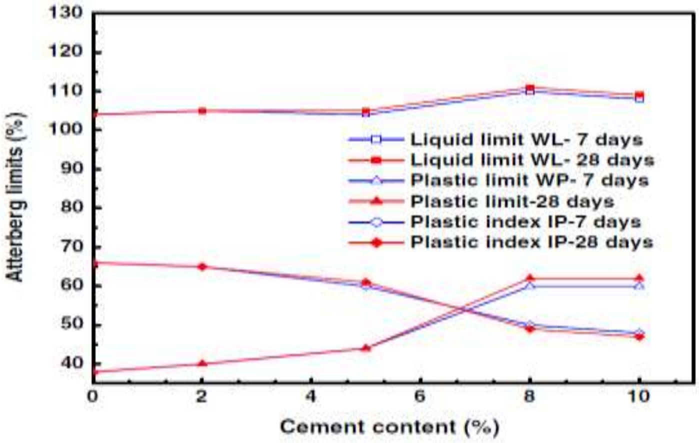


Figure 2.22 : Effect of cement content and curing time on Atterberg limits (Rekik et al, 2009).

Zhu et al. (2009) investigated the effects of cement content and curing time on the mechanical behaviour of dredged sediments. Figure 2.23 indicates that the relationship between unconfined compression stress and cement content for 7 and 28 days curing time. The unconfined compression strength increases linearly with addition of cement up to 300 kg/m^3. On the other hand, the unconfined compression strength increases nonlinearly beyond 300 kg/m^3.

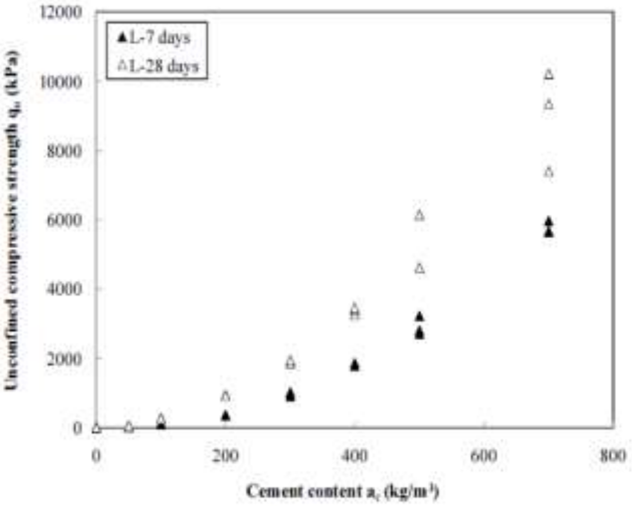


Figure 2.23 : Effect of cement addition on the unconfined compression strength (Zhu et al, 2009).

2.3 Effects of Lime and Cement on Characteristics of Dredged Materials

Wang et al. (2012) experimentally studied the effect of cement and lime on Atterberg limits and mechanical properties of dredged fine material for road construction. As indicated in Figure 2.24 and Figure 2.25, the liquid limits of both sample increase with addition 3% of binder, this value reaches peak when the binders content raise to 6% and decrease steadily with 9% binder.

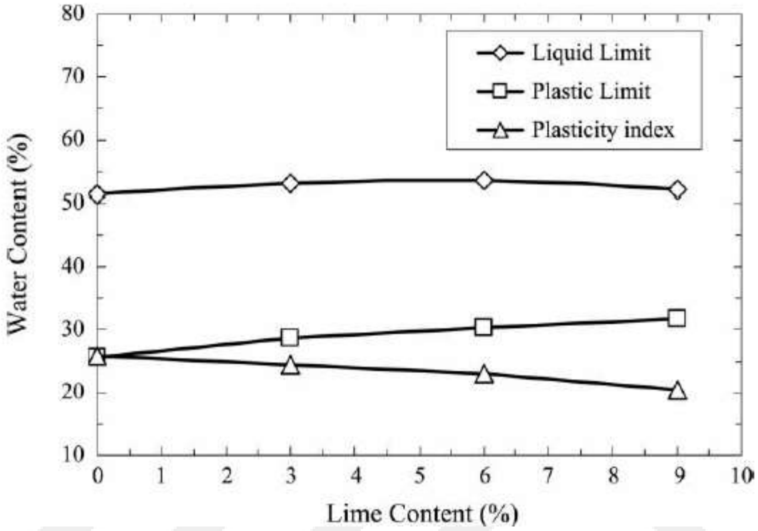


Figure 2.24 : Effect of lime addition on Atterberg limits (Wang et al, 2012).

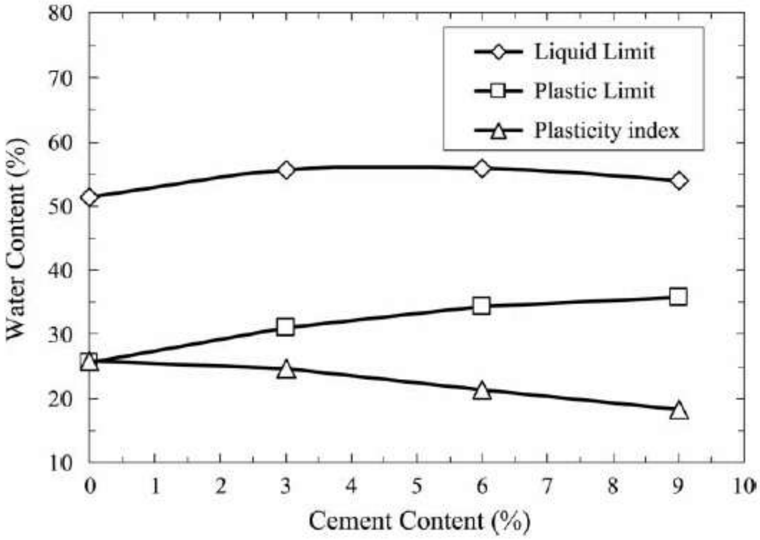


Figure 2.25 : Effect of cement addition on Atterberg limits (Wang et al, 2012).

Compaction test results indicate that with addition of binders, the optimum moisture content of materials increase when their maximum dry density reduce. They also indicate that the optimum moisture content of lime stabilized sediment is lower than that of cement stabilized sediment at the same binder content. Figure 2.26 shows the unconfined compressive strengths increase with binder content and curing time. However, the mechanical characteristic of cement stabilized samples is higher lime stabilized sample.

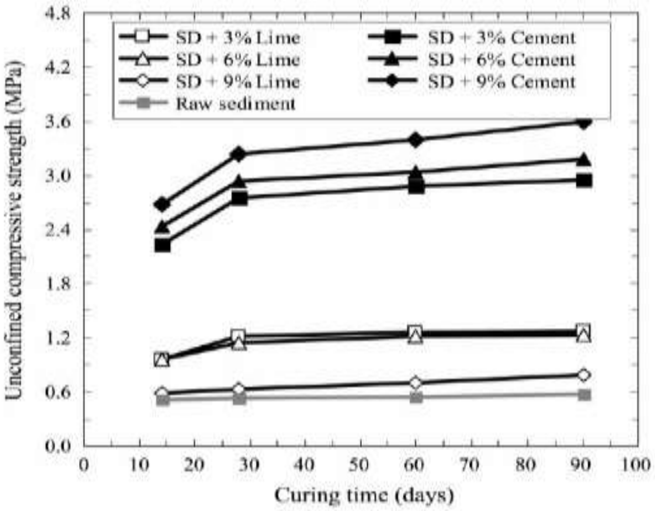


Figure 2.26 : Effect of binder content and curing time on the unconfined compressive strength (Wang et al, 2012).

Dubois et al. (2009) investigated the potential usage of dredged fine sediments in combination with sand and hydraulic binders as a road construction material. Mix 1 consist of 33% fine dredged sediments, 61.3% dredged sand, and 5.7% cement. Mix 2, differently from Mix1, consist of 2% lime. Figure 2.27 indicates that the optimum moisture content and the maximum dry density of the mixtures are similar and addition of lime does not cause any change. Also, the CBR test results indicate that the bearing ratio of both of mixtures three times higher than raw sediment.

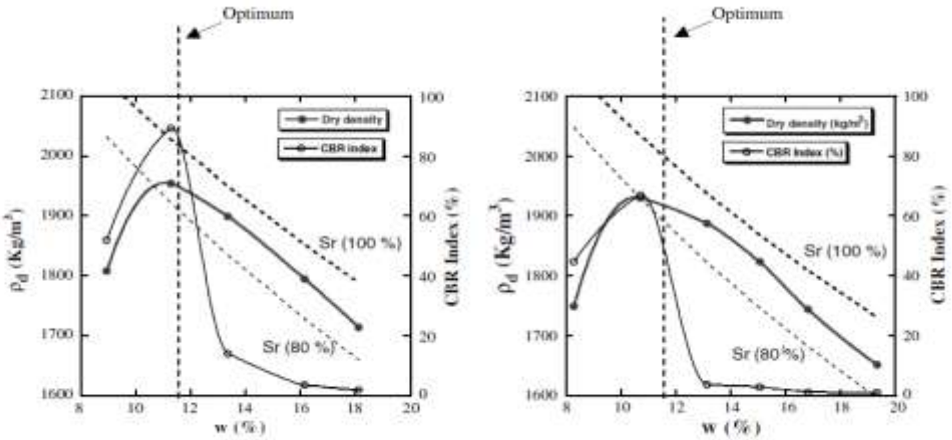


Figure 2.27 : The relationship between the optimum moisture content and maximum dry density (Dubois et al, 2009).

The Atterberg limit tests were conducted by Federico et al (2015) that gave the effects of different amount addition of lime and cement on the plasticity paths of dredged clayey sediments. Figure 2.28 and Figure 2.29 shows that two days curing time is enough to transform the dredged sediment from CH to MH soil regardless of type of binders and contents. Also, all plasticity paths are characterized by an increase of plasticity limit which leads to decrease of plasticity index. According to the test results, the sufficient content of binders is 8% for reducing plasticity index.

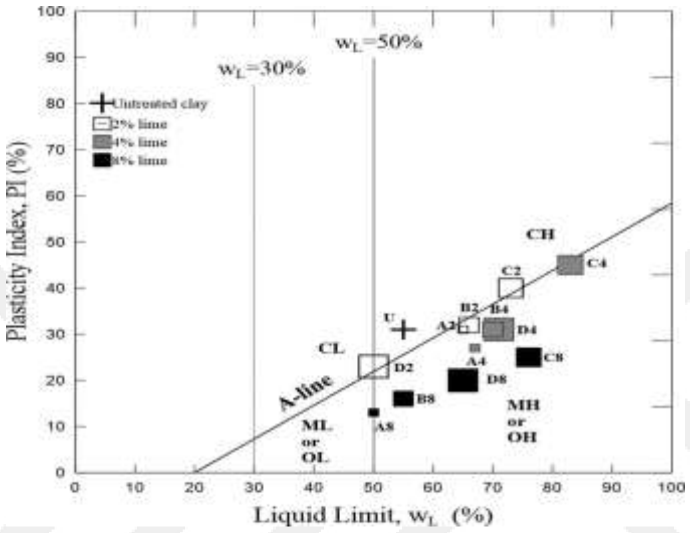


Figure 2.28 : The plasticity paths of lime treated clay (Federico et al, 2015).

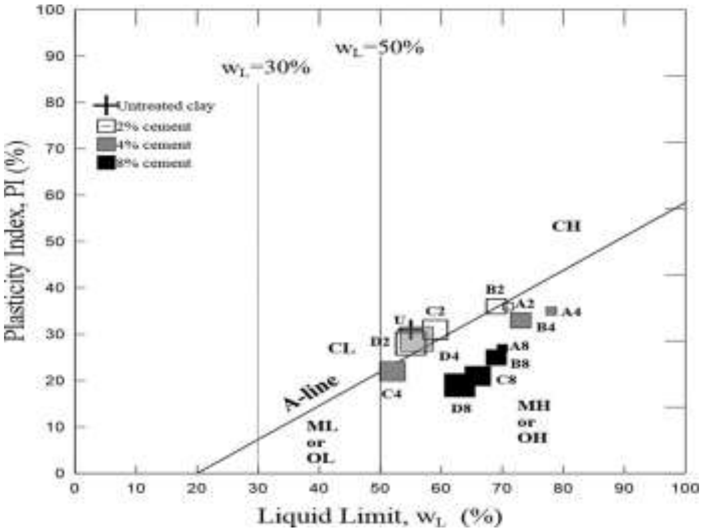


Figure 2.29 : The plasticity paths of cement treated clay (Federico et al, 2015).

Zarei et al. (2014) reported the improvement of the dredged clayey soil from Mahshahr Port by adding cement and lime for ratios between 2% and 15% of sediment dry weight and effects of lime or cement stabilization were investigated by performing unconfined compressive strength and Atterberg Limits tests. As summarized in Table 2.2 and

Table 2.3, the plasticity index decreases with the addition of hydraulic binders and curing time. This decreasing trend of plasticity index is seen more clearly for cement treated soil rather than lime treated soil. After addition of 6% lime by weight, the plasticity index of soil became steadier. Also, for higher than 6% cement content, Atterberg limits were not observed because the hardening of the samples.

Table 2.2 : The effects of cement content and curing time on plasticity index (Zarei et al,2014).

Cement Content Percent by Weight (%)	PI for 3 days curing	PI for 7 days curing	PI for 14 days curing	PI for 28 days curing	PI for 60 days curing	PI for 120 days curing
0	13	13	13	13	13	13
2	11	11	9	-	-	-
4	9	8	5	-	-	-
6	6	4	-	-	-	-
8	-	-	-	-	-	-
10	-	-	-	-	-	-
15	-	-	-	-	-	-

Table 2.3 : The effects of lime content and curing time on plasticity index (Zarei et al,2014).

Cement Content Percent by Weight (%)	PI for 3 days curing	PI for 7 days curing	PI for 14 days curing	PI for 28 days curing	PI for 60 days curing	PI for 120 days curing
0	13	13	13	13	13	13
2	12	12	11	10	8	-
4	12	11	10	8	7	-
6	13	9	8	5	3	-
8	13	12	10	8	8	-
10	13	12	11	10	8	-
15	13	13	12	10	9	-

The unconfined test results of cement or lime treated sediments are indicated in Figure 2.30 and Figure 2.31. As shown in the figures due to high sensitivity of these soils, the strength of soil decreases with addition lime or cement, initially. The unconfined compression strength increases gradually with time. Up to 6% cement content, the strength of samples is higher than undisturbed sample without curing time. On the contrary, the strength of lime treated samples are less than the undisturbed sample until 60 days curing time has passed.

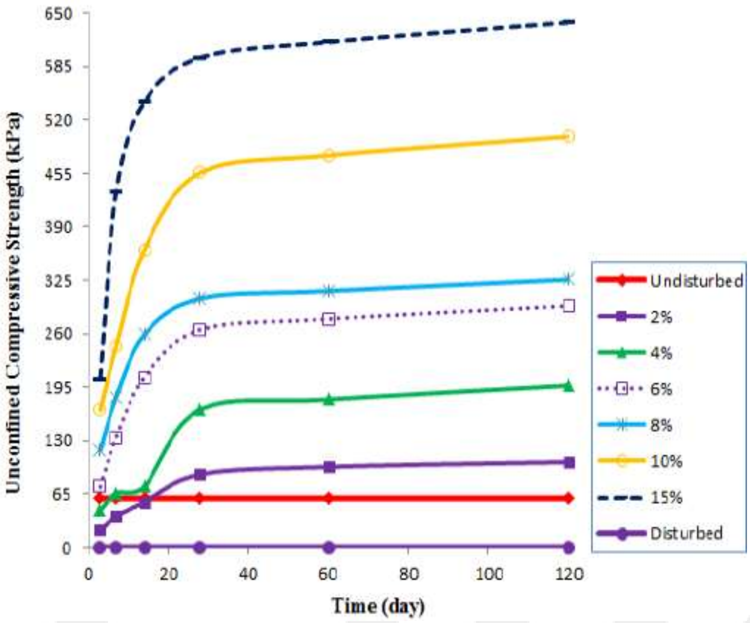


Figure 2.30 : Effect of curing time on the unconfined compressive strength (Zarei et al, 2014).

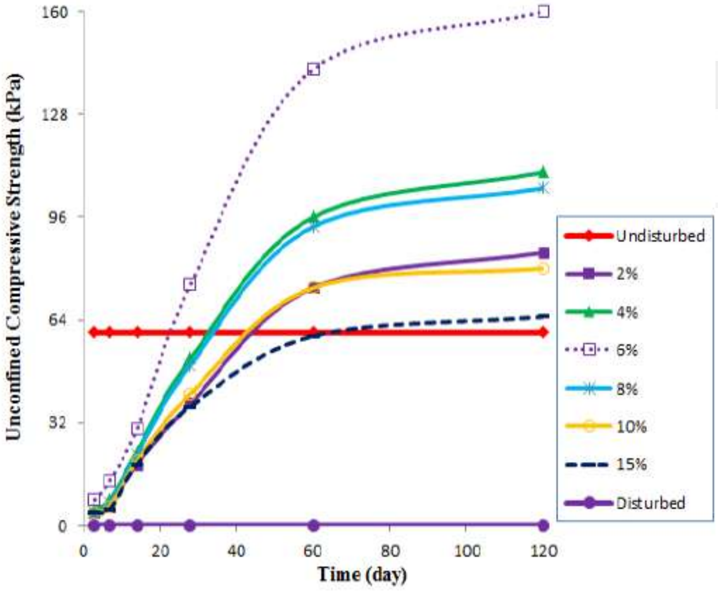


Figure 2.31 : Effect of curing time on the unconfined compressive strength (Zarei et al, 2014).

Figure 2.32 and Figure 2.33 represent the changes of compressive strength of the soil sample with different times for different the cement or lime content. The effect of cement content is more notable with addition of 8% cement and after 7 days of curing. On the other hand, the effects of curing time are more effective after 14 days of curing time for lime treated samples. Moreover, the strength of soil increases with addition of lime and reach peak value at 6 % lime content. The unconfined compression strength of soil decreases dramatically up to 6% lime content as result of formation of silicate ions in the soil.

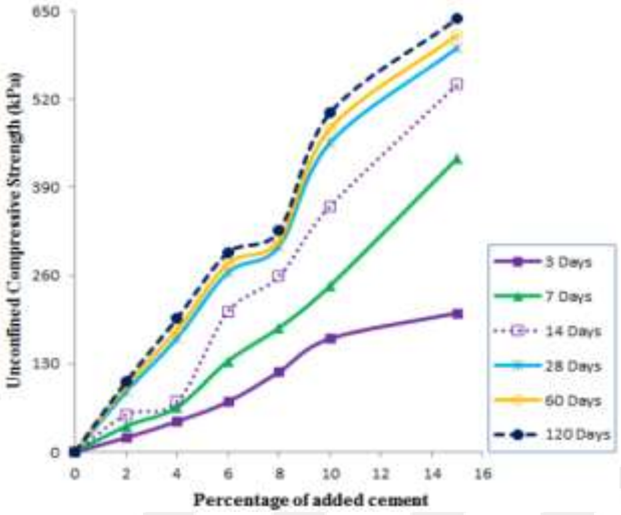


Figure 2.32 : Effect of cement addition on the unconfined compressive strength (Zarei et al, 2014).

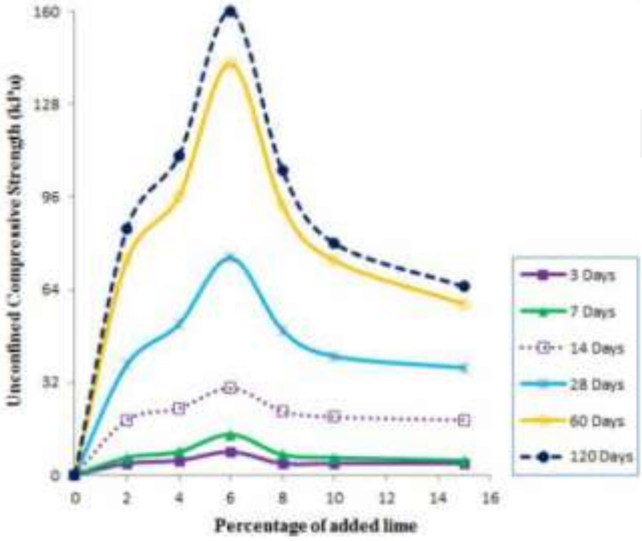


Figure 2.33 : Effect of lime addition on the unconfined compressive strength (Zarei et al, 2014).

Jauberthie et al. (2010) evaluated geotechnical suitability of lime and/or cement treated dredged estuarine silt for using as a sub-base for lightly trafficked local roads. The mixes were prepared at 1.5%, 3%, 4%,5% and 7% dry weight for both lime and cement. Also, cement-lime treated mixes were prepared at 0.75% +0.75%, 1.5%+1.5%, 2%+2% and 3.5%+3.5% cement and lime content.

The effects of lime content and curing time on the unconfined compression strength is given in Figure 2.34. The unconfined compression strength of material increases from

0.6 MPa to 1.0 MPa for lime addition of between 1.5% and 7% at 7 days curing time. The strength of material doubled after 28 days of curing time for 7% lime content. This dramatic increase because of the relatively slow lime reaction kinetics in the storage conditions.

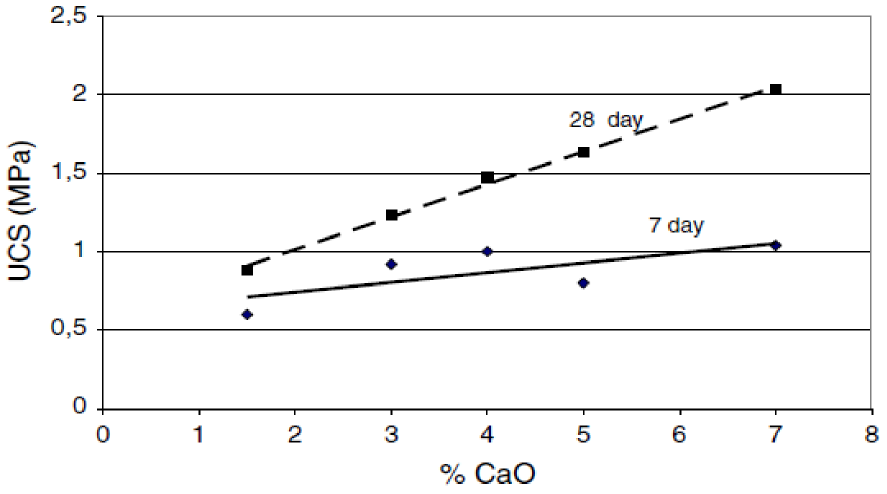


Figure 2.34 : Effect of lime addition and curing time on the unconfined compressive strength (Jauberthie et al, 2010).

The effects of cement content and curing time on the unconfined compression strength is given in Figure 2.35. The increase of the unconfined compression of cement treated sediment (1.7 MPa) greater than lime treated sediment (1.0 MPa) at 7 days of curing time. On the other hand, the increase of strength connected with the time of curing is more considerable for addition of lime rather than cement.

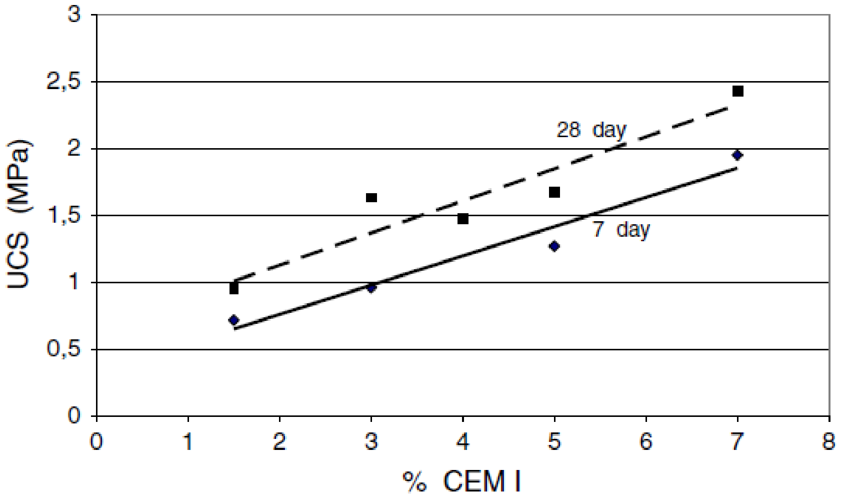


Figure 2.35 : Effect of cement addition and curing time on the unconfined compressive strength (Jauberthie et al, 2010).

Figure 2.36 indicated that cement lime stabilization ensures highest improvement of strength which is 3 MPa for 28 days curing. Besides, the moisture content prior to placement could be controlled by pre-treatment of sediment with lime. Reaction between and clay lead to binding of modified peds by cement with a degree of long term strength gain.

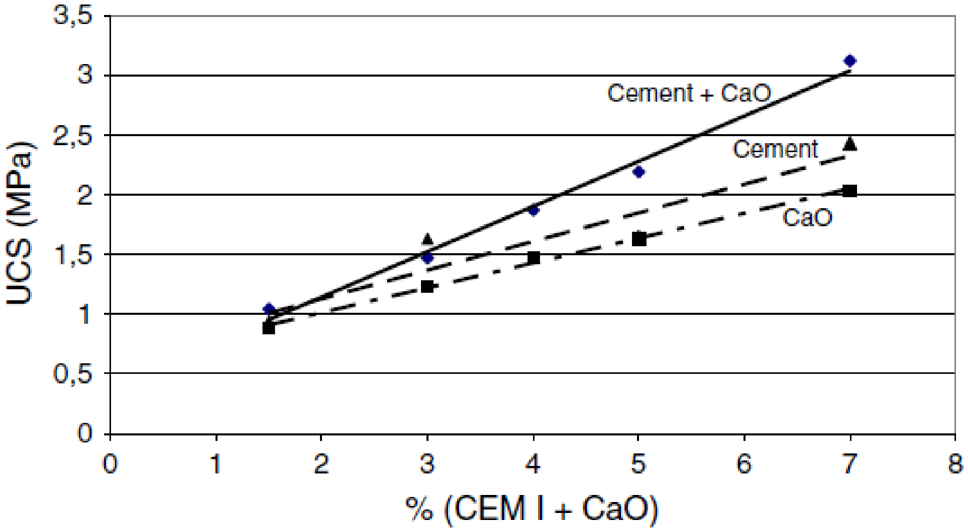


Figure 2.36 : Effect of cement and lime addition on the unconfined compressive strength (Jauberthie et al, 2010).

Banoune et al. (2016) carried out experimental work to assess the usage of lime or cement treated dredged sediments for use in the road field. Used sediments are dredged from the Soummam river and the dam of Kherrata; they are noted as (S) and (K), respectively.

Atterberg limits tests results indicate that the plasticity index decreases with addition of lime due to the formation of aggregation which cause to notable increase in the plastic limit while the liquid limit of samples increases slightly. Also, cement treatment cause rapid formation of physical connections between particles and this evolution causes to decrease in plasticity index.

Figure 2.37 and Figure 2.38 indicate that the unconfined compression strength of both sediments increase with addition of hydraulic binders. The most considerable increase in unconfined strength of Soummam sediment is seen for 4% cement content while this increase in unconfined strength of Kherrata sediment is seen for 15% cement content.

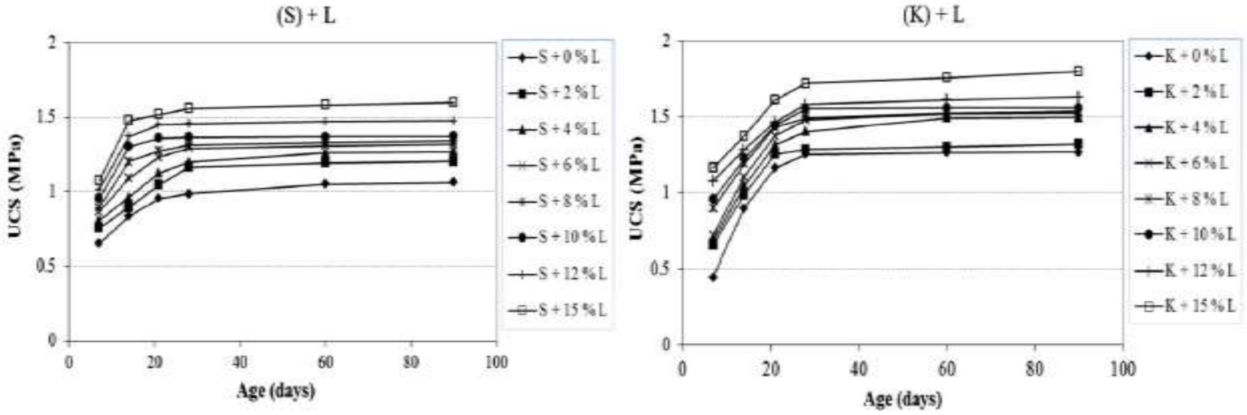


Figure 2.37 : Effect of lime addition on the unconfined compression strength of Soummam and Kherrata sediments (Banoune et al, 2016).

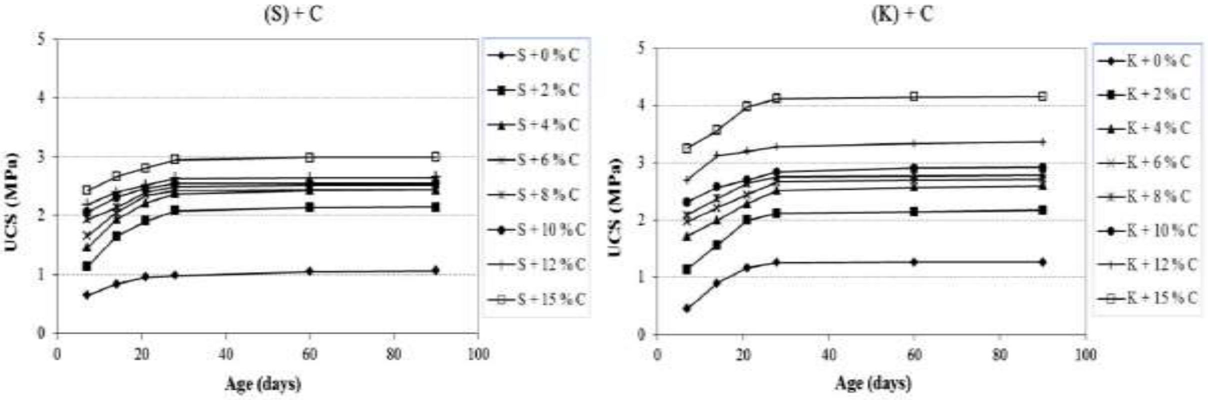


Figure 2.38 : Effect of cement addition on the unconfined compression strength of Soummam and Kherrata sediments (Banoune et al, 2016).

As can be seen in Figure 2.39, not only lime but also cement stabilization achieves required strength for road construction, which is greater than 1 MPa, with addition of 4% and 2% hydraulic binders after 7 and 21 days of curing time, respectively.

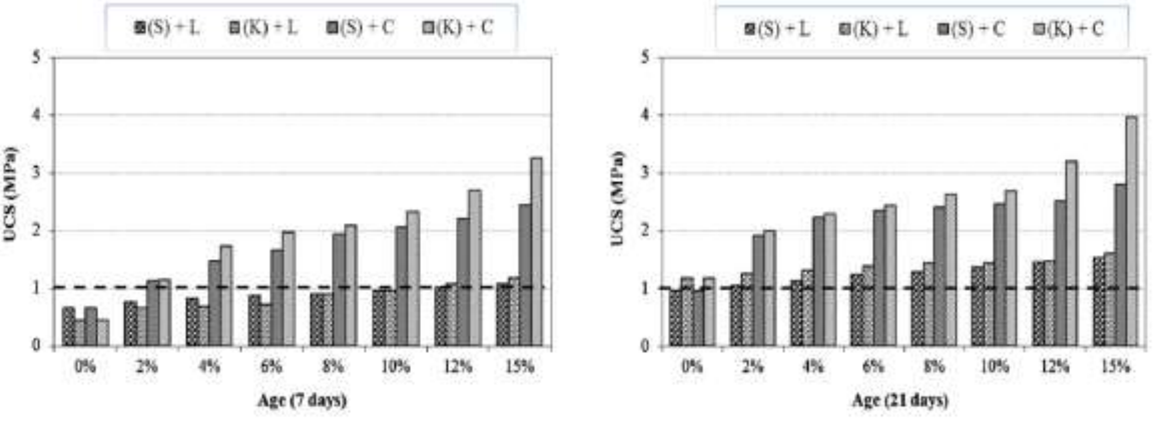


Figure 2.39 : Effects of curing time on the unconfined compression strength of Soummam and Kherrata sediments (Banoune et al, 2016).

3. DREDGING OPERATIONS

3.1 Reasons for Dredging

Waterways have been used to transport people, materials and goods from the beginning of civilization. Therefore, people needed dredge for construction of new harbors, channels and extension, maintenance of existing marine structures. Dredging operations have become more complex and a larger industry with the technological developments. Nowadays, millions of cubic meters of sediments are dredged easily with modern dredgers to build ports, basins channels, to create landfill for environment or to winning material for manufacturing concrete. As a result of wide range application purposes of dredging, dredging operations, have important role in social and national-international economic developments of countries and environmental system of the world. The needs of society determine the amount of dredging operations so there is a relationship between dredging and some factors such as global trade, energy supplies, demographic and urban development coastal protection, tourism.

The increasing global trade has most important effect on dredging operations. Seaborne transports nearly 85% of volume of world trade (Clarksons Research, 2016). The amount of ships and ships size are getting larger and the demand for appropriate ports is increasing with growing world trade. Dredging providing solutions to construct new harbors, to maintenance and deepen ports, channels. Filling for land creation or beach nourishment another important part of dredging operations. İncreasing world population and intensity of urban inhabitants are demanding more residential and industrial lands. As a result of erosion and sea level rise, dredging will be required for beach nourishment. Another important driver of dredging industry is the energy sector. The fossil fuels such as oil and gas are made use in offshore in. Dredging operation is required to prepare seabed, to excavate and backfill trenches for pipelines. Also, offshore wind tribunes’ construction needs excavation for foundation by dredging (IADC, 2015).

3.1.1 Navigation

The main purpose of dredging is generally navigation which includes sediment excavation for construction, and maintenance. Huge quantities of materials are dredged from seas and rivers to construct new harbours, canals, basins and to maintain existing marine structure and waterways. The Navigation Data Center estimates that approximately 90 million m^3 of material dredged for new navigation and maintenance project in U.S.A. in 2016. According to the datas of Turkish Rebuplic ministry of transport, maritime affairs and communication, annual volumes of dredged material is 1.5 million m^3 in Turkey.

Dredging operation for construction new harbour, channel and waterway or deepening, enlarging existing structures could be defined as capital dredging. The marine structures are needed to be capacity improvement to be able to provide increase demands of sector. As shown in Figure 3.1, the container ships become larger to carry enormous amounts of goods. Existing harbours and channels must be widened and deepened and turning basins are provided in order to accommodate larger ships.

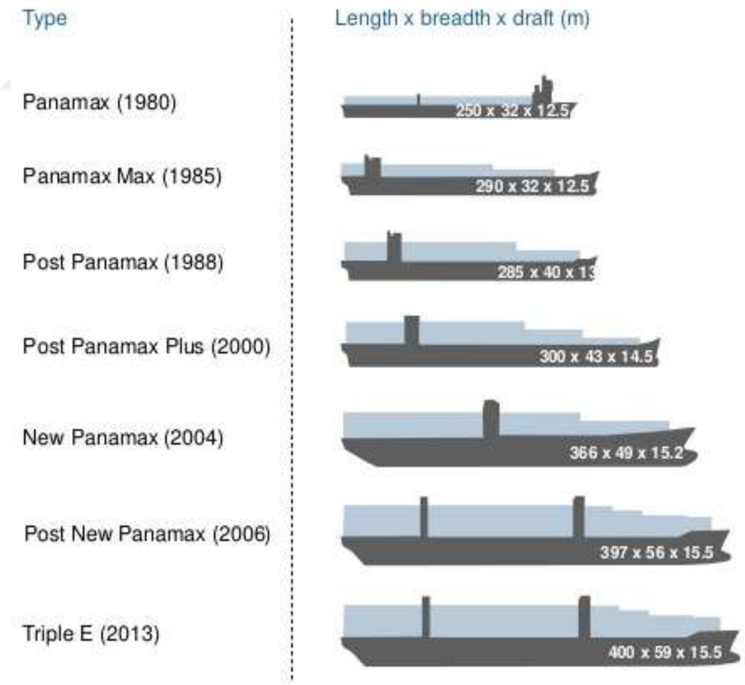


Figure 3.1 : The evaluation of container ships (https://www.slideshare.net).

Channels and waterways may become shallow for navigation due to accumulation of sediments such as sand, silt or mud. Maintenance dredging could be defined as the periodic removal of sediments and siltation from existing harbours, channels, berths to ensure that maintain adequate depth of waterways for accessible shipping traffic. Accumulation of sediments in the deepened area due to waves, river flow, tidal and water currents. There is need to a lot of knowledge about behaviour of sediments, estuary, tides, waves, currents, bends and flow channels.

3.1.2 Material winning

Aggregates are essential raw materials to build environment; they are used ever stages of construction projects. The main compounds of concrete, cement and asphalt are aggregates. With the increasing demand for aggregates and environmental restriction about land-based mining, alternative resources gain importance to obtain aggregates. Marine aggregate, which is vital source, is excavated from seabed by dredger to use in concrete production. International Council for The Exploration of The Sea (ICES) reported that the annual production of marine aggregates for construction in United Kingdom, France and Netherlands ranged between 12-14 million m^3 while only 1 million m^3 of marine aggregate is dredged from Turkey in 2013(as cited in Otay et al,2015).

The process of dredging includes extraction of aggregates and unloading into a ship's cargo hold. There are two types of dredging techniques; trailer suction dredging and static suction dredging. Trailer suction dredger, which is the main method of marine aggregate extraction, has large powerful pumps that enable dredge sand and gravel from the seabed. The drag head is trailed across the sea bed at slow speed. The pump system sucks up sediments and the vessels stores the dredged material in its own hopper. They are also suitable for harbour maintenance and land creation.

Static suction dredger need to be anchored while extract sediments. These vessels suitable for deep waters and thicker sand, gravel extraction. However, they are sensitive for rough weather conditions and the cannot operate harbour, channel construction.

There are different types of discharge system for instance bucket wheels, scraper buckets or wire hosted grabs for delivering cargo to wharf or processing plant. The most demanding products are coarse, medium sand and specific grades of gravel. Figure 3.2 indicates the process of marine aggerate separation. Oversize gravels are crushed into smaller grades. Conveyor carries aggregates to screening plant for washing and separating process of materials. Aggregates are separated as regard their grade size. The sand is dewatered and the material is stockpiled (Highley et al, 2007).

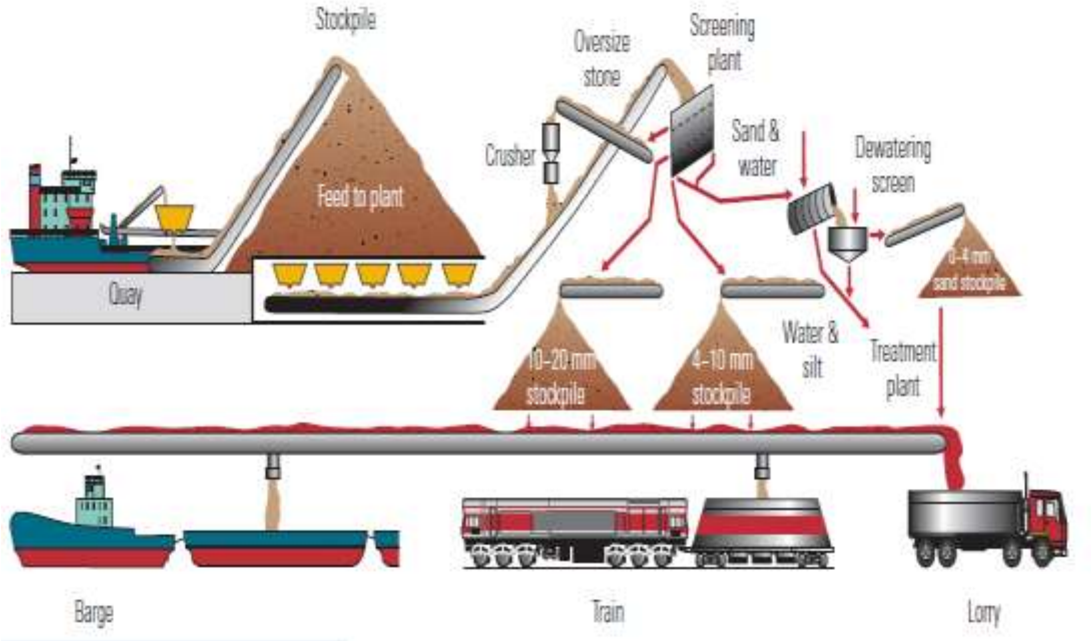


Figure 3.2 : Marine aggregate processing (Highley et al, 2007).

3.1.3 Land reclamation

The increasing world population and rapid development of urbanization and industrialization resulted in high demand for new lands. Especially, restricted coastal zones need to more residential and industrial areas. Hydraulic fill is used to create new land for airport, harbour, dam, housing, road, industrial projects by raising the sea-bed levels with recovered suitable dredged material. There are some many examples of large or small-scale reclamation projects in the Japan, Netherlands and Singapore.

The planning and design process of project is complex as require good knowledge and experience about geotechnical, hydraulic and environmental engineering. In the planning stage of project, the seabed condition, type of seabed soil, the availability of fill material and equipment’s, fill material features, the effects of reclamation project on environment should be assessed. The proper fill materials for reclamation are find to medium quartz sand. Carbonate sand, silt or clay may be chosen for reclamation when high quality material is not available. Fill material is excavated from offshore borrow source and transported to the reclamation area by dredger. Fill material is placed as a mixture of fill material and water in the reclamation area (Figure 3.3). The excavation and dumping of filling material has impacts on the environment. As a result of land reclamation, the fauna and flora of marine environment is changing dramatically. The habitats of many organism are deteriorated and destroyed. The water quality may influence due to changes in sediment movements, siltation and currents (Hoff et al, 2012).

Figure 3.3 : The dumping process of land reclamation (http://onyxresources.onyxgoc.com/).

3.1.4 Environmental dredging

Uncontrolled aggressive industrial production, consumption of human-made chemicals and urbanization resulted in accumulation hazardous chemicals in sediments. As shown in Figure 3.4, Vink et. al. distinguished the sources and the pathways of contaminants to three sections; rural areas, urban areas, industrial and mining. In rural areas, the sources of contaminants are waste dumps, geogenic background, agriculture and atmospheric deposition and they have been emitted through soil and ground water. Contaminants from traffic, building materials, industry and households are transmitted by sewer system to water in urban areas. Shipping, industry, tailing and effluents have directly effects on contamination (as cited in

SedNet, 2004).(8) Contaminated sediments constitute five different types of chemicals; nutrients and raw sewage(phosphorus and nitrogen), organic hydrocarbons(oil and grease), Halogenated hydrocarbons and pesticides (dichlorobiphenyl-trichloroethane (DDT), polychlorinated biphenyls (PCB’s)), polycyclic aromatic hydrocarbons (petroleum and petroleum by products), heavy metals (iron, zinc, lead, cadmium and mercury) (Tencate,2013).

Contaminants have adverse effects on the environment and human health. The presence of contaminants pose threat to marine ecosystem, which includes many types organism, and humans who directly contact and consume marine animals. Environmental dredging is removal of contaminant sediments from waterways, harbours, estuaries, rivers etc. Environmental dredging process is more precise and is affected by numerous factors. The process includes site investigation, determination of dredging techniques, transportation of sediments, selection of disposal or treatment type. The type and concentration of contaminants, depth, currents impact all stages of environmental dredging. Proper dredging technique should be selected to minimize the resuspension of contaminants and water content, remove all contaminant sediments with thin layer (EPA, 2005; IADC, 2014).

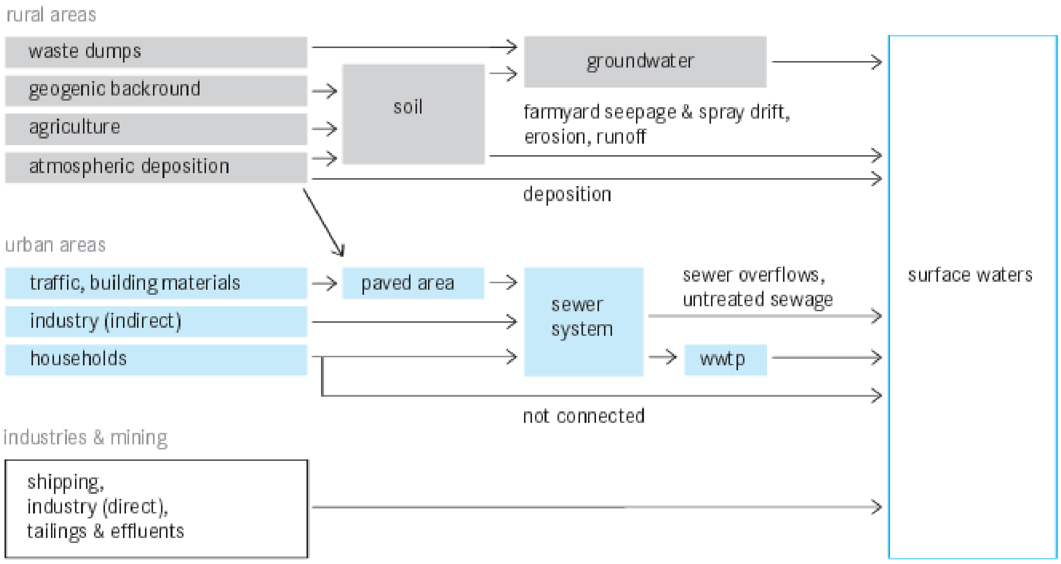


Figure 3.4 : The sources and pathways of contaminants (as cited in SedNet, 2004).

3.2 Dredging Equipment

A dredger could be defined as a machine which can excavate, transport sediments from the under the water and discharge to barge or proper area. Depending on excavation method dredgers could be divided two main categories; mechanical and hydraulic dredgers. The selection of dredging equipment depends on the water depth, weather and wave conditions, characteristics of dredged area, type of dredged material, dredging operation requirements, the accessibility to site etc.

3.2.1 Mechanical Dredgers

Mechanical dredger includes a bucket, clamshell or grab, which is mounted on the pontoon, to dig sediments from the bottom. Dredged material is discharged to a barge or their own hopper. These types dredged are also called as stationary dredger. Mechanical dredger is moored by anchors system or spud legs. The most suitable soil types for mechanical dredgers are cohesive soils.

3.2.1.1 The bucket dredger

The bucket dredger, which is one of the oldest type of dredger, is a stationary dredger. The most important part of bucket dredger is composed of endless chain of buckets, which has a cutting edge, mounted on a ladder (Figure 3.5). The top tumbler, at the upper part of ladder, drives chain while the lower tumbler fixes, at the bottom, its. These tumblers ensure rotation of buckets to excavate and transport sediment. When the bucket moves to downward and reaches to the seabed, sediment is loosened by each bucket. After, the material is transported to the highest point of ladder, the bucket overturns and material is discharged barges. The bucket is filled at the lower tumbler and is discharged at upper tumbler where the cycle begins again (Figure 3.6).

Figure 3.5 : The chain of buckets (http://www.qzauma.com).

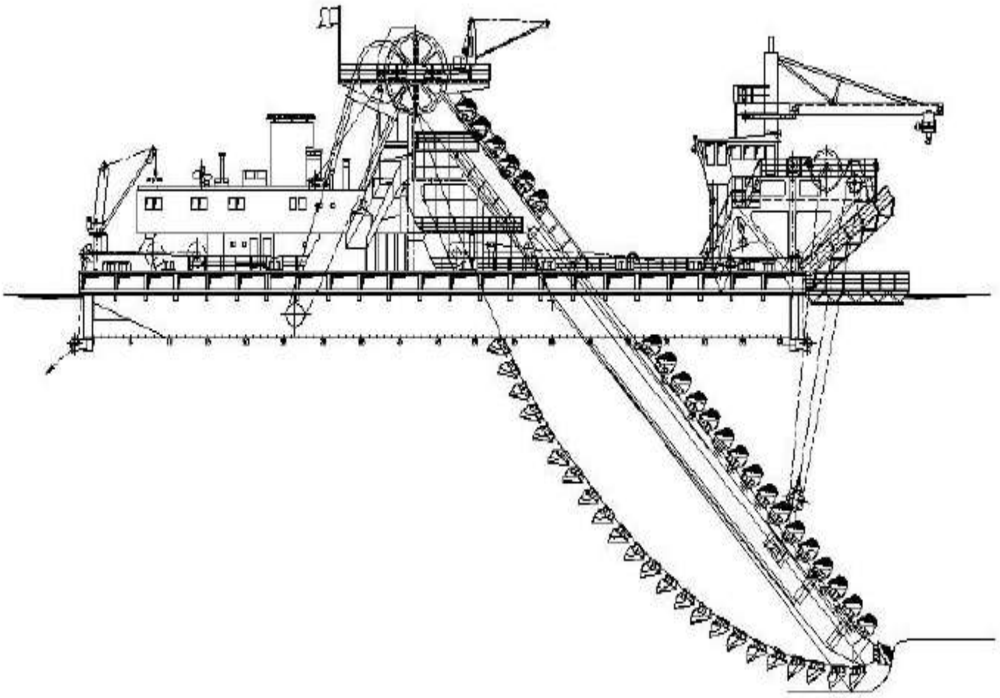


Figure 3.6 : The bucket ladder dredger (http://www.dsboffshore.com).

The bucket dredgers are suitable almost all types of soils from cohesive to non-cohesive soils. This type of dredgers can be used for rock materials with enough strength of the bucket chain. The bucket size is in the range from 30 litres to 2100 litres. The depth of dredging is related with dredger size and is varied in range between 8 m and 30 m. Bucket dredgers are complex and costly dredgers hence nowadays they are generally used for dredging contaminant mud (Vlasblom,2003).

3.2.1.2 The grab dredger

Another type of stationary dredger is a grab dredger, which provides simple and economic usage thus it is the most common used type of dredger (Figure 3.7). The grab is located on pontoon and there is a hopper in latter to store dredged material. Anchors or spud poles are used for mooring the dredger. The positioning system has an important effect on effectiveness of dredging operation.

The opening of two half shells of grab is controlled by closing and hoisting wire or hydraulically. When dredging, the grab is lowered to the seabed. Then, the garb is closed by pulling the hoisting wire. The filled grab is raised and opened by releasing the closing wire for discharging dredged material to the hopper or barge (Figure 3.8).

Figure 3.7 : The grab dredger (https://www.dredgingtoday.com).

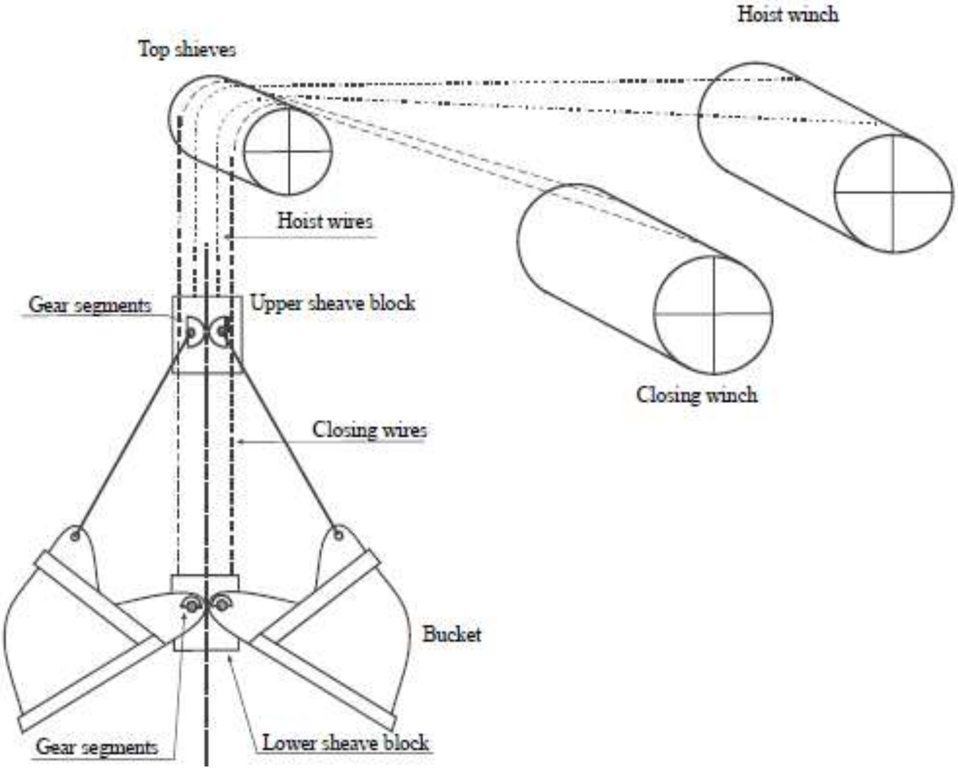


Figure 3.8 : The opening system of grab (Vlasblom,2003).

The grab dredger can be used consolidated silt, soft clay, loose and gravel extraction. Large and heavy grab dredgers are suitable for excavation of rubbish, old piles and rubbers while smaller grab dredgers can be used for reaching difficult accessible places of harbours, quay walls, docks and basins. The capacity of grab is varied in range between 1 m^3 to 20 m^3. The dredging depth is not depending on the size of dredger, it is related with length of the wires so the depth of dredging is not limited. However, it should be noted that the accuracy of dredging decreases with depth (Vlasblom,2003).

3.2.1.3 The backhoe dredger

A backhoe dredger is a hydraulic excavator equipped with a half open shell. The excavator unit is mounted on the pontoon (Figure 3.9). The excavator could be integral part of dredger or mobile type adopted for dredging operations. The backhoe dredger is moored by spud legs which look like heavy pile. Spud legs are penetrated seabed by dredger to secure the position of dredger when dredging. There are three spud legs; two spuds are mounted at the front side of the pontoon to provide to provide resistance and one of them is located at the aft side to assist in movement through working area. When dredging, the pontoon is elevated by spud legs to deliver the excavation forces to the seabed and backhoe pulls the bucket to the dredger. Material is dredged and loaded barges by bucket.

Figure 3.9 : The backhoe dredger (http://www.jandenul.com).

The backhoe dredger is suitable for excavation off compacted sand, stiff clay and weak rock. The bucket capacity is between 0.5 m^3 to 13 m^3. The production amount depends on bucket size and the hardness of material. The dredging depth is limited by spud legs so the depth of dredging could be maximum 25 m (Vlasblom,2003).

3.2.2 Hydraulic dredgers

Hydraulic dredgers are operated by pumping that sediment is transported by a pipe system in form of suspension from the bottom to the dredger. Mechanical loosening by water jets is required for harder soils while only suction is sufficient for soft soils. Hydraulic dredgers most suitable for non- cohesive soils such as sand, gravel.

3.2.2.1 Plain suction dredger

Plain suction dredger includes dredges pump, suction pipe and discharge pipe (Figure 3.10). The suction pump is connected to dredge pump and is placed at the front of the pontoon. When dredging, this type of dredger’s position is controlled by a wire or anchor system or one or more spud legs. The working method “suction dredging” is the erosive action of water flow near the suction pipe by created by dredger pump. When it is necessary, suction pipe is equipped with water jets for assisting to loosen material. The loosened material is mixed water and this sludge is transported through pipeline and discharged to barges or reclamation area. The plain suction dredgers are only suitable for non-cohesive soils. The most common usage areas of these type dredgers are material winning and environmental dredging projects. The diameter of the discharge pipe varies between 100 mm and 1000 mm. Plain suction dredger can dredge material from great depths over 100 m (Vlasblom,2003).

Figure 3.10 : The plain suction dredger (http://www.engineersdaily.com).

3.2.2.2 Cutter suction dredger

Cutter section dredger consists mechanical cutter head differ from plain suction dredger. Cutter head is mounted at the end of the ladder and it is used to loosen the material to be dredged. The loosened material pumped through suction mouth by the pumping action of dredger. The sand-water mixture is discharged to barges or is transported through the pipeline to reclamation area. The dredging action starts when the working spud is lowered into the ground, ladder is lowered and swing movement starts. The material is dredged with swing motion, which is controlled by pulling anchor wires at the end of two side of ladder. The force of wires depends on the soil type, the position of anchors and external forces such as weather condition, waves and currents. Forward motion of dredger, called as step, is generated by spud poles. After each swing motion, the spud carriage move the dredge one step forward. The working spud is hoisted, the spud carriage reaches end position and the step spud is lowered. After this, the spud carriage is repositioned to new start point and the working spud is lowered when the step spud is hoisted. This working method provides high accuracy.

Cutter suction dredger used widely in capital dredging for harbours, reclamation areas. This type of dredger can be suitable for all types of soils ranging from soft clay to moderately strong rock. The diameter of the suction pipe and the installed machinery power identify the capacity of dredger. The diameter of pipes varies between 100 mm and 1500 mm (Vlasblom,2003).

3.2.2.3 Trailing suction hopper dredger

Trailing suction hopper dredger, which is self-propelled dredger, includes its own hopper and one or two suction pipes ending in drag head (Figure 3.11). The dredger sails slowly and sweeps over the seabed when dredging. When a dredger reaches the dredging location, it reduces speed the suction pipes are lowered to the seabed. Trailing drag head moves over the seabed and pumping action starts. The dredged material is pumped through pipelines to hopper in the form of soil-water mixture. Dredging operation is stopped, when the hopper reaches to the maximum capacity. This type of dredger can provide discharge methods in various ways depending on the project requirements. The load of dredger could be dumped to ashore or offshore by opening doors or valves in the bottom of hopper. Also, the dredged material can be pumped through pipeline to reclamation or disposal area. Another discharge method is called as rainbowing, the dredged material is sprayed in an arch through air. This method is used for land reclamation where previously reclaimed are is above the surface.

Figure 3.11 : The plain suction dredger (http://www.engineersdaily.com).

Trailing suction hopper dredgers are suitable for dredging of soft clays, silt and sand. They are not suitable for hard materials. These dredgers could be used for harbour, channel maintenance or land reclamation and coastal protection projects (Vlasblom,2003).

3.3 Environmental Considerations

3.3.1 Impacts of dredging

Dredging operations influence on marine environment and shape which results in adverse direct and indirect impacts. The impacts of dredging depend on dredging equipment and methods, the physical and chemical characteristics of the sediment, the contamination level of the sediment, bathymetry and hydrological conditions (waves, currents). The degree of environmental impacts is influenced by the quantity, duration and frequency of dredging, the extent of area and depth of the dredging site, the grain size, contamination level of the sediment, current and waves and the sensitivity of dredged and adjacent areas.

The major impact of dredging is turbidity, which is resuspension of sediment particles into the water column and precipitating parameter for other adverse impacts. The level of turbidity is affected by the site conditions, the physical and chemical characteristics of dredged material, the type of equipment and movements of dredger such as dragging, spud movement. Due to excavation work during dredging, an increase of resuspension of sediment and turbidity alter water quality. The release of sediment and contaminants cause to change in organic, inorganic compounds of sediment and water.

Spreading of contaminant into a water leads to increase oxygen demand due to release of anaerobic sediments in water. Exposure of benthic habitat species and fishes to contamination can cause mortality of animals, plants and transmission of heavy metals and contaminant by food chain to human consumption. Increased rate of turbidity obstructs photosynthetic activities of organism associated with decline of transparency and light penetration. After dredging, the settlement of sediments may cause the blanketing of vulnerable areas such as coral reefs or sea grasses and restriction of navigation.

Due to excavation of seabed, the removal of sediments leads to destruction of invertebrates, benthic flora and substrate area of species, which result in the habitat changes. The long-term impact is changed bathymetry is alteration of hydrography, which includes currents, waves, sediment distribution and salinity.

3.3.2 Disposal at sea

Open water disposal could be defined as the dumping and placement of dredged material in rivers, lakes or sea. Dumping of dredged material into to the open water is widely used method throughout the world. The amounts of dredged material disposed at the sea in some European countries is presented in Figure 3.12. The annual volume of dumped dredged material from maintenance and capital dredging range from 100 to 130 million dry weight tonnes between 1995 to 2007 (OSPAR,2009).

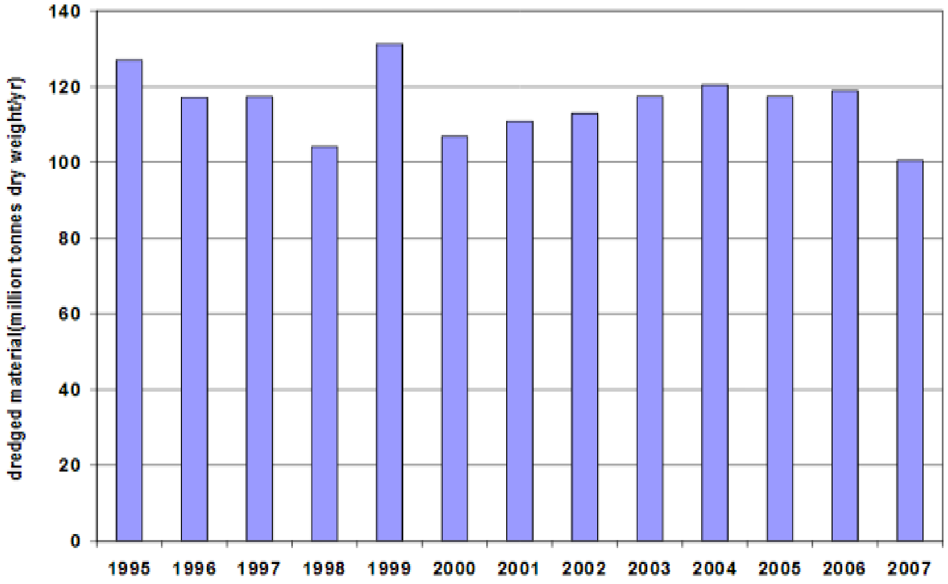


Figure 3.12 : The annual volume of disposed dredge material in some European countries from 1995 to 2007 (OSPAR, 2009).

Depending on the characteristics of dredged material, level of contamination, site conditions, operational considerations, there are two main methods for disposal of dredged material at open water; unconfined disposal and confined disposal. In the unconfined disposal method, the dredged material is directly disposed to the sea and deposited as a mound on the seabed without any isolation from marine environment (Figure 3.13). Unconfined disposal has been suitable for clean, coarse grained material, low wave and current energy site. The unconfined disposed dredged material inclines to erode and release into water column, so it effects very wide area. The coarse-grained materials settle narrowly on the seabed while the fine-grained materials suspend around the impact area just after dumped into the water. After the settlement of all materials, the mound completes its natural consolidation and the fine-grained material at the top of mound are eroded by force of current and waves.

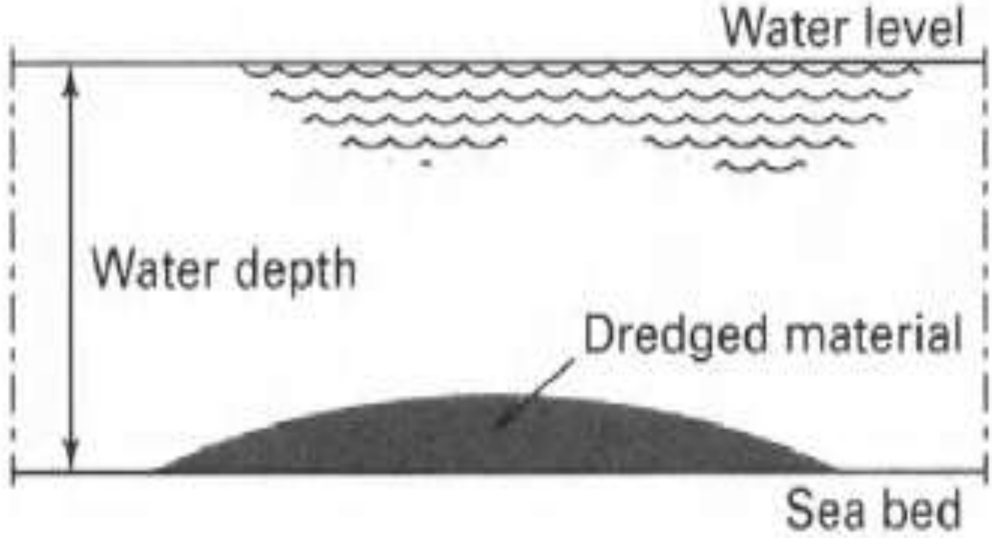


Figure 3.13 : The unconfined disposal at sea (Bray et al,1997).

Confined/semi confined disposal methods include disposal in seabed depressions and disposal between underwater bounds (Figure 3.14). This type methods entails the disposal of dredged material into natural or manmade depression or between constructed bounds. The capping is dredged material is determined by the contamination level of sediments. Confined/semi confined sites ensure lateral isolation from marine environment, therefore they are commonly preferred for contaminant dredged material disposal. The construction of bounds is more expensive than other options so abandoned borrow pits or subaqueous depressions are more widely used for disposal of dredged material. The erosion and spreading of dredged material is minimised with usage of confined/semi confined disposal areas.

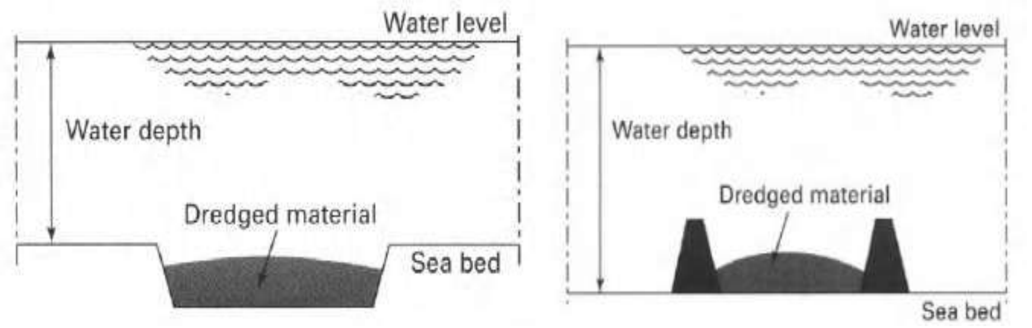


Figure 3.14 : The confine/semi confined disposal of dredged material (Bray et al,1997).

The behaviour and effect of dredged material after discharge into the sea depend on the dredged material characteristics and deposit site conditions. The important parameters for assessing of impacts of disposal actions are the grain size distribution, cohesiveness of material and contamination level of material, water depth at disposal site, velocity of currents, the wave height, depth and period and bathymetry. The effects of disposal can be observed during and immediately after discharge activity or afterwards settlement of disposed material.

The impacts of disposal at sea on the marine environment similar to the adverse effects of dredging. The dumping of dredged material into the sea contributes to increase of turbidity which leads to deterioration of water quality. The release of contaminants can cause adverse impact on aquatic flora and fauna habitats. The most important impact of disposal at sea is the blanketing of seabed associated with burial of benthic habitat. Accumulation of dredged material on the seabed can also influence water movements by causing detrimental change of bathymetry (Bray et al,1997).

3.3.3 Disposal at land

The upland confined disposal could be defined as an area constructed on unsaturated land for containment of contaminant dredged material that prevent release of contaminants to the environment. Dikes or ponds are used to retain dredged material and drain effluent water from confined area (IADC,2010). Dredged material-water mixture is pumped to the disposal site by pipeline or barges. After the dumping operation, the dredged materials descend and effluent is discharged from the containment site. The requirement large areas for disposal site, the high-water content of dredged materials and transport difficulties are restrictive parameters of disposal at land. The storage capacity, site access, topography of site, proximity of vulnerable areas, the potential physical and chemical impacts of disposal site must be assessed to achieve proper confined disposal of dredged material.

In order to determine possible environmental effects of dredged material, there is a need for the evaluation of pathways of contamination from confined disposal site to the environment. There are five main mechanism for release of contaminants from confined land disposal areas; leaching into the groundwater, rainfall surface runoff, release contaminant in the effluent, evaporation of effluent during and after the disposal operation and direct or undirect uptake by plants and animals.

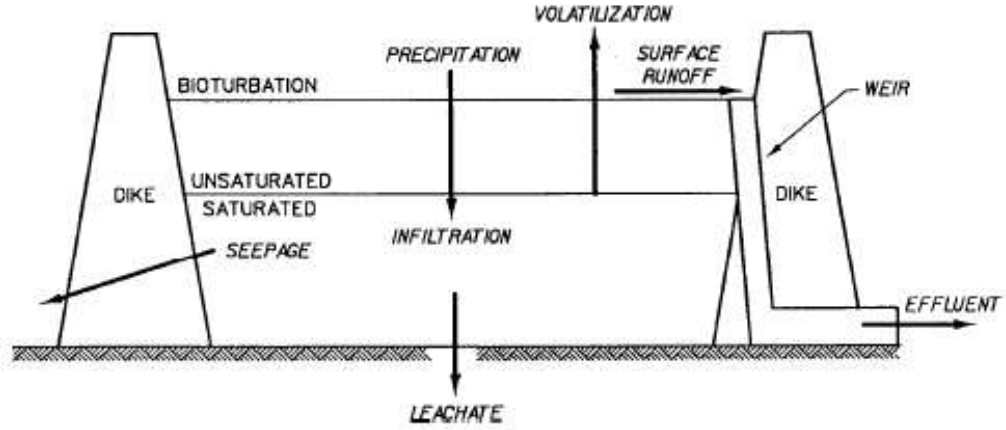


Figure 3.15 : The pathways of contaminant release at confined disposal (USACE,2004).

After the consolidation of dredged material in the ponds, the effluent is discharged from the confined area. This water may contain suspended sediment with contamination or dissolved contaminants and pose risk to the adjacent environment. If the contamination level of effluents is unacceptable, chemical treatment or removal of contaminants must be required to protect environment from potential adverse impacts of effluent. Another way contaminant transport is diffusion or infiltration of contaminants from disposal sites to subsoil as consequence of concentration difference and interaction between disposal site and subsoil. Leachate leads to spreading of contaminants to aquifers and ground water therefore physical barriers, vegetation and dewatering methods can be used to minimize ground water pollution. After the consolidation of dredged material and dewatering process, release of different contaminants begins along with the transformation of chemical composition of dredged material and organic content. These contaminants may be emitted by runoff water, which comprise of precipitation accumulation. Contaminant can be also emitted by evaporation of water to atmosphere. The covering of surface with membranes, lime addition to the surface, providing vegetation may be used to prevent release of contaminants by runoff and evaporation. The contaminant uptake of plants and animals is direct adverse impact of confined disposal site. The contaminants can be bioaccumulated in plants and animals and be transmitted through the food chain. Uptake controls consist of the covering of surface of disposal site, chemical treatment and providing vegetation to minimize or prevent from pollution(USACE,2004).

3.3.4 International and regional environmental conventions and guidelines

Dredged operations are the necessary part of nations economic development to keep alive global commerce and communication. Increase of dredged operations causes adverse effects on environment not only during dredging but also after disposal activities. There is various international organisation which are related with dredging activity such as PIANC, WODA and EuDA. These organizations aim to regulate and standardise dredging operations, to assess and prevent adverse environmental effects of dredged operation and to creating awareness about dredged material is a source not waste. Apart from these organisations, international and regional conventions have regulated disposal of dredged material to minimise adverse impacts on marine environment. Different guidelines for dredging material disposal have been prepared by conventions to assist decision making process of disposal activities.

London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, also known as London Convention, is an important international convention to protect and prevent seas from pollution by dumping of wastes and other matter from vessels, aircraft and platforms. London convention have been signed by 89 countries, not includes Turkey, since 1972. The agreement includes 22 articles and 3 annexes; articles summarizes the aim of convention and promote to take precaution against pollution of marine environment, annexes itemize permitted and prohibited waste materials for dumping at sea. The convention was revised by The Special Meeting of Contracting Parties to the London Convention at 1996. The 1996 protocol strengthens control marine dumping and change content of annexes to the reserve list. The reserve list material, which includes dredged material, requires permit and detailed assessment for dumping activities. The specific guidelines have been developed for all wastes, including dredged material (IMO, n.d.). The first guideline for dredged material was prepared at 1995 as Dredged Material Assessment Framework and it was adopted on 2013 as Revised Specific Guidelines for Assessment of Dredged Material. This guideline aims to reduce disposal of dredged material, chart out for determining the suitability of dredged material for disposal and promote to beneficial use of dredged material. The dredged material is defined as the resource not the waste. According to the guideline, the physical, chemical and biological properties of dredged material, the disposal site conditions, the alternatives of disposal action and the potential impacts of disposal must be evaluated before a permit for disposal of dredged material at sea. These intensive assessment requirements ensure that stakeholders evaluate the dredged material as resource and encourage to reduce adverse impacts of disposal at sea on the marine environment (London Convention,2013).

Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, also referred to as Barcelona Convention, is regional convention, to prevent pollution in the Mediterranean Sea, is signed by Turkey and another 21 parties on 16 February 1978. Members agreed to cooperate and take to measures for prevent and dealing with pollution in the Mediterranean Sea (European Commission, n.d.). Guidance document on the development of National Threshold Limit Values (NTLVs) for dredged materials which could be dumped into the Mediterranean Sea have been prepared based on Barcelona Convention, however guidelines is still draft document. The document is adopted from Specific Guidelines for Assessment of Dredged Material and Guidelines for the Management of Dredged Material. The main goals of the guidelines are the management of dredged material into the Mediterranean Sea and assisting decision making process of disposal of dredged material at the sea. The guideline emphasizes the need for dredging operation and the beneficial use options of dredged material (UNEP,2009).

1992 Bucharest Convention for the Protection of the Black Sea Against Pollution (Bucharest Convention) is signed by six counties, including Turkey, to prevent contamination of the marine environment and preserve the natural sources and facilities of Black Sea. The convention consists of three protocols; the control of land-based sources of pollution, dumping of waste and joint action in the case of accidents (Black Sea Commission, n.d.).

The guideline for dredged operation at sea and inland waters was published by Turkish Republic Ministry of Transport, Maritime Affairs and Communication in 2016. The guideline aims to define method and principle of dredging operations at sea and inland waters. The document includes four main parts; duty, authorization and responsibilities, dredging license, dredging project, permits of dredging and dredging operation and controlling and sanctions. This guideline is inadequate for technical aspects of dredged operations although it gives information about administrative matters.

4. BENEFICIAL USE OF DREDGED MATERIAL

Dredging operations are vital to construct new marine structures, to maintain harbours, channels, waterways, to improve port facilities and to remediate environment. The dredging of ports, canals, harbours, waterways, rivers and lakes produces huge quantities of material. Disposal of dredged material at sea or land has chemical and biological impacts on environment. Moreover, environmental and local legislations have begun to restrict disposal activities with increased awareness of environment and sustainability. Beneficial usage option of dredged material is gaining importance to achieve most economical and environmental friendly solution. The major proportion of dredged material is not polluted and is suitable for reuse purposes. However, polluted dredged material may be used for some types of beneficial use with proper treatment methods such as dewatering, separation, thermal immobilization, bioremediation or hydraulic binder additives. Independently from contamination situation of dredged material, there is need for decision making process of reuse of dredged material which includes cost-benefit analysis, sediment modelling studies, environmental impact assessment and ecological models for choosing most economical and efficient beneficial usage method (Deibel et al, 2007).

The knowledge about chemical and physical characteristics of dredged material must be required to determine beneficial use options. The chemical and physical characteristics include grain size distribution, water content, organic content, salinity, contaminant levels and engineering properties of material. Table 4.1 summarizes the beneficial use options depending on soil type of dredged material. Coarse grained dredge materials have wide range beneficial use options and they are generally not contaminant sediments so they are used without treatment. Rocks can be used for habitat creation, road construction, offshore berms construction part of beach nourishment projects. The most obtained material from dredging is sand and gravel and they can be used almost in every type of beneficial use options such as construction, beach nourishment, agriculture, habitat creation projects and aggregates for concrete production. Consolidated clay is most suitable for habitat creation and enhancement, agriculture and forestry. Moreover, consolidated clay can be used in brick and ceramic production. Silt and soft clay materials are dredged from harbours, rivers and estuaries for maintenance so they can be polluted due to accumulation of heavy metals or pesticide spoils. These type materials are used for habitat creation, wetland restoration, agriculture and forestry purposes(USACE,2007).

Table 4.1 : The suitability of different dredged material soil type for beneficial use (USACE,2007).

Beneficial Use	Dredged Material Soil Type				
	Rock	Gravel Sand	Consolidated Clay	Silt/Soft Clay	Mixture
Land Remediation	+	+		+	+
Beach Nourishment		+			
Capping		+	+	+	+
Building Materials	+	+	+	+	+
Land Creation	+	+	+	+	+
Replacement Fill	+	+			+
Habitat Creation	+	+	+	+	+
Wetland Restoration			+	+	+
Manufactured Top Soil				+	+
Agriculture, Forestry	+	+	+	+	+

4.1 Land Remediation

One of the beneficial usage area of dredged material is land remediation. Dredged material can be used as fill and/or covering material to remediate contaminated or disturbed areas such as solid waste landfills, brownfields, abandoned mines and quarries. Abandoned subsurface and surface mines pose to physical and environmental hazardous effects such as leaching toxins or erosion. Mines can be returned to its natural state by removed hazards and covered with dredged material. Brownfields are unused commercial and industrial areas where release hazardous substances and contaminants: brownfields can be covered by dredged material.

Dredged material is generally treated with binding agents such as cement, lime, fly ash and kiln dust to dry material, improve strength and immobilize contaminants before beneficial use for land remediation. Dredged material is transported to the placement site by rail, truck or barge. Dredged material is needed for dewatering process to avoid spillage during transportation with rail and truck. When it is disposed to the site, the process of spreading, grading and compaction is applied. For vegetation, the topsoil layer is used as dredged material cover (Davidov et al,2007).

4.2 Beach Nourishment

Beaches are important part of coastal lands; they provide habitats for animals and plants protect the coastal line from storms by mitigating effects of waves. Also, beaches make contribution to economy as being tourist attraction. The sediments movement, the dry and wet part of beaches and its dunes are shaped by waves, tides, currents and winds. As a result of storms, increased human activities and a rise in sea level cause beach erosion. The “soft solution” of erosion is beach nourishment, which is process of dumping coarse grained soil onto an eroding area to create new beach or widen existing beach (Figure 4.1). Beach nourishment is a temporary solution and it does not stop erosion and is required renourishment periodically.

Figure 4.1 : The dumping of dredged material through pipeline for beach nourishment (Vidal et al, 2010).

The coarse grained dredged material can be used as fill material for beach nourishment. The grain size, shell content, texture of dredged material should match as similar as the natural sediment to ensure the project requirements. The material must be noncontaminated. Vidal et al. (2010) investigated that usage of dredged material is more economical and environmental friendly than quarry sources. The guideline price of quarry source, which include extraction and transportation price, three times higher than the guideline price of dredged material. The carbon dioxide (CO_2) emission of quarry source is 22.005 kg CO_2 / m^3 while this rate decreases to 2.89 kg CO_2 / m^3 for dredged material.

4.3 Habitat Creation, Enhancement and Restoration

Dredged materials can be used for habitat creation, enhancement and restoration project to provide nesting areas, to protect animal and plant species. Habitat creation could be defined as construction of sustainable terrestrial areas to ensure suitable place, food, shelter and water for wildlife species while habitat enhancement and restoration include improvement or recovery of existing habitat conditions. The cost of habitat creation, enhancement and restoration related with proximity to dredged material site, dredged material characteristics, accessibility to the habitat site, site characteristics, wave energy regimes and requirements of protective structures etc. Sediment, waves, tidal currents, elevation, site size must be evaluated before determining dredged material use for this type projects. Testing and evaluation of chemical, biological and physical properties of dredged material is very crucial for habitat creation, enhancement and restoration project. The nutrient level, grain size distribution, presence of debris, contamination level must be determined to evaluate suitability of dredged material (English Nature, 1992). Habitat creation, enhancement and restoration projects include upland habitats, nesting islands, wetlands, intertidal marshes and mud flats.

Terrestrial uplands and bird islands provide nesting areas and shelter for birds and another wildlife species. They have very crucial role in sustainability and improvement wildlife and mitigation adverse effects of human activities on environment. The elevation of islands must be 1 to 3 meters above the water level to protect from inundation. The size of habitat usually ranges from 2 ha to 20 ha. Vegetation of island must be sufficient to ensure food, shelter and nesting area for animals. The habitat must be far from human activities and predators. The suitable soil type of dredged material for uplands and islands is sand which provides suitable substrate with shells for nesting. Although fine grained materials more suitable for vegetation, this type material can be influenced easily by wind and rain erosion and they generally contain contaminated sediments. There will be needed for desalinization of dredged material due to vulnerability of animals and plants against salt. Besides, nutrient level, water content, contamination level of dredged material is important for habitat creation, enhancement and restoration projects (English Nature, 1992).

Mudflats and sand/mud marshes provide valuable habitat for invertebrates and prey for birds. They protect coastal line from waves and floods. They have disappeared and eroded as a result of high wave and current energy and intensive human activity in coastal areas. The creation and restoration of mudflats and sand/mud marshes is needed for conservation of environment and protection of coastal zone. Dredged material could be used to enhance erosive parts of flat or marsh thus substrate is ensured for vegetation (Figure 4.2). Dredged material is also used to create new flat and marsh and to increase elevation. The appropriate dredged material type for mudflats are silt, clay and silty sand while silt and fine sand dredged material is suitable for sand/mud marshes. The grain size impacts the stabilization and vegetation of site. The biological and physical characteristics of dredged material, the hydrodynamic regime, rich habitats in adjacent must be considered in design and construction phase of project (PIANC, 2009).

Figure 4.2 : The dumping of dredged material through pipeline for marsh nourishment (http://www.nola.com).

Wetland is inundated land areas for permanently or seasonally where provide flood protection, water filtration and valuable habitats for wide range animal and plant types. Dredged material is used for new creation of wetlands to recycle and remove contamination from waste water and improvement of wildlife habitat and to build erosion protection structures. Consolidated clay, silt and soft clay dredged material suitable for wetland creation. Wetlands must be constructed at low energy areas and protection structures are needed when exists high energy areas (Conway, n.d.).

4.4 Agriculture, Forestry and Aquaculture

Dredged material has been used for agriculture, forestry (commercial tree production), horticulture (cultivation of fruits, vegetables and nuts) purposes in marginal soils which are inadequate areas for farming. Dredged material is also used for aquaculture to rear aquatic animals for food consumption.

Valuable topsoil is diminished by erosion and the remained soil layer has insufficient chemical and physical characteristics, weak drainage and inappropriate soil texture for cultivation purpose. Dredging material can be used as topsoil to improve chemical and physical characteristics enabling essential nutrients and organic contents for cultivation. Also, it is used to elevate the ground surface, enhance drainage and protect soil moisture. The chemical and physical properties (salinity, water content, grain size distribution, nutrient content, contamination level) of dredged material, site characteristics and site location must be assessed for the potential use of dredged material in agricultural production. Before Appling the dredge material to on area, dredge material should be dewatered and purified from salt content. High salt content restricts transmission of water thus the growth of plants is obstructed. The most suitable dredged material types are silt and clay for agricultural uses. Sand and sandy silt dredged material can be used for horticulture purposes.

They abound in nutrients (nitrogen, potassium, metals, phosphorus) and organic content. However, the analyse of contaminant level and type is important for cultivation applications, due to the inclination of fine grained sediments to pollution and direct consumption of agricultural products by humans. Forestry is another area for beneficial use of dredged material for commercial tree and tree production. The contamination level is less crucial for forestry applications than agriculture purposes.

Dredged material containment areas and aquaculture areas have similar design criteria, legislation and permitting requirements for construction, therefore dredged material containment areas could serve as aquaculture ponds. Both of them include perimeter levees, impervious layer and drainage system. Consolidated clay and silt/soft clay are used for aquaculture applications and void ratio, water content, degree of saturation, settlement behaviour, contamination level of dredged material must be evaluated (PIANC, 2009).

4.5 Building Materials

High demand for construction material, limited natural resourced and environmental effects of open new quarries result in incline to find innovative solutions to meet the need of raw materials for construction industry. Dredged material can replace as a raw material to produce construction materials such as cement, brick, asphalt, light weight aggregate, ceramic titles. Dredged material is generally required dewatering and desalinization for used as building materials. Not only coarse grained dredged material but also fine-grained materials can be used to as different types of building materials.

Brick production is one of the fine grained dredged material usage area as a raw material. Clay type dredged material must be dewatered and screened to separate from debris before the transfer to the production facility. The evaluation of the physical and chemical characteristics, mineralogical composition of dredged material is very important to determine for brick product quality. Due to low plasticity of dredged material, it is mixed with brick clay to enhance plasticity.

Dredged material could be substituted as main components of Portland cement. Salt content of dredged has adverse effect on durability of cement based product, therefore it must be washed from salt. Portland cement production takes shape in two different methods; dry and wet methods. Due to high water content of dredged material, wet method is more suitable for cement production with dredged material. The components of cement are melted in form of clinker at the rotary kiln with high temperature so that the organic content of dredged material is eliminated.

Dewatered and separated from debris dredged material can be used to manufacture light weight aggregate. Addition of polymer reduces the time required for dewatering process of dredged material and increases mechanical properties of material. The water-dredged mixture is prepared and this mixture is pelletized in 12.7 mm in diameter and 25.4 mm in length (Derman et al, 1998; USCE, 2002).

4.6 Capping

Clean sand or silt dredged material can be used as capping material to cover the contaminated dredged material which is discharged to the open water disposal site. The contaminated dredged material must be isolated from aquatic environment with suitable cap material.

According to the contaminated dredged material characteristics and ground surface condition there are two types of capping method; level-bottom capping and contained aquatic disposal. The contaminated dredged material is discharged to the bottom of the sea as a mound and then the mount is capped with appropriate techniques in level-bottom capping method. Contained aquatic disposal is disposal and capping of dredged material in natural or constructed pits with lateral confinement.

Proper capping must provide impermeable layer to protect aquatic environment from contaminants and must be durable for all site conditions. Therefore, all components must be carefully evaluated in design phase of capping. First of all, dredged material must be noncontaminated. The most suitable types of dredged material silt or clay which has lower permeability than sand so the movement of contaminant will be blocked. Also, sand with high silt or clay content widely used for capping purpose. The most significant part of design phase is determining cap thickness which influences directly effectiveness of impermeability and erosion resistance. The physical and chemical properties, the potential consolidation of capping material and contaminated dredge material, the contamination level of dredged material, disturbance of sediments, bioturbation, currents and waves effect must be considered when cap thickness is designed. The cap thickness must be 1 meter at least.

Capping operations must be prevented from the capping material displacement, resuspension and mixing of contaminated and capping material, which are associated with capping equipment and methods. Different types equipment and placement methods could be used for capping operations. The selection of equipment and placement method depends on capping material type, water depth, wave and currents. Clean dredged material may be released by barge, hopper dredger or pipeline with several methods. As shown in Figure 4.3, barge release provides firm accumulation of material on surface and less sediment distribution rather than pipeline or hopper release. There are two placement methods; conventional and spreading method. For conventional method, the capping area is divided particular parts for each barge or hopper load and capping material is discharged at water surface according to the cap thickness. Spreading method involves a controlled release of capping material and movement of barge or hopper. The capping material is released through half opened doors of barge or hopper while vessel is travelling.

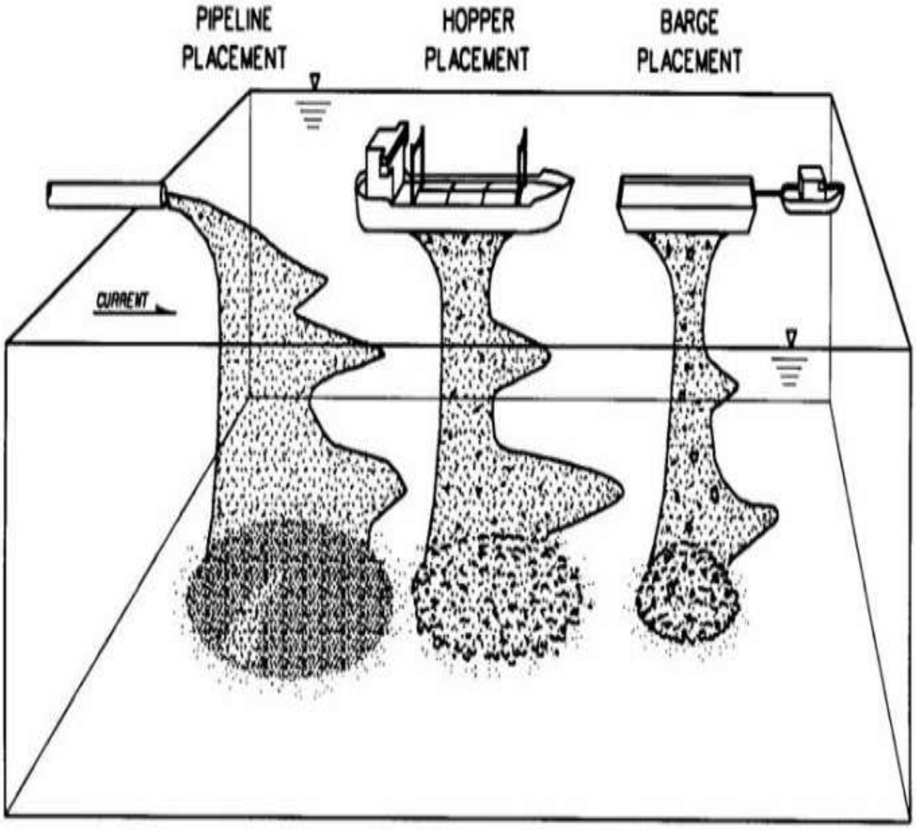


Figure 4.3 : The dumping of capping material through several equipment (Palermo et al, 2005).

Monitoring is essential part of capping operation to observe and check the progress of capping, cap thickness, short term and long-term effects not only during construction phase but also after the construction. Capping operation is monitored to make certain that the design requirements of cap such as impermeability and thickness of cap. Consolidation of cap material and contaminated dredged material, the short and long-term effects of capping on bathymetry, aquatic environment and water quality must be checked during all phases of capping. The methods and tools of monitoring involves water samples, sediment cores and samples, plan view photographs, current meters, side-scan sonar, optical backscatter sensors and bottom acoustic profiling (Palermo et al, 1999; Bailey,2005).

5. USED MATERIALS AND THEIR CHARACTERISTICS

5.1 Materials

5.1.1 Lime

Lime is common binder for the stabilization of dredge materials. Dredged material which is treated with alkaline and cementitious additive(s) to dry to wet solids, increasing bearing strength, inactive heavy metals and buffer acid production. With considering the previous research, lime was selected for the stabilization of fine grained marine sediment. Besides, Lime stabilization is very crucial in road construction for improving subgrade soils, subbase materials, and base materials (Little et al, n.d.).The used lime is commercial product and there is no additional test on the product.As a result of reaction between lime and medium, moderately fine and fine-grained soils, lime stabilization creates a number of important improving of engineering properties in soils, including decreased plasticity, increased workability, reduced swelling, increased strength, improved resistance to the damaging effects of moisture. The major soil properties and characteristics such as pH, organic content, natural drainage, and clay mineralogy influence the soils ability with lime to produce cementitious materials.

Ion exchange and flocculation-agglomeration and pozzolonic reaction are the main reactions for the improvement strength of lime soil mixture. Other reaction such as carbonation have minor effect on the improvement strength. While ion exchange and flocculation-agglomeration take place rapidly, cementation and carbonation are long term reactions. Ion exchange consequence of replacement of univalent sodium (Na^+) and hydrogen (H^+) ions of soil with divalent (Ca^+) calcium ions of lime. This reaction binds clay, resulting in decrease of clay content and in parallel with reduction of plasticity. This reaction take place approximately 96 hours. Collapsible characteristic of silts is destroyed by agglomeration reaction of lime and soil (Fang,1991). Flocculation and agglomeration result of the increased electrolyte content of the pore water and ion exchange by the clay to the calcium form (Mallela et al,2004). The increase in strength of stabilized soil with time mainly due to pozzolonic reactions. Calcium hydroxide which is in the soil water, with silicates and alimunates (pozzolans), from clay particles, for cementing materials or binders (Diamond et al, 1996). When calcium ions react with SiO_2 and Al_2O_3, they produce hydrated gels of calcium silicate (CSH) and calcium alimunate hydrate (CAH). These gels blend the soil particles that act as a cement like Portland cement (Mohamed et al,1998).

$$Ca(OH)_2 \longrightarrow Ca^{++} + 2(OH)^-$$

$$Ca^{++} + OH^- + SiO_2 \longrightarrow CSH$$

$$Ca^{++} + OH^- + Al_2O_3 \longrightarrow CAH$$

Lime carbonation is an undesirable reaction that occurs as when lime added to soil and they do not react with, but draws CO_2 from air or soil to form $CaCO_3$. Because of inadequate amount of pozzolanic clays in the soil because extreme amount of lime has been added. CaCO3 which is a plastic material, rise the plasticity of soil and bind lime therefore it cannot react with pozzolonic materials (Fang,1991).

Lime react with medium, moderately fine and fine-grained soils to produce reduced plasticity, decreased swell potential and increased strength and workability. U.S. Army Corps of Engineers suggests a soil, which has plasticity index 12 or greater, for suitable lime stabilization (USACE,2004). The National Lime Association suggest fine grained clay soils and plasticity index 10 or greater are potential candidate for lime stabilization (National Lime Association, 2004). Also, according to the Turkish Highway Standards, based on AASHTO classification, A-5, A-6, A-7, A-2-6 and A-2-7 soil types and based on Unified Soil Classification Systems, CH, CL, MH, ML, GC, SC soil types, which a plasticity index 10 or greater, or CBR lesser than 10 or CBR swelling percentage 3 or greater, are suitable for lime stabilization (Kavak et al, 2008).

5.1.2 Cement

Cement is used widely for stabilization of soil like lime binders. Cement has been found to be effective in stabilizing an extensive variety of soils not only silts and clays but also granular materials. Cement-modified soil is soil which is stabilized with a relatively small proportion of Portland cement, with purpose of change weak properties of soils or other materials so they become suitable for use in construction. Cement-modified soil is generally used to improve subgrade soils or treat local aggregates for a use as base in location of costlier transported aggregates (Little et al, n.d.).

In stabilization, the most commonly used kind of cement is Portland cement, which is a finely powdered hydraulic cement, essentially consisting of hydraulic calcium silicates. The major compounds in Portland cement are tricalcium silicate ($3CaO.SiO_2$; C_3S), bicalcium silicate ($2CaO.SiO_2$; C_2S), tricalcium aluminate ($3CaO.Al_2O_3$; C_3A), and terracalcium aluminoferrite ($4CaO. Al_2O_3.Fe_2O_3$; C_4AF) (Fang,1991). Very stable hydrated silicates and aluminates and calcium hydroxide ($Ca(OH)_2$) are formed as a result of reaction between compounds of cement and water or water and available lime. One such stable product is called tobermorite gel ($3CaO.2SiO_2.3H_2O$), a calcium silicate hydrate (CSH) that resembles the natural tobermorite mineral. Calcium hydroxide produced during the hydration of Portland cement can further react with the silicates and aluminates of the clay soil and produce more cementing material (Herzog et al,1963).

Cement helps improve of engineering properties of soils, improve cation exchange of clay, decline cohesiveness (plasticity), decrease volume expansion or compressibility, increase strength of soil (Makusa, n.d.).

Although the cement is mixed with enough fines, which provide homogenous mixture, is suitable for stabilization, cement is used with different types of soil. The plasticity index of 30 or less sandy soils are may be suitable for stabilizing with cement. Cement may be effective stabilizer for fine grained soils with the plasticity index must be less than 20, the liquid limit must be less than 40 and more than 50 percent passing the No.200 sieve (USACE,2004). According to the AASHTO classification system, suitable soil types are A-2, A-3, A-4 and A-7 for cement stabilization (Little et al, 2009).

5.1.3 Dtm-1

The first fine-grained sample is called as DTM-1. This material is dredged from the Tuzla marina port. The sampling depth is 6.5 m and the distance of sampling from shore is between 850 m and 900 m (TUBITAK MAM, 2015). The main physical characteristics of dredged material are reported in Table 5.1. Using oven drying method, the initial water content is about 60%. The liquid limit (LL), defined as the limit between liquid and plastic state and measured by Casagrande method, is about 44 %. The plastic limit (PL), defined as the limit between plastic and solid state and measured by the rolling test method, is about 20 %. The plasticity index of soil (PI), which is difference between the liquid limit and the plastic limit, is about 24%.

Table 5.1 : The main physical characteristics of Dtm-1.

Parameters	Value
Initial Water Content (%)	60
Liquid Limit (%)	44
Plastic Limit (%)	20
Plasticity Index	24
Percent Passing No. 200 sieve (%)	87
Optimum water content (%)	20
Maximum dry unit weight (kN/m^3)	17
Unconfined compression strength (kPa)	37

The particle size distribution curve (Figure 5.1) shows that 87% of this dredged material particles finer than 75 μm. According to the Unified Soil Classification System (ASTM D 2487), the fine dredged material could have classified as CL material. According to the soil classification system of American Association of State Highway and Transportation Officials (AASHTO), the fine dredged material could be classified as A7.

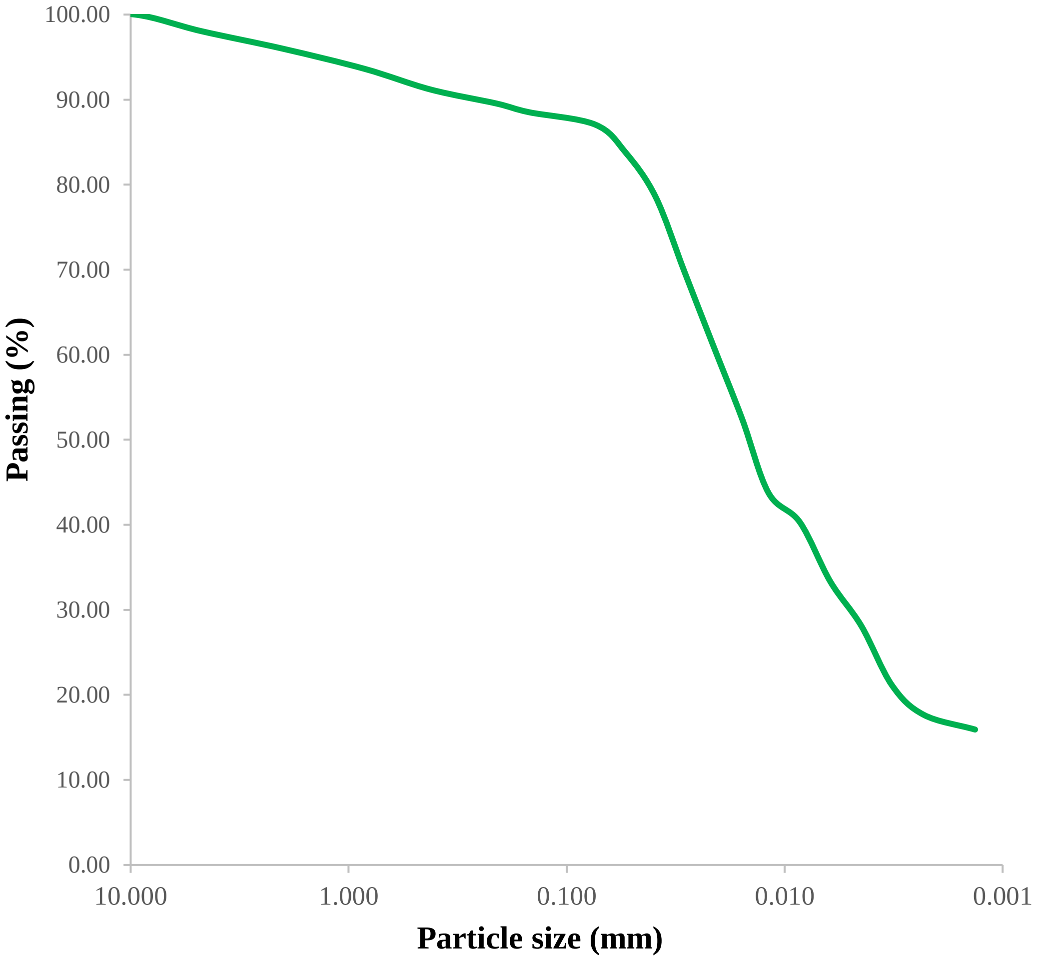


Figure 5.1 : Particle size distribution of Dtm-1.

The leaching tests were performed to determine the environmental impacts of marine sediment. According to the Turkish Regulation on the regular storage of wastes (ADDDY/Annex 2), the parameters of eluate analysis of marine sediments between the prescribed limits and marine sediment was classified as III. Class Inert Waste (TUBITAK MAM, 2015).

5.1.4 Dtm-10

The fine-grained material DTM-10 was collected from Tuzla shipyard. The sampling depth is 17 m and the distance of sampling from shore is about 350 m (TUBITAK MAM, 2015). The grain size distribution is shown in Figure 5.2 and it shows that the soil is fine grained as more than 70% of the soil fraction passes sieve No. 200 (75 μm).

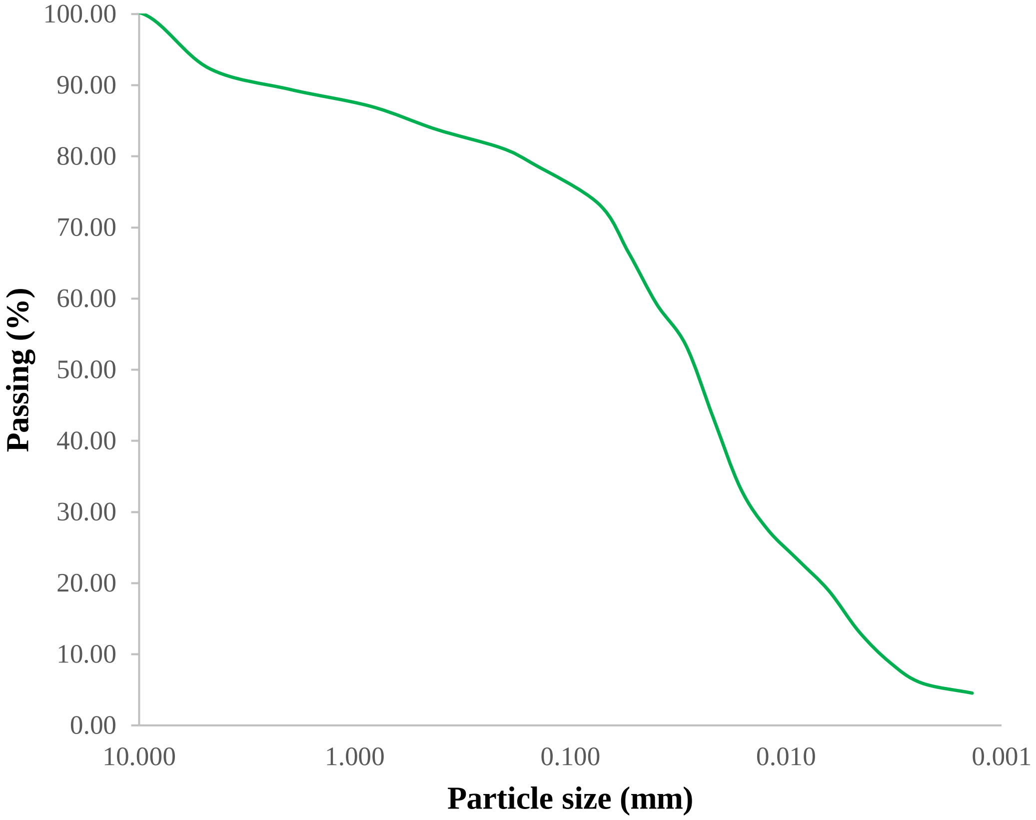


Figure 5.2 : Particle size distribution of Dtm-10.

The main physical characteristics of dredged fine material are reported in Table 5.2. The liquid limit of sample is about 30% and it indicates that it is clay of low plasticity. The plastic limit and plasticity index of sample is about 18% and 12%, respectively. According to the Unified Soil Classification System, the soil could be classified CL. Adopting AASHTO classification system, the soil could be classified as A-6.

Table 5.2 : The main physical characteristics of Dtm-10.

Parameters	Value
Initial Water Content (%)	
Liquid Limit (%)	30
Plastic Limit (%)	18
Plasticity Index	12
Percent Passing No. 200 sieve (%)	72
Optimum water content (%)	15
Maximum dry unit weight (kN/m^3)	19.4
Unconfined compression strength (kPa)	61

The leaching tests were performed to determine the environmental impacts of marine sediment. According to the Turkish Regulation on the regular storage of wastes (ADDDY/Annex 2), the parameters of eluate analysis of marine sediments between the prescribed limits and marine sediment was classified as III. Class Inert Waste (TUBITAK MAM, 2015).

5.2 Mix Design

In the world, large amount of material dredged each year from open waters and rivers to maintain and construct harbours and waterways. After dredging, management of dredged materials cause several problems such as environmental and economic impacts of dredged material disposal and storage. Therefore, the beneficial usage of dredge material has gained importance and there are different types of beneficial use of dredged material. The beneficial use of dredged material in road construction, which consumes huge quantities of natural aggregates, is one of the most important area of reuse dredged materials (Siham et al, 2008). Because of the weak geotechnical properties of dredged materials, they need treatment by hydraulic binders.

In this study, the types of binders and the amounts of binders are determined by consideration of previous researches, international and national specifications.

Lime stabilization for road, airport and railway construction has become a widely-used technique all over the world (Benedetto,2010). The quicklime, is form of lime, commonly is used for soil stabilization. The lime reduces rapidly the water content and the plasticity of soil, thus soil become stronger and more workable. Also, the strength of soil increases considerably over time (Brice et al,2012).

Researches have proven that effective lime content may be 4-6 percent weight of dry soil mass. According to the Bell (1996) “The optimum gain in strength appears to be with 4-6% lime content". Also, Ciancio et al. (2013) suggested that the stiffness modulus of soil increase with addition of lime and reaches a peak at 4 % lime content. Little et al. (1987) noted that "Most fine-grained soils can be effectively stabilized with 3 to 10 percent (dry weight of soil basis) lime". The National Lime Association (2004) recommends that 3 to 6 percent of lime and 2 to 4 percent lime content is suitable for subbase and base stabilization, respectively. According to Carpenter et al. (1992), fine-grained soils can be effectively stabilized with 3 percent lime and this amount of lime can be homogenously distributed and mixed with soils.

Cement is widely used material for stabilization for the safe management, reuse and treatment for disposal of contaminated waste. Calcium-silicates and calcium-aluminates are the predominant cementing compounds in Portland cement (Mohan, 2015). Portland cement may be successful stabilizer a wide range of soil types. The recommended cement ratio for different soil type is given in Table 5.3.

Table 5.3 : Cement requirement for AASHTO soil groups (Little et al,2009).

AASHTO Soil Group	Usual Range in Cement Requirement		Estimated Cement Content, Percent by Weight
	Percent by Volum	Percent by Weight	
A-1-a	5-7	3-5	5
A-1-b	7-9	5-8	6
A-2	7-10	5-9	7
A-3	8-12	7-11	9
A-4	8-12	7-12	10
A-5	8-12	8-13	10
A-6	10-14	9-15	12
A-7	10-14	10-16	13

According to Okonkwo et al. (2015) "The addition of 5.36% and 6.48% of cement help the soil meet the CBR requirement for sub-base and base course respectively". Besides, Chew et al. (2004) suggested that when the cement content of soil exceeds 10 percent, the puzzolanic reaction, the changes in cementitious product, water content as well as unconfined compressive are fixed at certain a value.

Lime and cement are selected binders for both DMT-1 and DMT-10. According to the Turkish Highways Technical Specifications, for determining optimum lime content, the required tests should be carried out on samples with at least three hydraulic binder contents. Therefore, three different lime and cement contents are determined for all soil types and they are presented in Table 5.4.

Table 5.4 : Determined lime and cement contents for treatment.

Soil Sample	ASSHTO Soil Group	USCS Soil Group	Lime Content Percent by Weight (%)			Cement Content Percent by Weight (%)		
Dtm-1	A7	CL	2	4	6	5	10	15
Dtm-10	A6	CL	2	4	6	5	10	15

6. LABORATORY TESTING PROGRAM

6.1 Consistency Limit Tests

The Atterberg limits of samples were determined by using the ASTM D 4318 procedure. Liquid and plastic limit tests are performed to evaluate physical state and index properties of fine-grained soils.

The soil sample was dried in an oven at a 105/110°C and then it was pulverised by hammer to decrease the size of particles for the liquid limit test. The pulverised material was sieved with No.40 (425 μm) to separate finer materials. The soil sample and water were mixed in dish until the mixture became uniform state. After, a portion of prepared sample was placed in the bowl of calibrated Casagrande device and divided into two equal halves by grooving tool. The bowl of device was lifted and dropped until the two halves of the soil come in contact at distance of 13 mm. Then, the small portion of sample was taken to determine the water content of soil sample. These steps were repeated each time with adding a small amount of water. The number of blows to close groove was recorded for different water contents and the water content - the number of blows graph was plotted to determine the water content at which requires 25 drops.

The plastic limit of samples was determined by rolling out a thread of the small portion of soil which was used for liquid limit test, on non-porous surface. The sample had been rolled between the palm and the surface until the diameter of the thread formed soil reached 3 mm. It had been kneaded and re-rolled till the cracking and crumbling of thread started. The crumbled threads were collected to determine water content at plastic stage.

6.2 Sieve and Hydrometer Analysis

The sieve analysis is used for determination of grain size distribution and classification of coarse-grained soils. The particle size analysis was conducted by using ASTM D 422 Standard.

Oven dried and weighed sample of soil was shaken and washed through No. 200 (75 µm) sieve. The material which is passed under the No. 200 sieve was collected for hydrometer analysis. After the drying process of portion retained on the No. 200 sieve, the material was poured on the No. ¾’’ sieve which has the largest screen openings and sieve was moved vertically and horizontally to get material through sieve. The retained material on the sieve was weighted. This process was repeated for each sieve size which each previous sieve has smaller openings than the one above (no. 3/8’’, 3/16 ‘’, 10, 20, 40, 70, 100, 200).

Hydrometer analysis used to determine the grain size of soil which is smaller than 75 µm. The hydrometer test was conducted based on ASTM D 7928 standard. 50 g of soil passing the No. 200 sieve was weighed and mixed with 125 ml of 4% sodium metaphosphate ($NaPO_3$) solution. The soil mixture was waited about 24 hours to disperse. The control cylinder was prepared by adding 125 ml of 4% sodium metaphosphate ($NaPO_3$) solution and sufficient distilled water to reach 1000 ml. After that, the soil mixture was transferred to the sedimentation cylinder and distilled water was added. The mixture was mixed for 10 minutes. Then, distilled water was added to fill cylinder to the 1000 ml. The hydrometer was slowly inserted into the sedimentation cylinder. The hydrometer readings were taken for t= 0.25, 0.5, 1 and 2 minutes. Then, the hydrometer was removed and placed into the control cylinder. The hydrometer was slowly inserted into the sedimentation cylinder again before each reading. After the reading was taken, the hydrometer was removed and putted back into the control cylinder. The readings are taken for 4, 8, 15, 30 minutes, 1, 2, 4, 8 and 24 hours.

6.3 Standard Proctor Compaction Test

Compaction could be defined as the process which remove air from pores between the soil particles by applying mechanical energy. Compaction is generally necessary for construction of highways, airports, and other structures to improve soil strength. Also, compaction increases stability of slopes and decreases permeability, settlement of soil. Compaction causes an increase in dry unit weight of soil, thus the compaction degree of soil is evaluated in terms of dry unit weight of soil.

R.R. Proctor (1933) developed a laboratory compaction test procedure which evaluates the relationship between maximum dry density and optimum moisture content of soil to use for field compaction. This test is named as Standard Proctor Compaction Test.

In the proctor test, the soil is compacted in a mold having a capacity of 944 cm^3 and diameter of 101.6 mm. Before the test, the volume and weight of mold is controlled and determined. Then, the soil is mixed with water in the pan. The mixture is placed into the mold to in three equal layers. Each layer is compacted with 25 blows by Standard Proctor hammer, which has a mass of 2.5 kg and has a drop of 30.5 cm. After each layer is compacted, the top attachment of mold is removed and the excess soil is trimmed. The mold and compacted soil is weighted and recorded. Representative samples of the material from above and bottom of the sample is taken and their moisture content is determined. These steps are repeated at least 5 time with increasing water content of soil.

The moist unit weight of each test sample (γ) can be calculated as

$$\gamma = \frac{W}{V_m} \tag{6.1}$$

The dry unit weight of each test sample (γ_d) can be calculated as

$$\gamma_d = \frac{\gamma}{1+w} \tag{6.2}$$

The graph of dry unit weight against the corresponding moisture content is plotted for obtaining compaction curve to determine the maximum dry unit weight and optimum moisture content.

6.4 Miniature Compaction Test

Compaction tests are conducted to obtain the relationship between the moisture content of material and resulting densities when compacted in the laboratory to evaluate the state of compactness for naturally or artificial state of soil. One of the compaction test method is miniature compaction test which requires less time and material (0.8-1.2 kg) to perform than the standard Proctor compaction test.

The miniature compaction test apparatus consists of mold 5 cm in diameter and 10 cm in height having a volume of 196.25 cm^3. The compactive effort is achieved by dropping a cylindrical hammer 5 cm in diameter and 1.1 kg in weight from a height of 20 cm. Selection of appropriate number of layers, number of blows per layer depends on the type of material. For the studied samples in this thesis, the determined number of layers are 3 and the number of blow per layer is 18, which ensures the standard

Proctor test energy. The soil is placed in the mold in layers and each layer is compacted by predetermined number of blows. Since the specimen has a height to diameter ratio of 2.0, it can be used for unconfined compression test directly.

According to the Essigman (1976), it is not possible to achieve the same maximum dry density at the same optimum water content because of the differences in the compaction method and densisties from the miniature compaction are slightly greater than the densities of standard Proctor compaction test. On the contrary, Scavuzzo (1984) reported that maximum dry unit densities from the miniature compaction lower than maximum dry densities of the standard compaction test. The optimum water contents obtained from the miniature compaction test greater than the optimum water content of standard Proctor compaction test.

Figure 6.1 and Figure 6.2 show that results of the standar Proctor test and the miniature compaction test of Dtm-1 and Dtm-10, respectively. The maximum dry density of Dtm-1 from the miniature compaction test are lesser than the maximum dry density obtained from the standard Proctor compaction test. This situation shows opposite behavior for results of Dtm-10 which is the maximum dry density from miniature compaction test is greater than the maximum dry density obtained from standard Proctor compaction test. The optimum water contents of both sample from the miniature compaction test are greater than the optimum water content obtained from the standard Proctor compoction test.

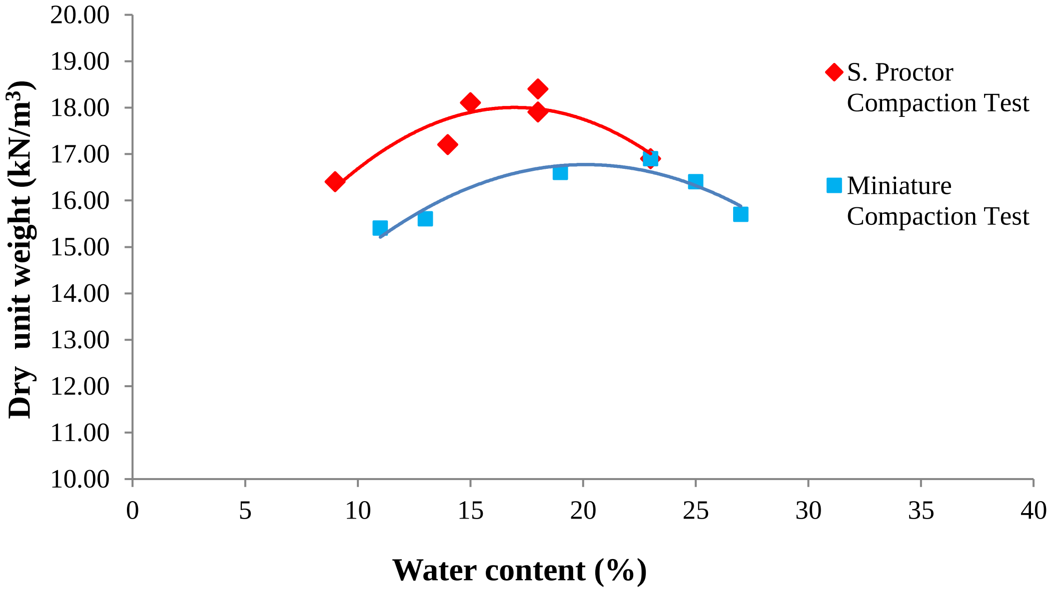


Figure 6.1 : The miniature vs. standard Proctor compaction test results of Dtm-1.

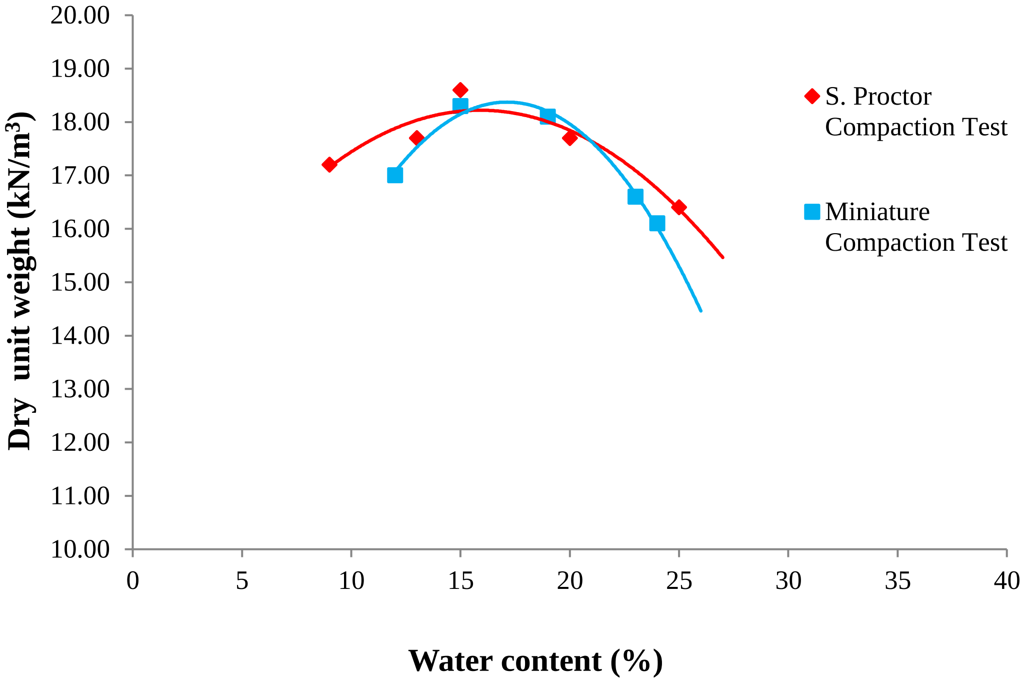


Figure 6.2 : The miniature vs. standard Proctor compaction test results of Dtm-10.

6.5 Unconfined Compression Test

The unconfined compression test is used to determine the shear strength of cohesive soils. The test is conducted by using ASTM D 2166 standard test method. In the unconfined compression test, a cylindrical soil specimen is loaded by axial stress while the confining pressure is 0.

The cylindrical soil specimen is prepared with height of 10 cm and diameter of 5 cm at optimum water content and weighed. Then, the soil specimen is placed on the load frame and axial load is applied to the specimen to record vertical displacement readings for 0.25 mm. The axial load is applied until the failure occurs. The axial stress-strain curves are obtained from the unconfined compression test results. The unconfined compression strength (q_u) is the maximum value of the total major principal stress (σ_1).

$$\tau_f = \frac{\sigma_1}{2} = \frac{q_u}{2} = c_u \qquad \textbf{(6.3)}$$

7. ANALYSIS OF TEST RESULTS

An experimental program was performed on raw dredged material and material mixed with various percentages of lime or cement to evaluate the improvement in engineering properties and the potential use of dredged material for road filling. Atterberg limit tests, miniature compaction test and unconfined compression test were carried out as per the relevant ASTM standards. The percentages of binders were determined based on previous researches, national and international guidelines. The percentage of lime mixed with dredged material were fixed at 2%, 4% and 6% of the dry mass of raw dredged material. The percentage of cement mixed with dredged material were fixed at 5%, 10% and 15% of the dry mass of raw dredged material. The needed amount of dredged material was first dried in oven at 105° C for 24 hours to ensure having soil with zero initial water content.

Atterberg limit tests were carried out on the raw and lime or cement treated dredged material, based on the fine material that was sieved through No.40 (425 μm) sieve. Miniature compaction test were performed to determine the optimum water content and the maximum dry density of raw dredged material and all mixes. Unconfined compression test was carried out on samples, which were prepared at the optimum water content and the maximum dry density as defined by the miniature compaction test. Before the test, the samples with a diameter of 50 mm and a height of 100 mm were cured and two samples were prepared for each mix. For curing, the samples were closely wrapped in a plastic bag and placed in a dessicator kept in a room where tempature was around 21° C and average relative humidity was around 98%. The samples were cured for 1, 7 and 28 days.

In this section, the results of performed test are explained in detail. The impacts of lime and cement treatment on the dredged material and the impacts of different binder contents are presented in figures and tables comparatively. Detailed graphics and tables, which were obtained from laboratory studies, are presented in appendices.

7.1 Test Results of Dtm-1 Mixed with Lime

The liquid limit, plastic limit and plasticity index of the untreated and lime treated materials are shown in Figure 7.1. The results of Atterberg limit test showed that addition of lime to the samples increases their plastic limit and decreases their liquid limit and plasticity index. The addition of 2% lime leads to decrease in liquid limit from 44% to 41%. After the addition of 4% lime, liquid limit increases to 42% and the liquid limit of sample treated with 6% lime does not change. According to Osula, decrease in liquid limit is due to a cation exchange reaction between the cations of soil and those of lime, which flocculates clay particles together and thus reduces the clay size fraction and the soil surface area (as cited in Wang et al, 2012).

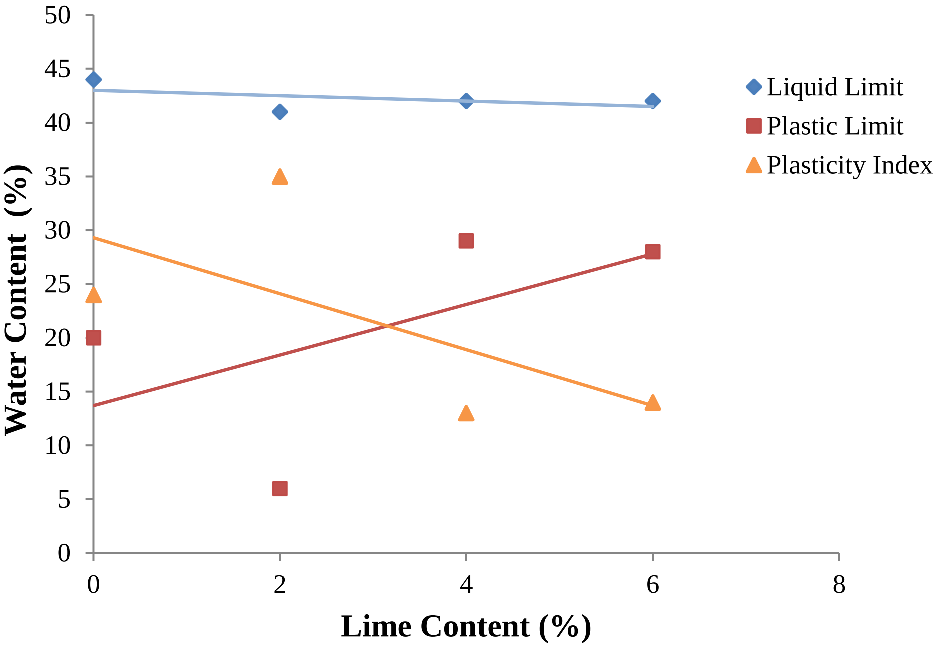


Figure 7.1 : Impact of lime on Atterberg limits of Dtm-1.

Lime addition results in increase in the plastic limit of samples. The plastic limit reaches peak value at 24% water content with addition of 4% lime. The increase in plastic limit is explained by the alteration of the water film surrounding the clay particles (Wang et al, 2012). Due to the decrease in liquid limit and great increase in the plastic limit, plasticity index of samples decrases from 24% to 13% with addition of 4% lime.

The water content-dry density curves of the raw and lime treated samples are shown in Figure 7.2. It is observed that addition of lime flattens the compaction curve, so ensuring that prescribed density can be achieved by larger water content and relaxed moisture specifications are possible (Mir, 2015).

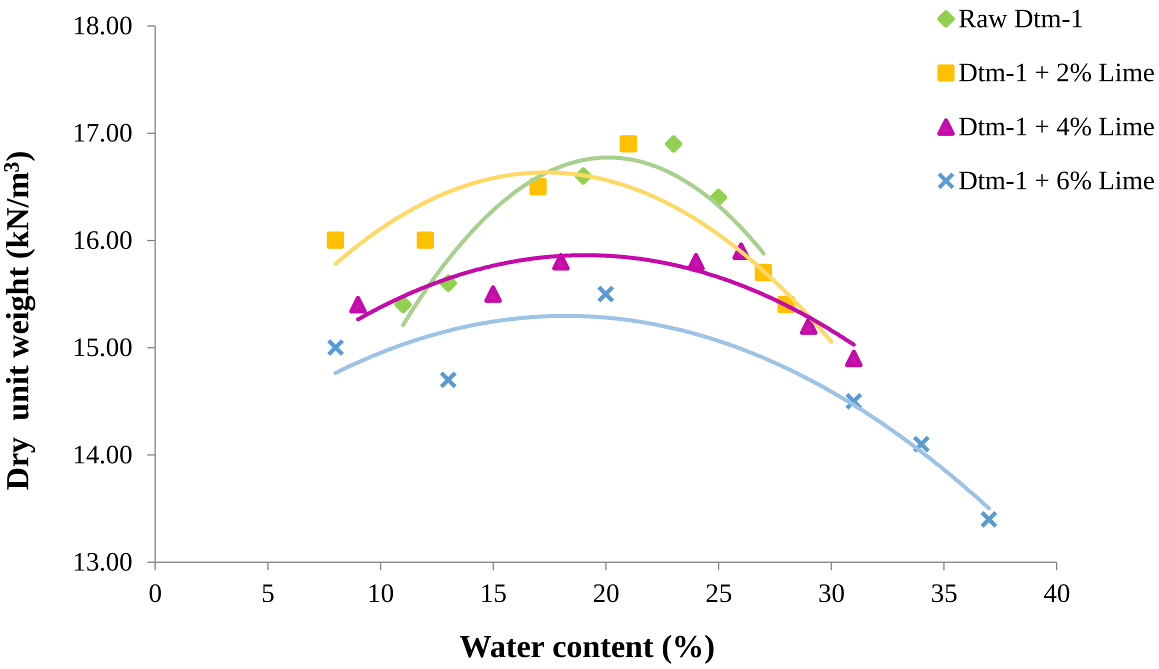


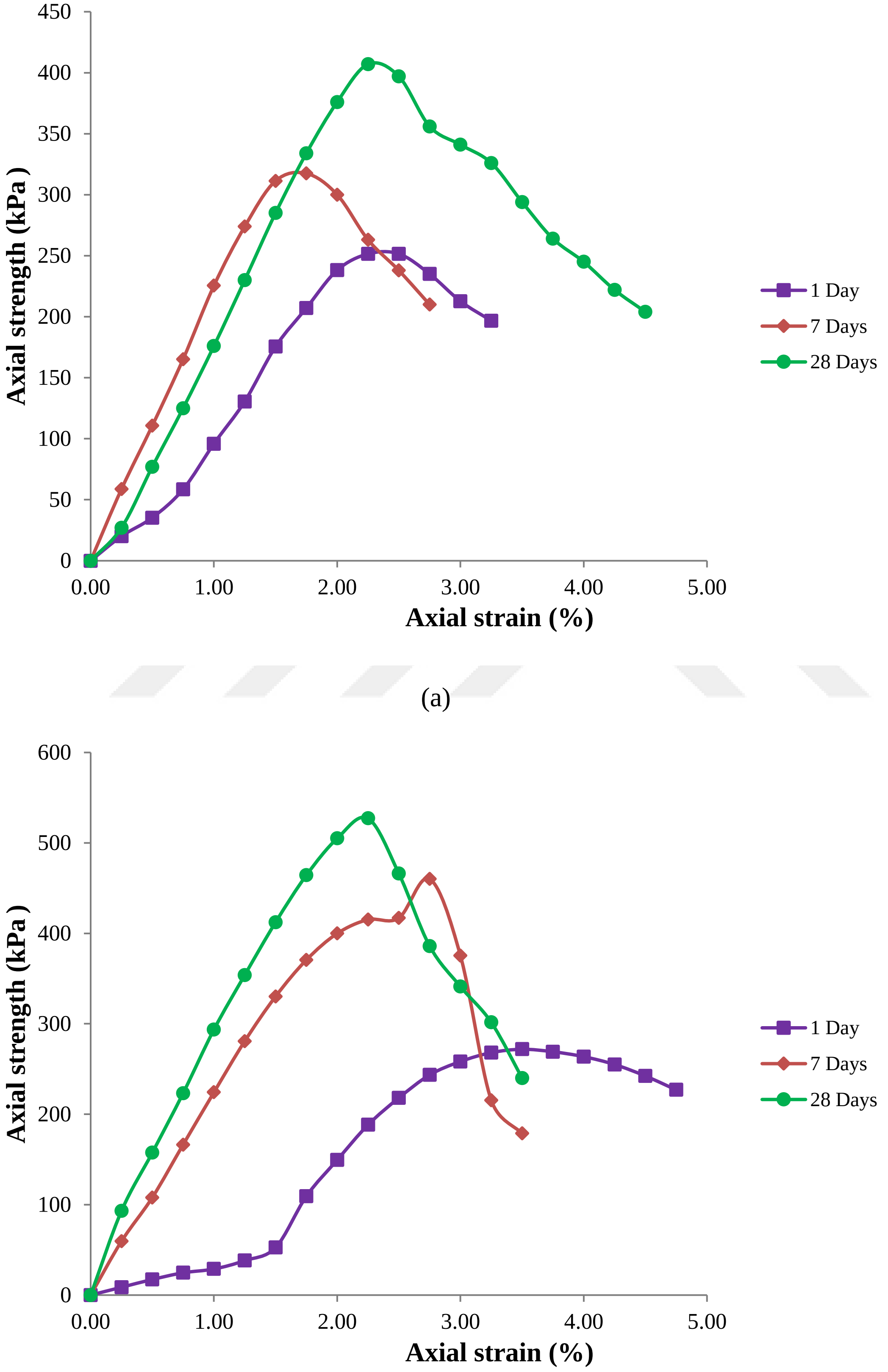
Figure 7.2 : Impact of lime on compaction characteristics of Dtm-1.

The variation of maximum dry density and optimum water content with lime content is shown in Table 7.1. The increase in lime addition results in decrease in dry density values, which is similar to findings of Dermatas et al. (2003). The optimum water content slightly decreases from 20% to 18% with addition of 2% lime and increases to 19% after addition of 4% lime. Addition of 6% lime does not alter the optimum water content of material.

Table 7.1 : Compaction parameters of raw and lime treated Dtm-1.

	w_{opt} (%)	γ_k (kN/m^3)
Dtm-1	20	17.0
Dtm-1 + 2% Lime	18	16.8
Dtm-1 + 4% Lime	19	15.8
Dtm-1 + 6% Lime	19	15.3

The results of unconfined compression tests for 2%, 4% and 6% lime content after 1, 7 and 28 days curing are presented in Figure 7.3. Test results shows that the unconfined compression strength of the lime treated materials increases with the curing period increasing from 1 day to 28 days. The behavior of the treated samples becomes more brittle with the increase in curing time, due to puzzolonic reaction between the clay particles and lime.



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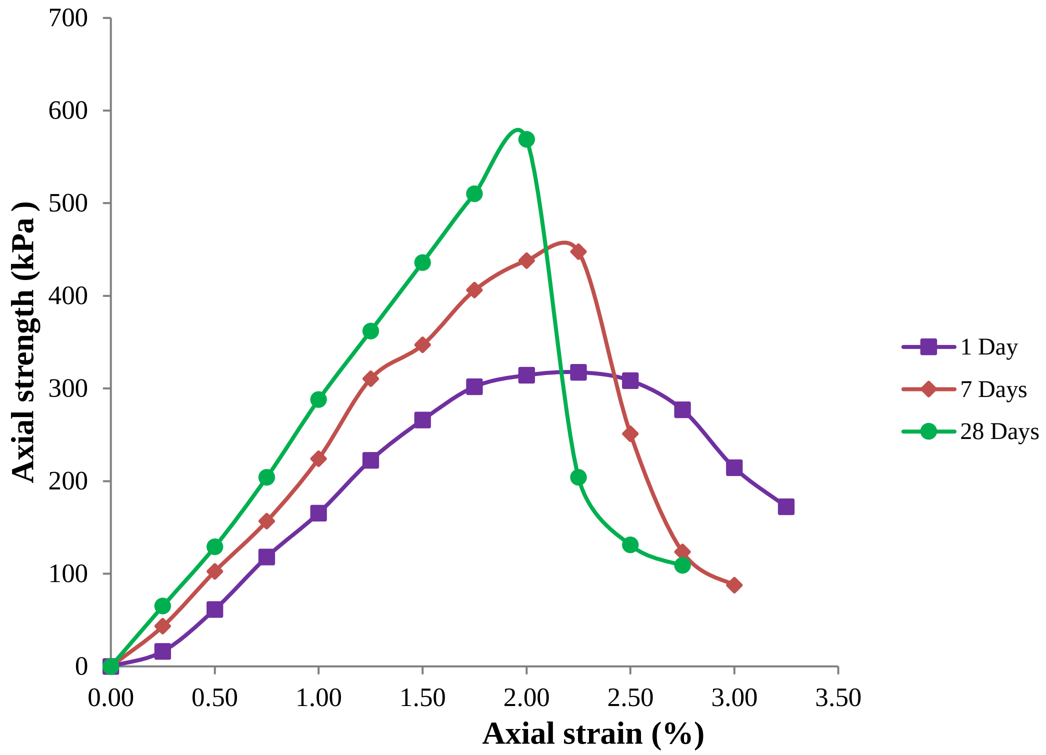


(c)

Figure 7.3 : Axial strength-strain curves of treated dredged material Dtm-1 with lime: (a) 2% lime. (b) 4% lime. (c) 6% lime.

The impact of lime addition on unconfined compression strength of dredged material is shown in Figure 7.4. It is found that the lime treatment enhances the strength of dredged material. The unconfined compression strength increases from 37 kPa to 317 kPa with addition of 6% lime after 1 day curing. On the other hand, the maximum values of q_u is obtained with addition of 4% lime after 7 and 28 days curing. When 6% lime is added, the unconfined compression strength decreases from 459 kPa to 409 kPa (after 7 days) and from 527 kPa to 482 kPa (after 28 days).

Figure 7.5 shows the unconfined compression strength of cured samples at different lime contents in relation to curing time. The strength of lime treated samples is improved with curing time. The unconfined compression strength increases in the range of 226 kPa (2% lime), 244 kPa (4% lime) and 317 kPa (6% lime) for 1 day curing time while for 28 days curing time, q_u is 380 kPa (2% lime), 527 kPa (4% lime) and 482 kPa (6% lime). Increase of strength in the lime content of 4% is higher than the samples treated with 6% of lime. It is explained by Amoudi et al. that the increase in unconfined compression strength is not significantly affected by the quantity of lime content and improvement of strength is more sensitive to the methodology of curing (as cited in Wang et al, 2012).

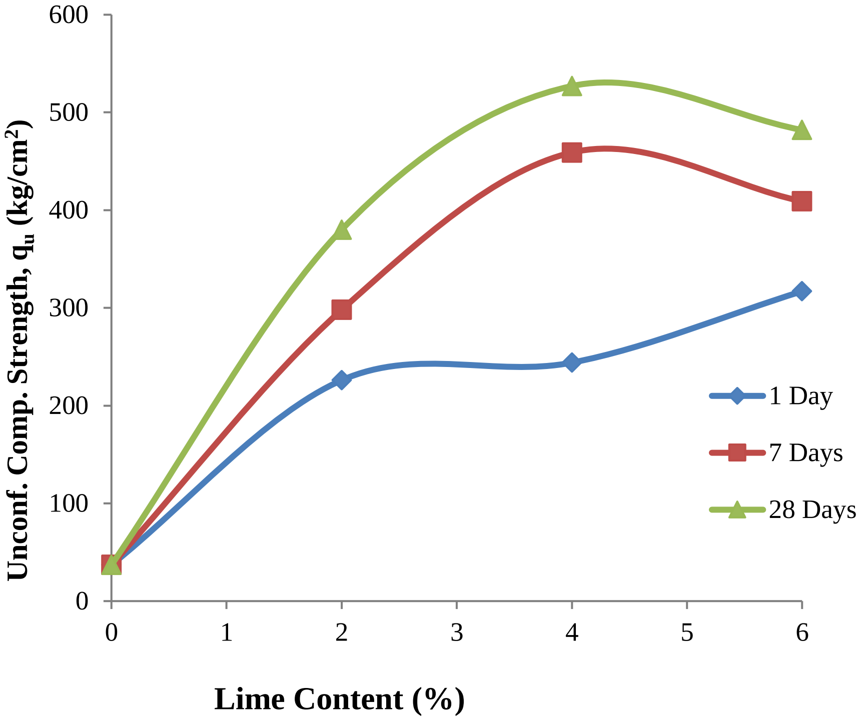


Figure 7.4 : Impact of lime content on unconfined compression strength of Dtm-1.

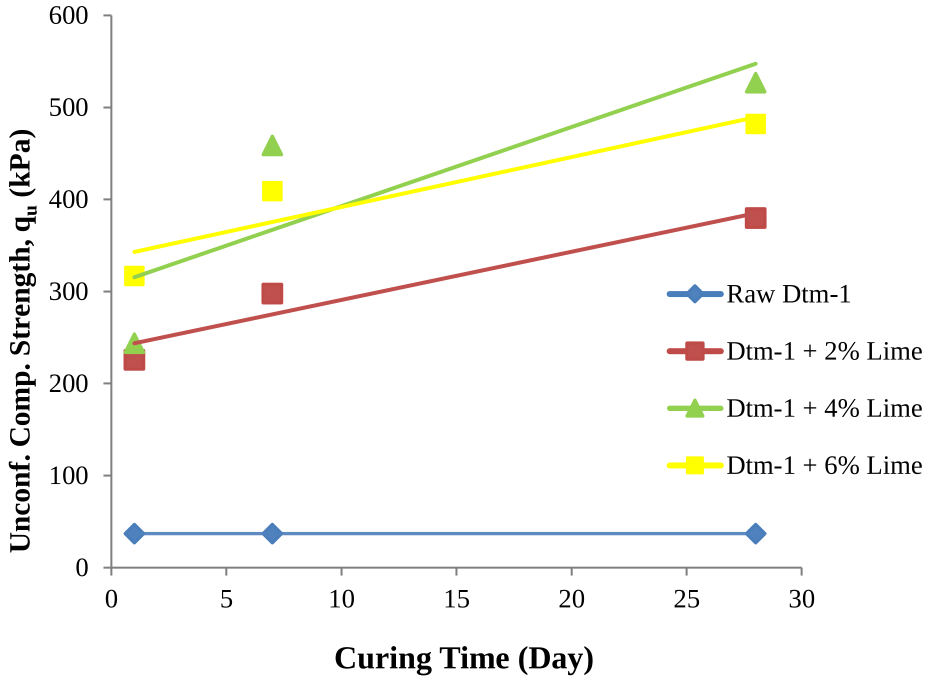


Figure 7.5 : Impact of curing time on unconfined compression strength of Dtm-1 mixed with lime.

Table 7.2 summarized the values of unconfined compression strength and the undrained shear strength of raw and lime treated dredged materials. The maximum value of c_u (264 kPa) is obtained with addition 4% lime after 28 days curing time.

Table 7.2 : The unconfined compression test parameters of raw and lime treated Dtm-1.

	q_u (kPa)			c_u (kPa)		
	1 day	7 days	28 days	1 day	7 days	28 days
Dtm-1	37	37	37	19	19	19
Dtm-1 + 2% Lime	226	298	380	113	149	190
Dtm-1 + 4% Lime	244	459	527	122	230	264
Dtm-1 + 6% Lime	317	409	482	159	205	241

7.2 Test Results of Dtm-1 Mixed with Cement

The results of Atterberg limit tests are summarized in Figure 7.6. The Atterberg limits of samples are significantly altered by addition of cement. The liquid limit of dredged material first decreases from 44% to 42% with addition of 10% cement and then increases to initial liquid limit (44%) when cement content increases to 15%. Cement causes remarkable increase in the plastic limit (20% to 32%) when the cement content ranges from 0% to 15%. The similar mechanism between lime and clay particles is valid for the cement treatment which increases plastic limit of dredged material. Hydration of added cement results in reduction in the plasticity index. The plasticity index reaches minimum value (9%) at 5% cement content.

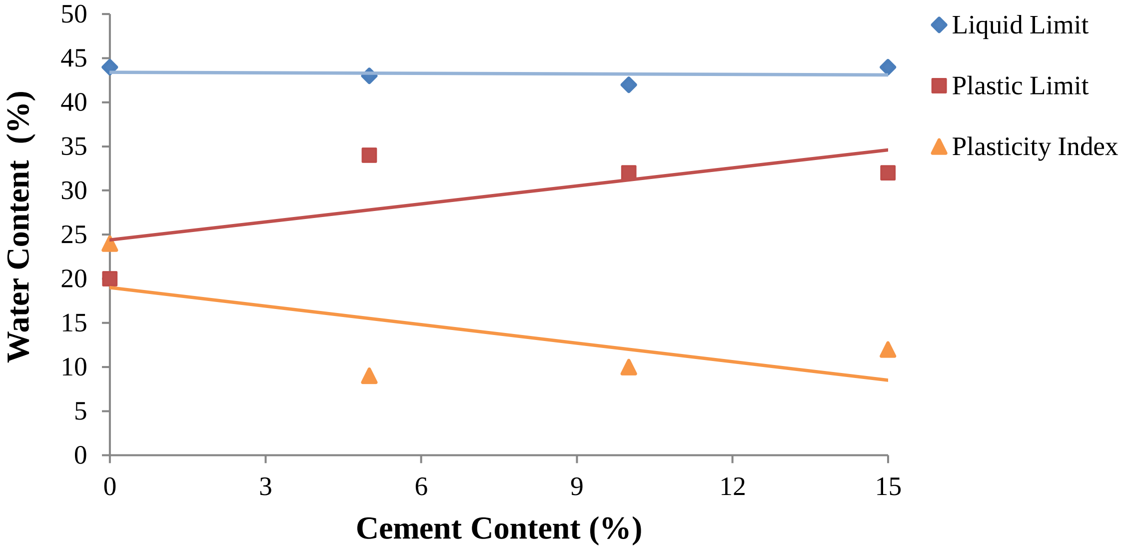


Figure 7.6 : Impact of cement on Atterberg limits of Dtm-1.

The results of compaction tests are reported in Figure 7.7 and Table 7.3. The maximum dry density decreases from 17.0 kN/m^3 to 16.3 kN/m^3 when the cement content increases from 0% to 5%. γ_k remains almost constant and equal to initial value when the cement content increases from 10% to 15%. Wang et al. (2012) observed similar results and explained that the maximum dry density initially decreased with cement content and until the cement compensated for the larger spaces.

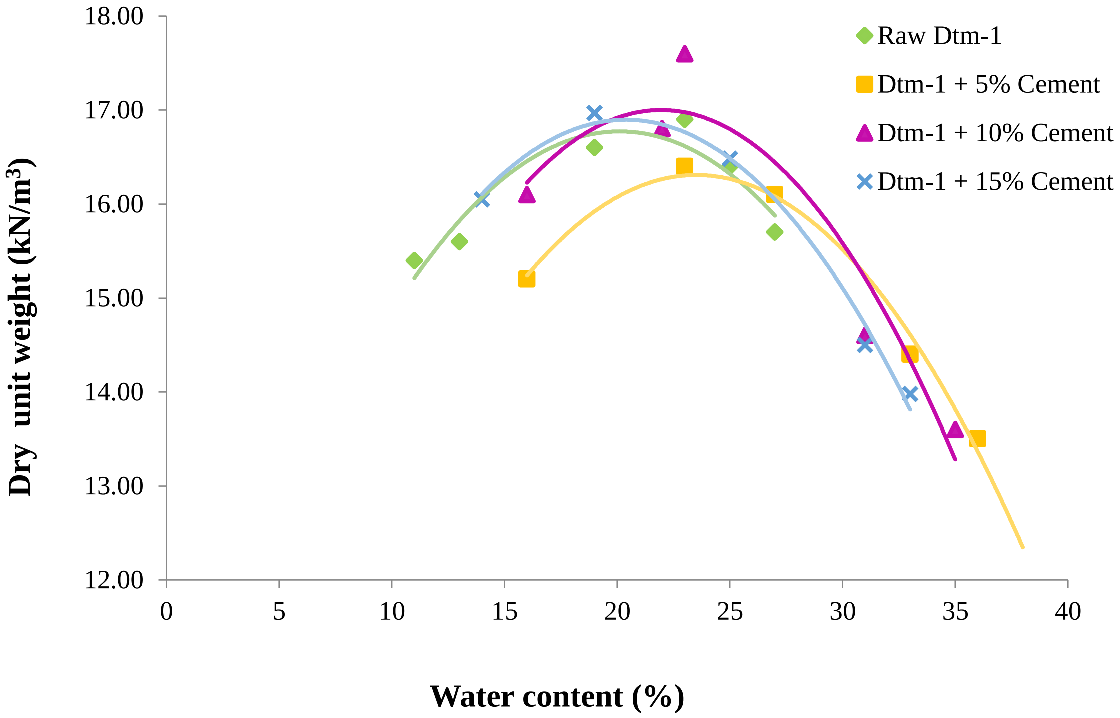


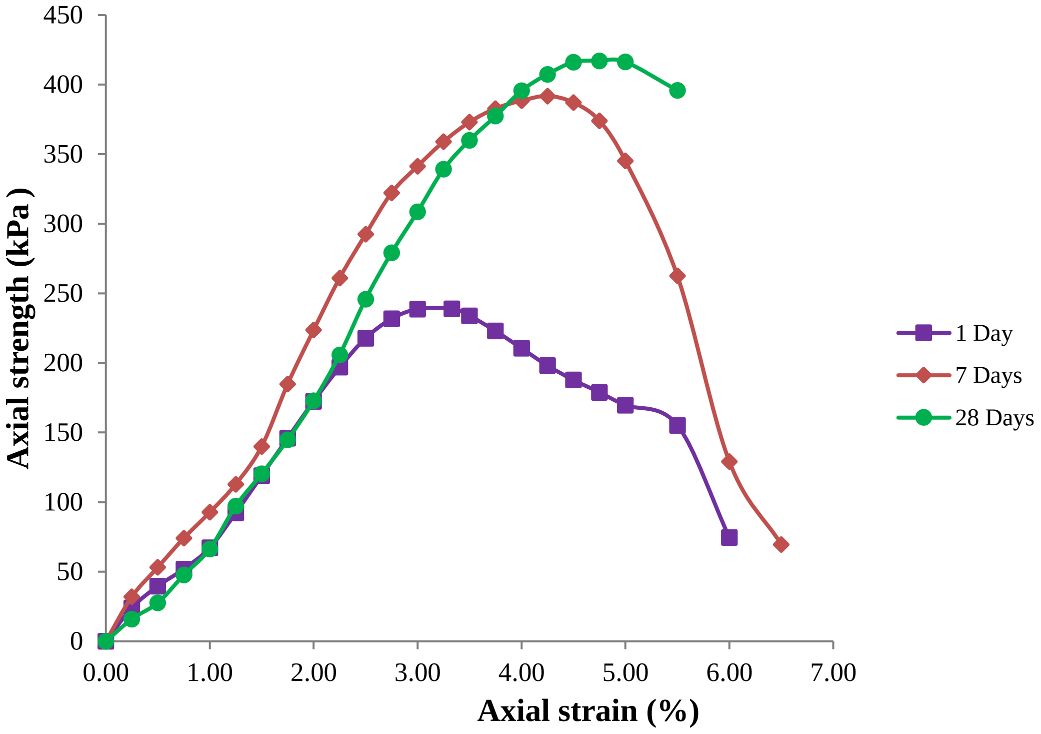
Figure 7.7 : Impact of cement on compaction characteristics of Dmt-1.

The increase in cement content causes to increase in optimum water content due to the hydration of cement. The hydration of cement requires more water (Sharma, 2016). The optimum water content increases from 20% (0% lime) to 24% at 5% cement and then, this value reduces to 21% at 15% cement content.

Table 7.3 : Compaction parameters of raw and cement treated Dtm-1.

	w_{opt} (%)	γ_k (kN/m^3)
Dtm-1	20	17.0
Dtm-1 + 5% Cement	24	16.3
Dtm-1 + 10% Cement	22	17.0
Dtm-1 + 15% Cement	21	16.9

The results of unconfined compression tests for 2%, 4% and 6% cement content after 1 day, 7 and 28 days curing are presented in Figure 7.8. In the samples mixed with cement, most of strength development is observed after 7 days of curing time. The unconfined compression strength of all samples slightly increases after 28 days curing time.



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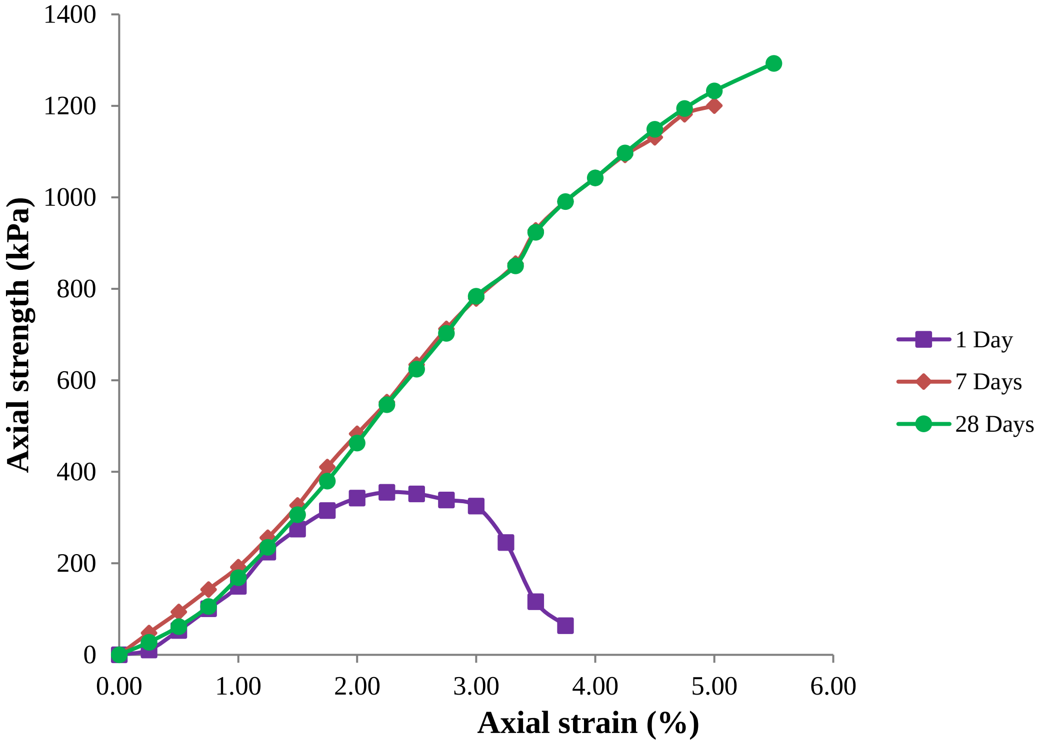

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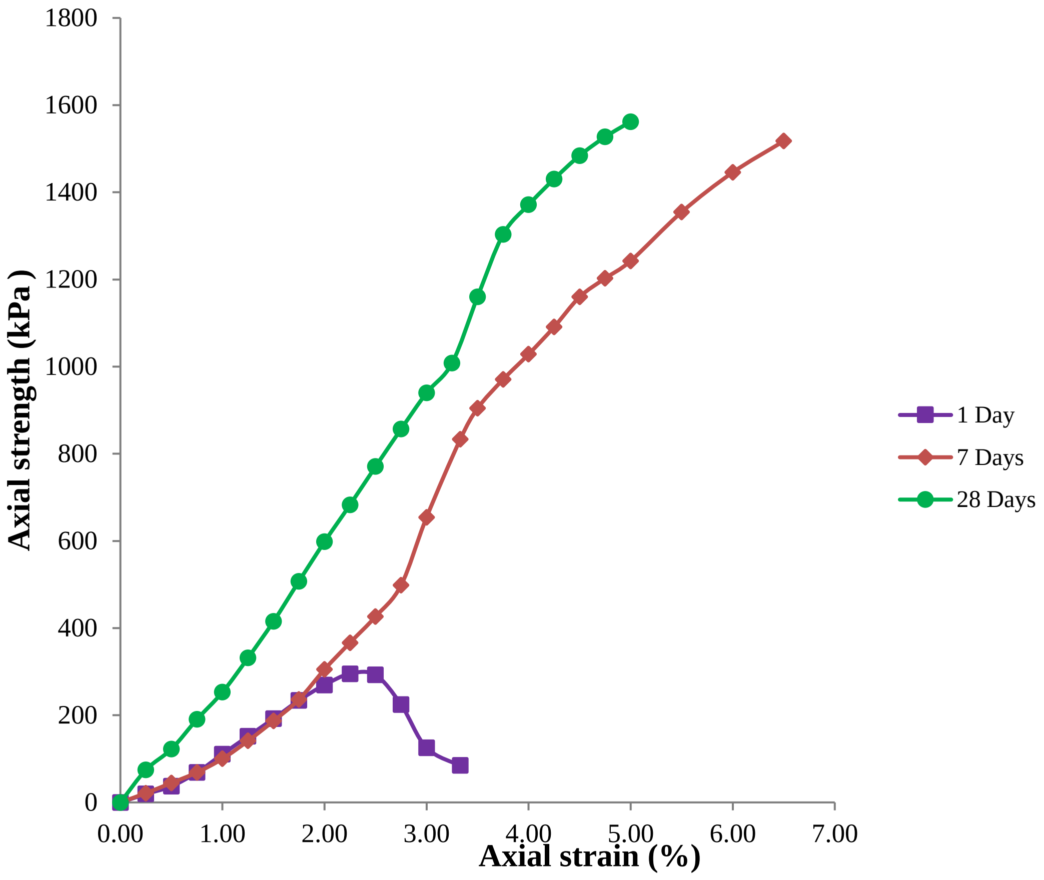


(c)

Figure 7.8 : Axial strength-strain curves of treated dredged material Dtm-1 with cement: (a) 5% cement. (b) 4% cement. (c) 6% cement.

The variation of unconfined compression strength with addition of cemen content is shown in Figure 7.9. The unconfined compression strength of Dtm-1 increases from 37 kPa to 405 kPa with addition of 5% cement. The qu strengths significantly increases when cement content is %10. Addition of 15% cement does not cause important alteration of unconfined compression strength.

The results from unconfined compressive strength test of Dtm-1 mixed with cement for all mixtures revealed that the unconfined compressive strengths increased with curing time. At early curing time (1 to 7 days), the qu strengths increased markedly. In addition, the qu strengths increased slightly at longer curing time (7 to 28 days), as shown in Figure 7.10. The impact of curing time is seen more clearly when cement content is greater than 5%. The strength increase in the range of 390 kPa (5% cement), 1120 kPa (10% cement) and 1407 kPa (15% cement) for 7 days of curing time while 28 days of curing time, the strength is 405 kPa (5% cement), 1290 kPa (10% cement) and 1430 kPa (15% cement).

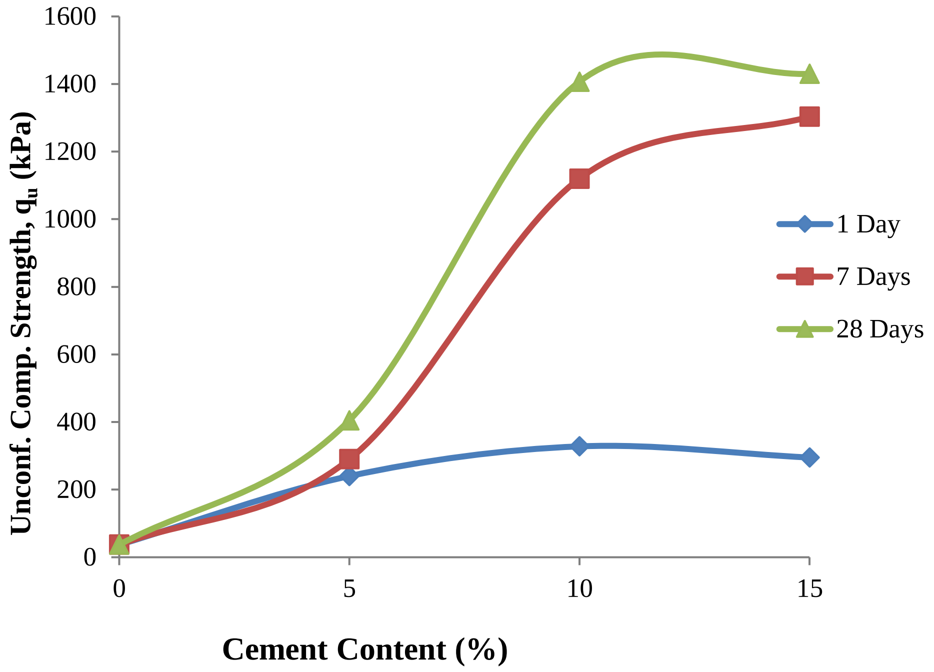


Figure 7.9 : Impact of cement content on unconfined compression strength of Dtm-1.

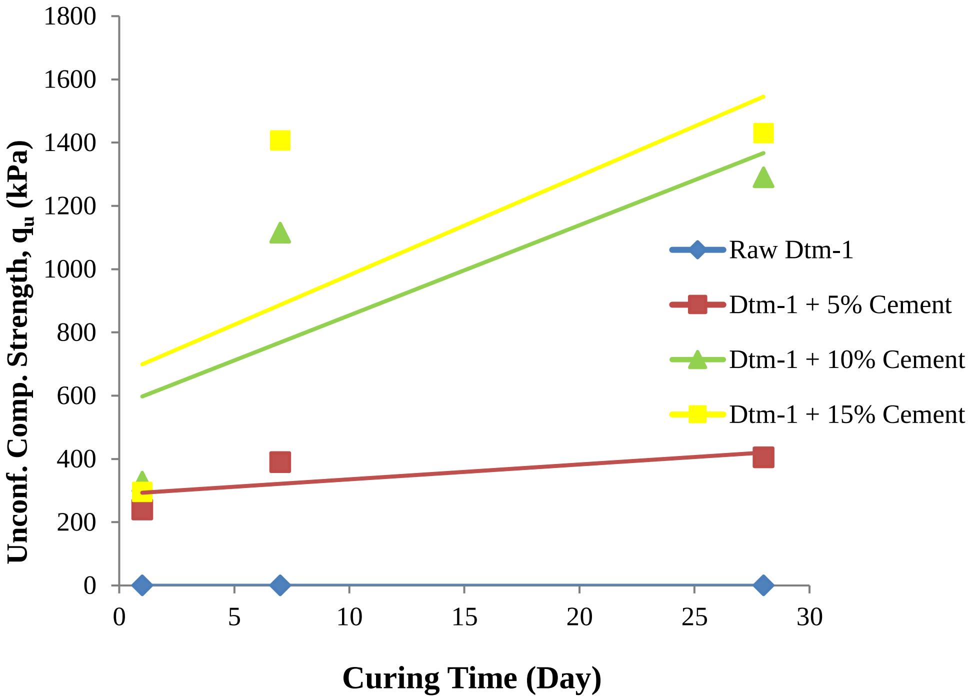


Figure 7.10 : Impact of curing time on unconfined compression strength of Dtm-1 mixed with cement.

Table 7.4 summarized the values of unconfined compression strength and the undrained shear strength of raw and cement treated dredged materials. The maximum value of c_u (715 kPa) is obtained with addition 15% lime after 28 days curing time.

Table 7.4 : The unconfined compression test parameters of raw and cement treated Dtm-1.

	q_u (kPa)			c_u (kPa)		
	1 day	7 days	28 days	1 day	7 days	28 days
Dtm-1	37	37	37	19	19	19
Dtm-1 + 5% Cement	240	390	405	120	195	203
Dtm-1 + 10% Cement	328	1120	1290	164	560	645
Dtm-1 + 15% Cement	295	1407	1430	147	704	715

7.3 Test Results of Dtm-10 Mixed with Lime

The alteration of Atterberg limits with addition of lime is reported in Figure 7.11. The liquid limit of dredged material increases from 30% to 35% with addition of 6% lime. According to the Prakash, the increase in liquid limit with the increasing binder content could be the result of entrapment of water in the wide void spaces of the flocculated structure of the soil fabric (as cited in Ramesh et al,2013).

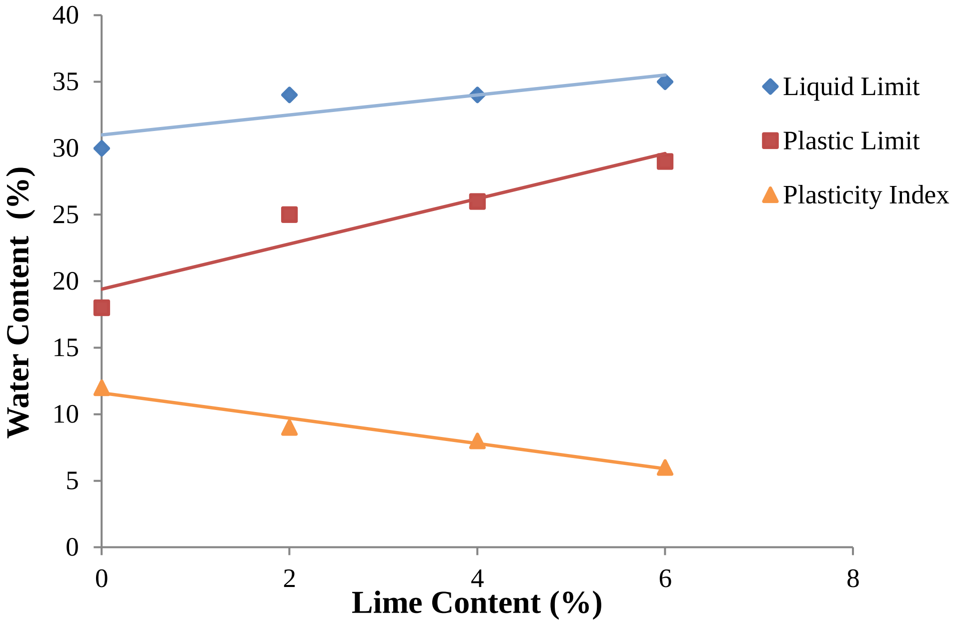


Figure 7.11 : Impact of lime on Atterberg limits of Dtm-10.

The plastic limit increases continuously when the lime content ranges from 0% to 6% due to the reduction of diffuse double layer thickness and flocculation of the clay particles (Mir,2015). The plasticity index of dredged material reduces from 12% to 6%

at 6% lime content. Due to the treatment-induced flocculation, the reduction of plasticity index enhances greatly workability (Dermatas, 2003).

The water content and dry density curves of untreated and lime treated dredged materials are shown in Figure 7.12. The maximum dry density reduces from 18.4 kN/m^3 to 18.2 kN/m^3 when the lime content is 2%. γ_k is lowest (17.1 kN/m^3) for 4% lime content and then, it increases to 17.2 kN/m^3 at 6% lime content.

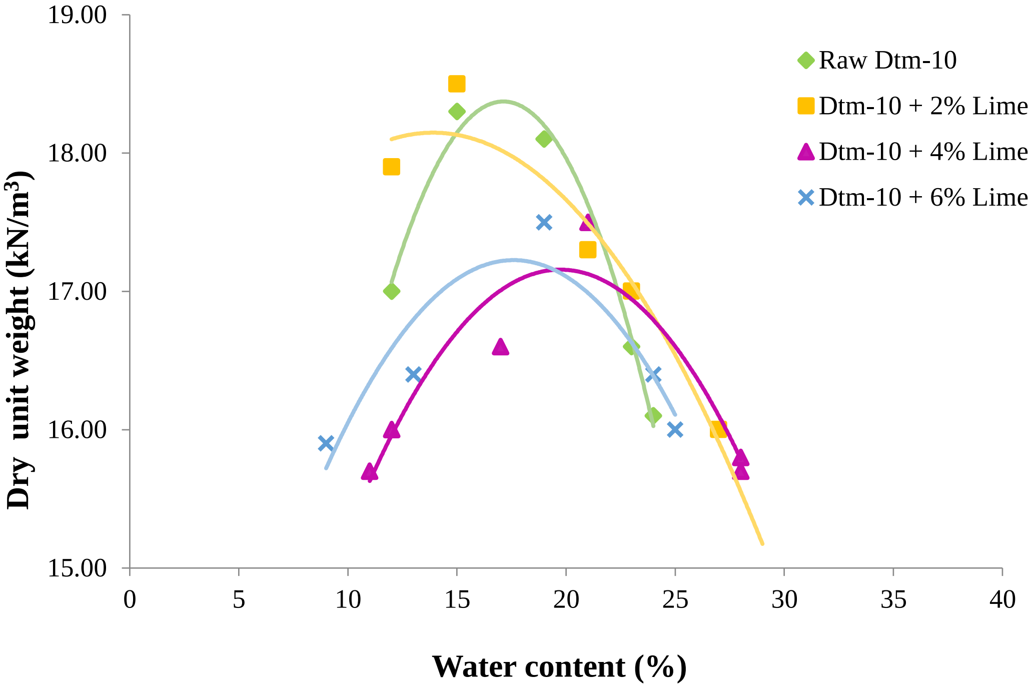


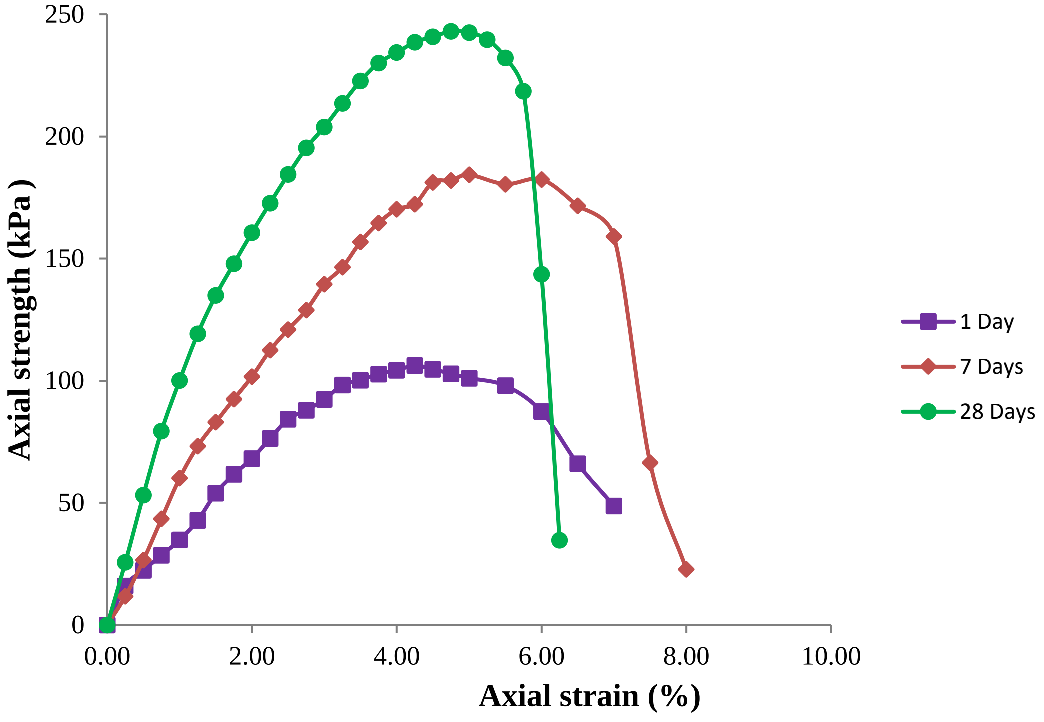
Figure 7.12 : Impact of lime on compaction characteristics of Dmt-10.

The optimum water content first decrases (17% to 15%) and then increases and reaches peak value at 20% with addition of 4% lime content. The addition of 6% lime causes decrasea in w_{opt} to 18% (Table 7.5). The variation of axial strength-axial strain curves of dredged material mixed with different lime contents after curing periods 1 day, 7 and 28 days is shown in Figure 7.13.

Table 7.5 : Compaction parameters of raw and lime treated Dtm-10.

	w_{opt} (%)	γ_k (kN/m^3)
Dtm-10	17	18.4
Dtm-10 + 2% Lime	15	18.2
Dtm-10 + 4% Lime	20	17.1
Dtm-10 + 6% Lime	18	17.2

The unconfined compression strength of dredged material enhances with addition of lime. The unconfined compression strength varies from 61 kPa for untreated soil to 402 kPa for a lime content of 6% respectively (Figure 7.14).



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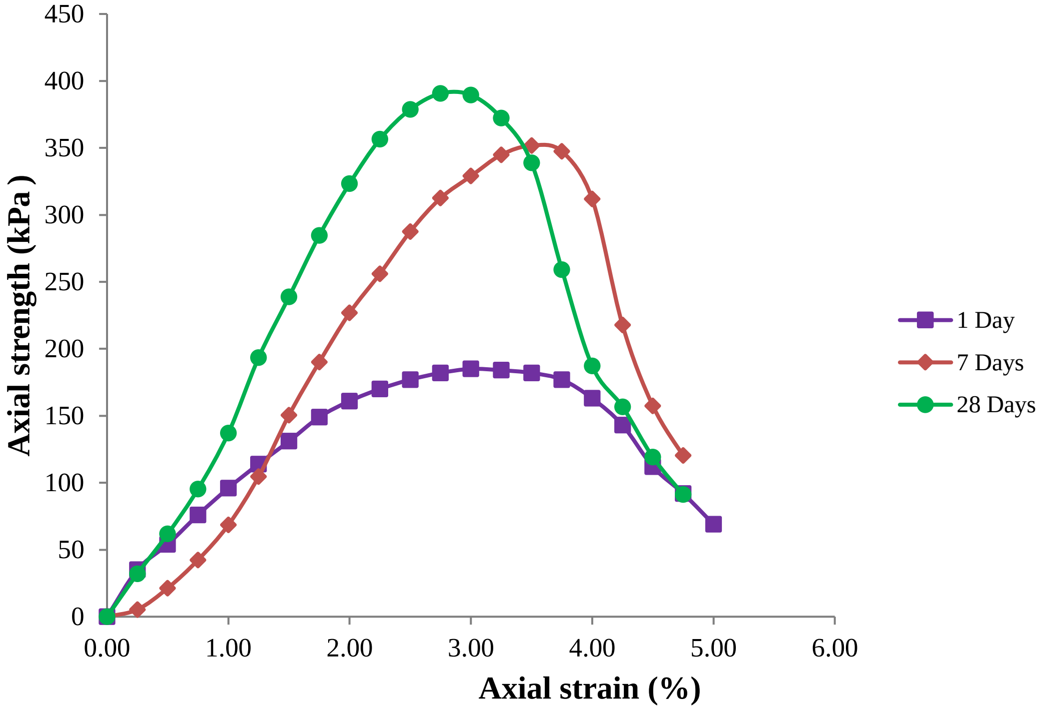

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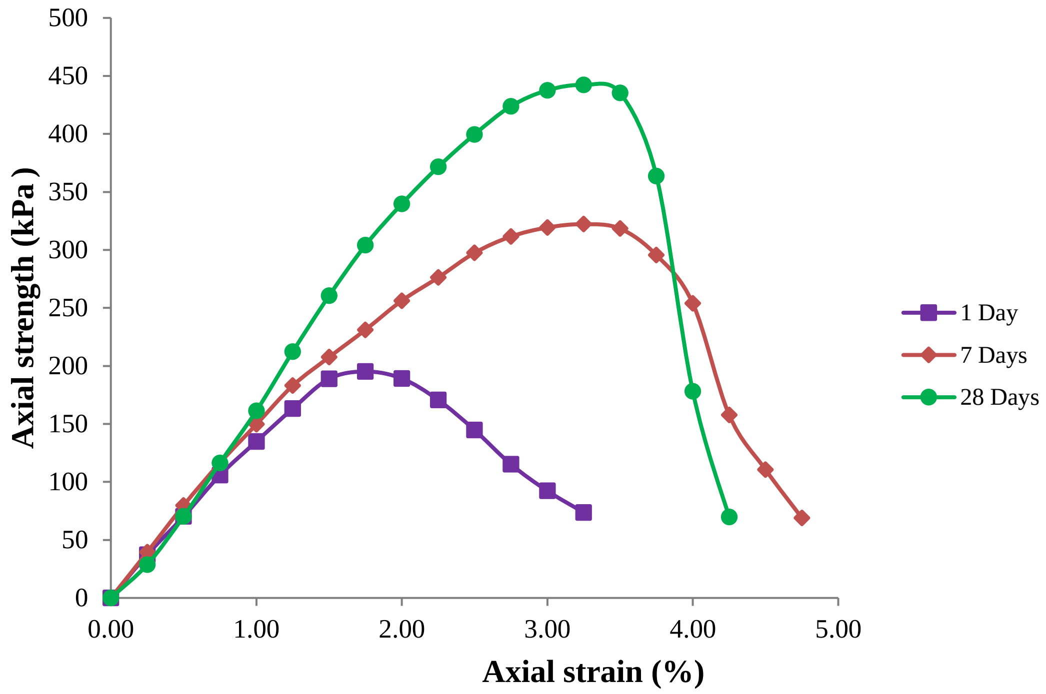

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Figure 7.13 : Axial strength-strain curves of treated dredged material Dtm-10 with lime: (a) 2% lime. (b) 4% lime. (c) 6% lime.

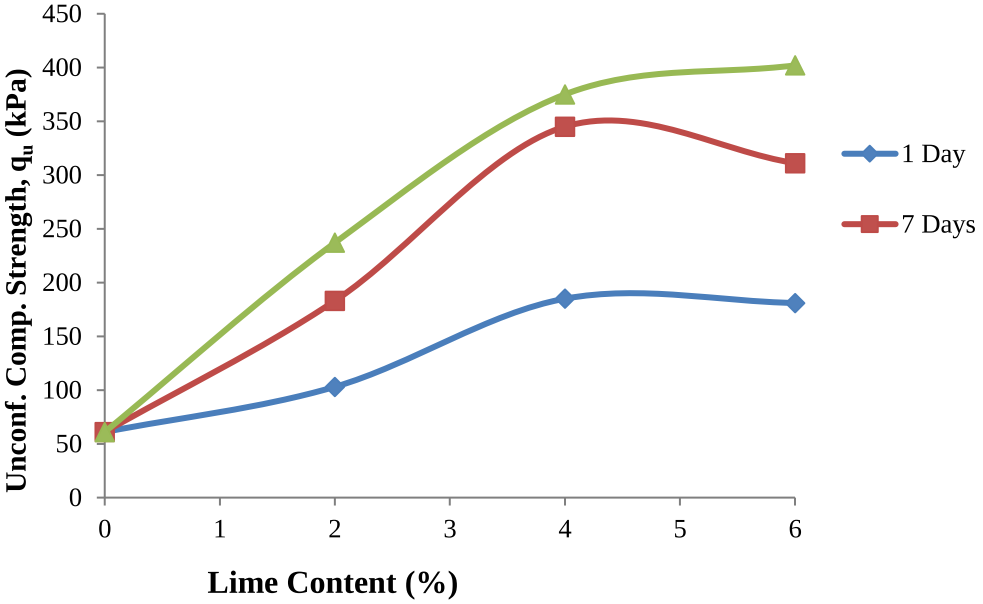


Figure 7.14 : Impact of lime content on unconfined compression strength of Dtm-10.

As can be seen in Figure 7.15, q_u development of the dredged material is not only influenced by the lime content, but also the curing time. The unconfined compression strength of dredged material with treated 2% lime is substantial (103 kPa) and increases to (237 kPa) with the curing period increasing from 1 day to 28 days. The strength of 4% lime treated material increases from 185 kPa after 1 day to 375 kPa after 7 days curing time. The unconfined compression strength of 6% lime treated material is 181 kPa after 1 day which increases to 402 kPa after 7 days curing.

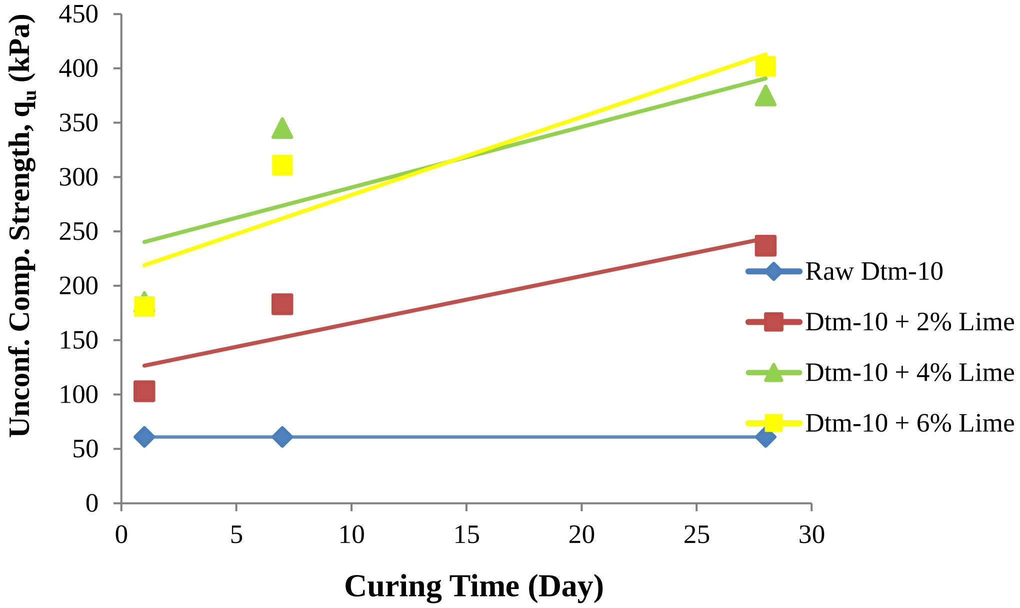


Figure 7.15 : Impact of curing time on unconfined compression strength of Dtm-10 mixed with lime.

Table 7.6 indicates that the values of unconfined compression strength and the undrained shear strength of raw and lime-treated dredged materials. The maximum value of c_u (201 kPa) is obtained with addition 6% lime after 28 days curing time.

Table 7.6 : The unconfined compression test parameters of raw and lime treated Dtm-10.

	q_u (kPa)			c_u (kPa)		
	1 day	7 days	28 days	1 day	7 days	28 days
Dtm-10	61	61	61	31	31	31
Dtm-10 + 2% Lime	103	183	237	52	92	119
Dtm-10 + 4% Lime	185	345	375	93	173	132
Dtm-10 + 6% Lime	181	311	402	80	156	201

7.4 Test Results of Dtm-10 Mixed with Cement

The liquid limit, plastic limit and plasticity index of the untreated and lime-treated dredged material are illustrated in Figure 7.16. The liquid limit increases from 30% to 39% with addition of 5% cement and then it reduces gradually to 32% at 15% cement content. The same trend is shown for plastic limit which first increase to 31% when 5% cement is added and after, it decrases to 29% for 15% cement content. The plasticity index shows a decrease with the addition of 3% cement, followed by an increase with addition of 10% cement. The addition of 15% leads to the lowest value in plasticity index (3%).

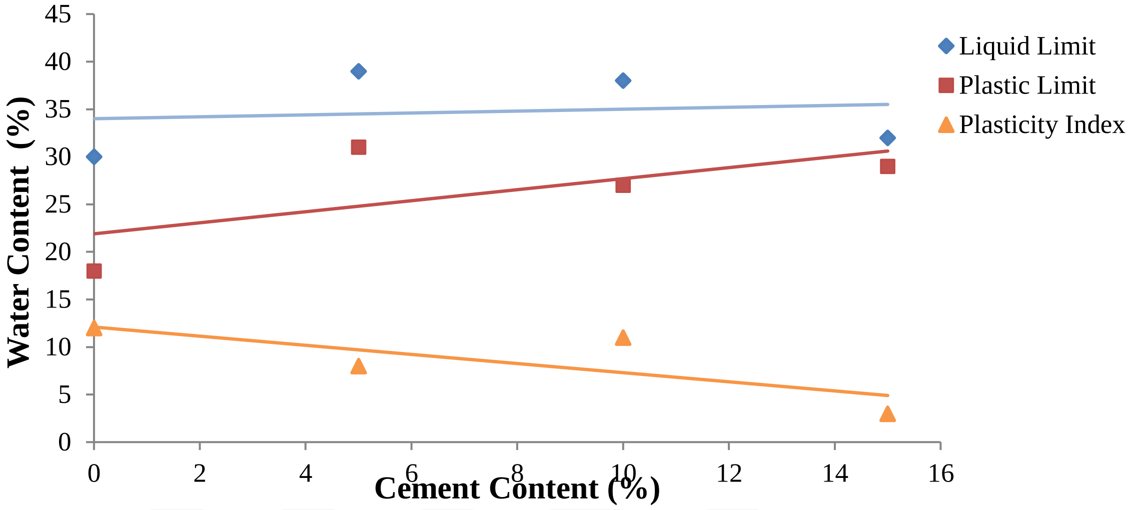


Figure 7.16 : Impact of cement on Atterberg limits of Dtm-10.

The water content-dry density curves of the raw and cement-treated samples are shown in 7.17. The maximum dry density decreases from 18.4 kN/m^3 to 17.9 kN/m^3 when the cement content increases from 0% to 15%. For only 10% cement content, the maximum dry density increases to 18.6 kN/m^3.

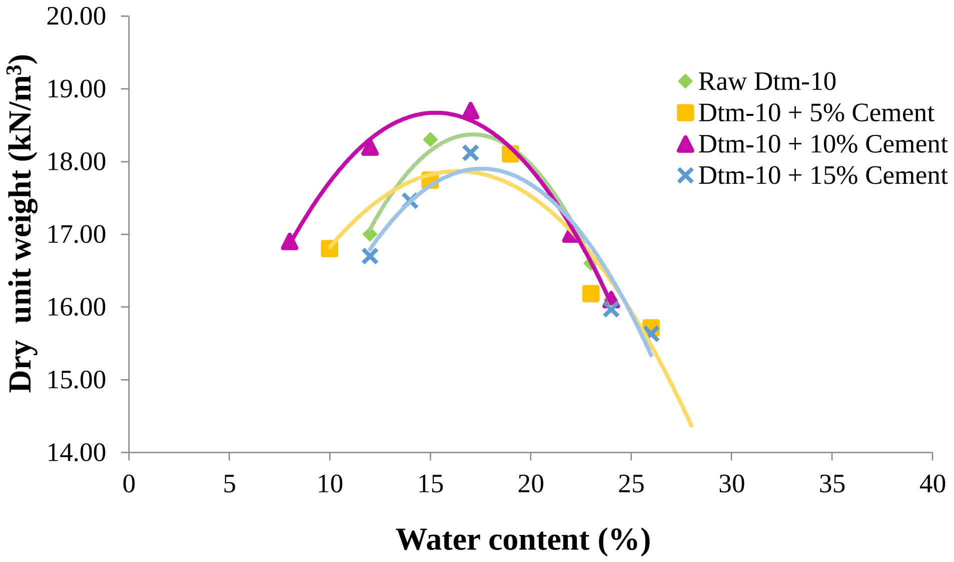


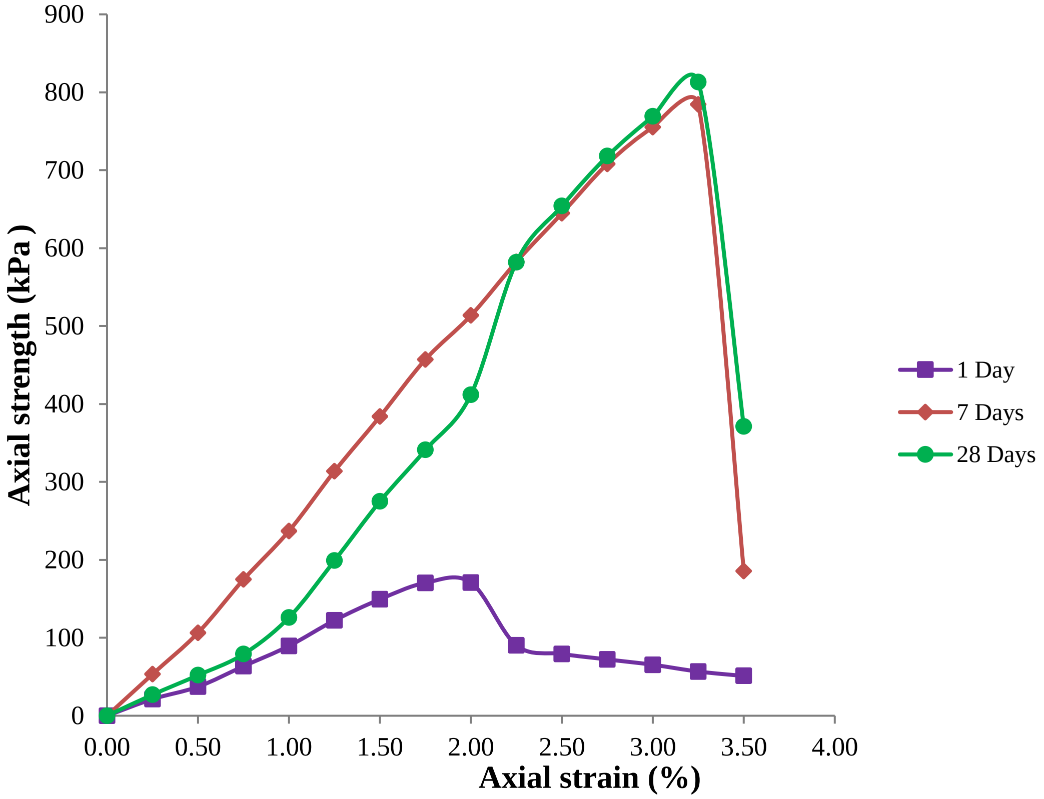
Figure 7.17 : Impact of cement on compaction characteristics of Dmt-10.

The optimum water content is almost constant when the cemen content increases from 0% to %5. This value reduces to 16% with addition of 10% cement content and then it increases to 18% with addition of 15% cement (Table 7.7).

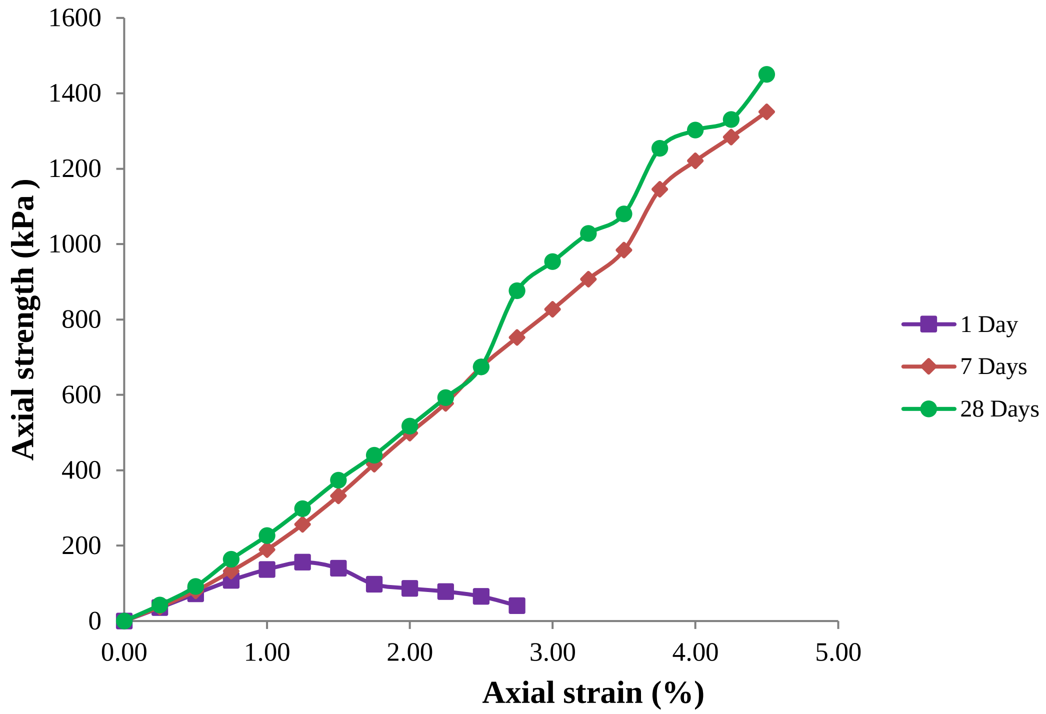
Table 7.7 : Compaction parameters of raw and cement treated Dtm-10.

	w_{opt} (%)	γ_k (kN/m^3)
Dtm-10	17	18.4
Dtm-10 + 5% Cement	17	17.8
Dtm-10 + 10% Cement	16	18.6
Dtm-10 + 15% Cement	18	17.9

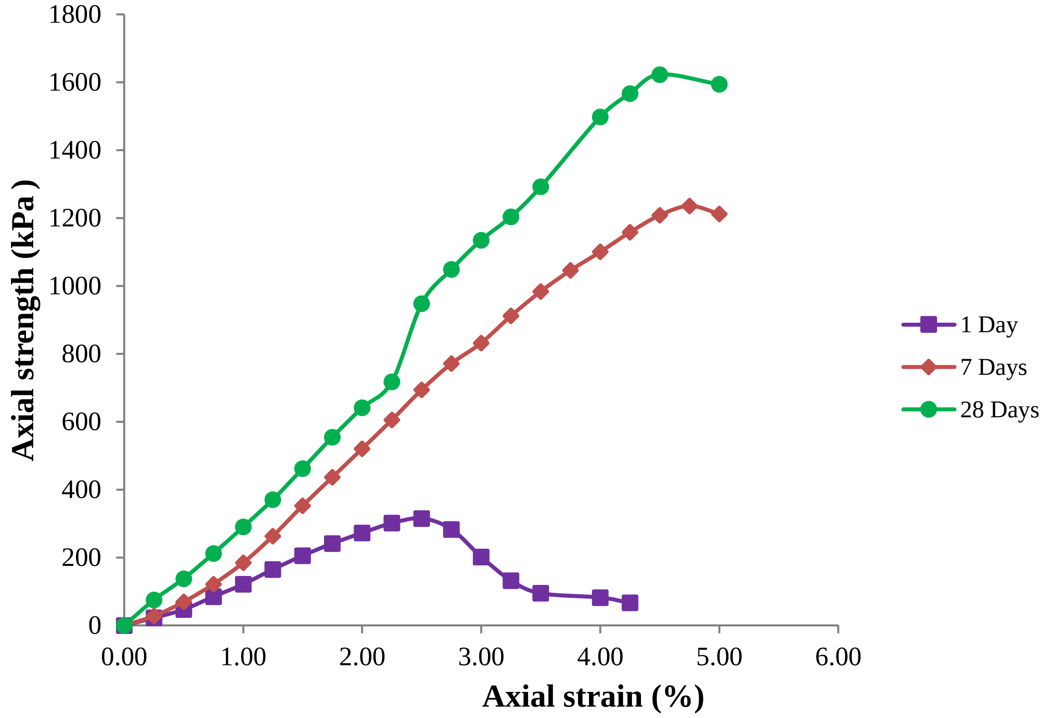
The variation of axial strength-axial strain curves of Dtm-10 mixed with different cement contents after curing periods 1 day, 7 and 28 days is shown in Figure 7.18. The unconfined compression strength of material increases with addition of cement and increases in curing time.



(a)



(b)



(c)

Figure 7.18 : Axial strength-strain curves of treated dredged material Dtm-10 with cement: (a) 5% cement. (b) 10% cement. (c) 15% cement.

The relationship between the unconfined compression strength and cement content is shown in Figure 7.19. Increase in cement content result in development of unconfined compression strength of Dtm-10. the qu strengths of these mixtures increases linearly with increase in cement content for 7 and 28 days curing. The unconfined compression strength increases from 5% to 15% cement content however, this increase is more remarkable in 10% cement content compared with 5% and 15%.

Figure 7.20 shows the relationship between the unconfined compression strength of Dtm-10 mixed with cement samples and curing time. The strength of cement treated samples is improved with curing time. The unconfined compression strength of samples treated with cement increases gradually after 1 day and 28 days curing. On the other hand, after 7 days the strength has noticeably increased in all samples.

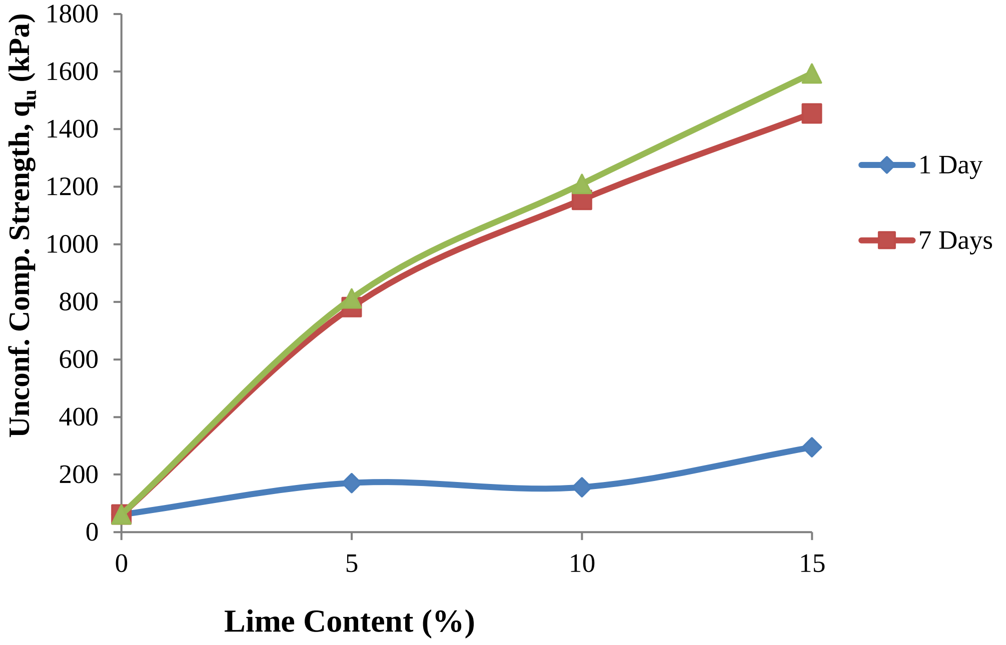


Figure 7.19 : Impact of cement content on unconfined compression strength of Dtm-10.

Table 7.7 shows that the values of unconfined compression strength and the undrained shear strength of raw and cement treated Dtm-10. The maximum value of c_u (795 kPa) is obtained with addition 15% cement content after 28 days curing time.

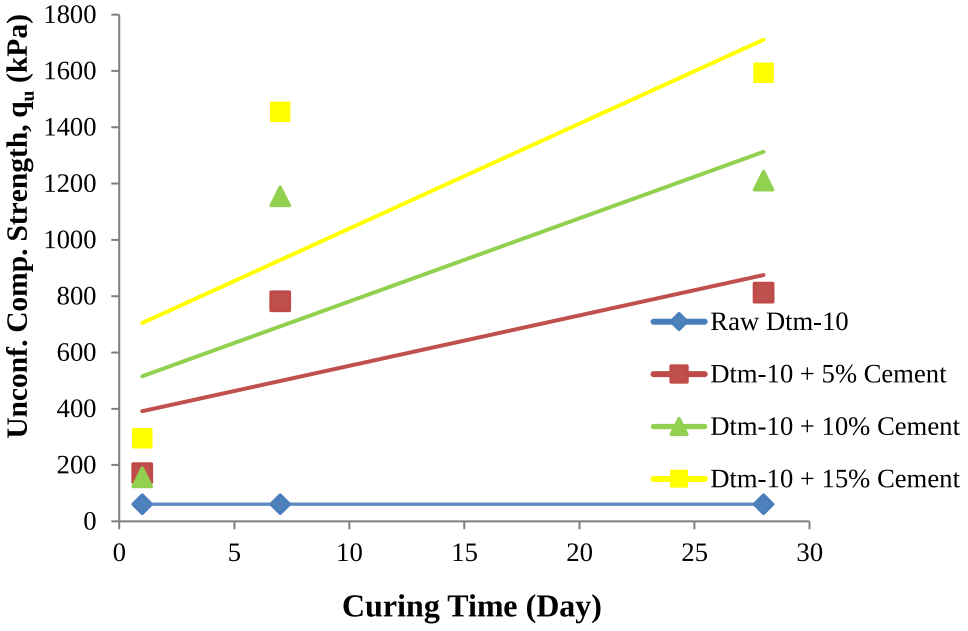


Figure 7.20 : Impact of curing time on unconfined compression strength of Dtm-10 mixed with cement.

Table 7.8 : The unconfined compression test parameters of raw and lime treated Dtm-10.

	q_u (kPa)			c_u (kPa)		
	1 day	7 days	28 days	1 day	7 days	28 days
Dtm-10	61	61	61	31	31	31
Dtm-10 + 5% Cement	171	782	812	86	391	406
Dtm-10 + 10% Cement	160	1150	1210	80	575	605
Dtm-10 + 15% Cemnet	295	1455	1590	148	728	795

8. CONCLUSIONS AND RECOMMEDATIONS

8.1 Summary of Test Results and Conclusions

Dredging is essential to construct and maintain harbours and waterways and huge amounts of material are dredged every year. Dredged material is dumped in the sea or disposed at land disposal site. Due to adverse impacts of disposal activities of dredged material and restrictions of international and national regulations, benefical use options of dredged material is gaining importance. Road construction is one of the main area for the beneficial use of dredged material.

In this thesis, the reuse of dredged materials as a new material for road fill and the effects of lime and cement treatment on the engineering properties of dredged materials were investigated by performing Atterberg limit tests, compaction tests and unconfined compression strength test. The experimental programme was conducted on two different clayey materials which are called as Dtm-1 and Dtm-10, respectively. To enhance mechanical properties of dredged materials, lime was mixed in the dry state and the percentage of lime varies from 0% to 6% with 2% increment. Cement was mixed in the dry state and the percentage of cement varies from 0% to 15% with 5% increment.

Treatment of fine grained clayey dredged materials with cement and lime leads to increase of their plastic limit and decrease of their liquid limit and plasticity index. The minimum value of plasticity index is obtained as 14% at 4% lime content and 6% at 6% lime content for Dtm-1 and Dtm-10, respectively. The minimum values of plasticity index for cement treatment are 9% at 5% cement content and 3% at 15% cement content for Dtm-1 and Dtm-10, respectively.

The maximum dry density of treated dredged materials decreases with addition of cement or lime content and the alteration of optimum water content is not observed clearly. The maximum dry density of lime treated dredged materials is lower than that of cement treated dredged materials.

The unconfined compressions strength of dredged material increases with binder content and curing time. The axial stress-strain curves indicate that the behaviour of samples with increasing cement or lime content resulting in more brittle type of failure. For lime treatment, strength in the first days occurs with higher rates and as the time passes this trend is decreased. In the samples cured by cement, most of strength development is observed after 7 days of curing time. The improvement of unconfined compression strength of lime treated Dtm-1 is more superior than Dtm-10. The unconfined compression strength of Dtm-1 increases from 37 kPa to 527 kPa when the unconfined compression strength of Dtm-10 increases from 61 kPa to 402 kPa. The maximum values of q_u are obtained by adding 4% and 6% lime to Dtm-1 and Dtm-10, respectively. Cement treatment leads to increase in unconfined compression strength which increases from 37 kPa to 1430 kPa for Dtm-1 and increases from 61 kPa to 1594 kPa for Dtm-10. The maximum value of q_u is obtained by adding 15% cement to Dtm-1 and Dtm-10.

8.2 Practical Application of This Study

This thesis deals with the beneficial use of non-contaminated dredged material, which were obtained from different regions of Tuzla, as a new material for road construction which requires good mechanical properties. Reuse of dredged material with lime or cement treatment for road construction purposes requires checking specific geotechnical criteria that are specified in Turkish highway technical guideline and USACE guideline. Turkish highways technical guideline only specifies the characteristics of lime treatment while USACE guideline specifies not only required characteristics of lime treatment but also the required characteristics of cement treatment for road construction purpose.

Turkish highways technical guideline specifies the limits of engineering properties of lime treated materials for each layer of road construction. Table 8.1 summarizes the recommended engineering characteristics for lime treatment of different sections of road in Turkish highways technical guideline. The optimum lime content is choosen as the minimum lime content which ensures the recommended characteristics for different layers of road. The guideline specifies any limit for minimum value of unconfined compression strength. On the other hand, the value of unconfined compression strength at 7 days curing time is one of the most important parameter for design (Kavak et al., 2008).

Table 8.1 : Recommended engineering characteristics for lime treatment of road sections in Turkish highways technical guideline.

	LL (%)	PL (%)	q_u (7) (kPa)
Subbase	<25	<6	-
Subgrade	<30	<10	> 500
Embankment	<40	<20	-

According to the USACE guideline, the unconfined compression test is the main test recommended to be determine the suitability of a specific material to be used as a structural material in one of the different layers of road construction and the lowest lime concentration that meets the compression strength requirement is considered as the optimum lime content for treatment purposes. The recommended unconfined compression strength after 7 days curing time for lime treatment of different road sections is given in Table 8.2 (Little et al.,2009).

Table 8.2 : The recommended unconfined compression strength for lime treatment of road sections in USACE guideline.

Anticipated use of stabilized layer		q_u (7) (kPa)
Sub-base	Rigid pavements/Floor slabs/Foundations	350
	Flexible pavement	420-630
Base		910

Turkish highway guideline does not prescribe protocol for cement treatment and therefore cement treatment results were evaluated only according to the USACE guideline. The required unconfined compression strength for cement treatment to use in road layers is shown in Table 7.8. The lowest cement content in the mixture design that meets the requirements of Table 7.8 should be used as the design content (Little et al.,2009).

Table 8.3 : The recommended unconfined compression strength for cement treatment of road sections in USACE guideline.

Anticipated use of stabilized layer	Minimum q_u (7) (kPa)	
	Flexible pavement	Rigid pavement
Base course	5270	3520
Subbase, subgrade	1760	1405

Based on the laboratory tests and national and international guidelines, Dtm-1 and Dtm-10 can be used as road fill material. From the point of view of mechanics and applicability in road construction, the optimum lime content of Dtm-1 is 4% which can be used for embankment. The optimum lime content of Dtm-10 is 6% which can be used for embankment. According to the USACE guideline, Dtm-1 mixed with 4% lime can be used as subbase (rigid pavement/floor slab/foundation/flexible pavement) material. Moreover, Dtm-10 mixed with 6% lime can be used for subbase layer of road.

7 day unconfined compression strength of Dtm-1 mixed with 15% cement is 14.07 kg/cm^2 and 7 day unconfined compression strength of Dtm-10 mixed with 15% cement is 14.55 kg/cm^2. Based on the USACE guideline, 15% cement content could be optimum content for Dtm-1 and Dtm-10 that meets the minimum requirements of subbase, subgrade layer of rigid pavement.

8.3 Recommendations for Future Research

In order to definitively conclude on this topic, further research is needed. It is proposed to perform California bearing ratio test for accurately investigation of potential use of dredged material as a road construction material according to the Turkish highway guideline.

Due to time limitation and limited availability of dredged materials, more studies need to be undertaken this topic in order to have a larger comparative base. More design mixes can be explored to determine more optimum lime or cement content. In addition, the impact of other additives such as fly ash could be investigated to enhance engineering properties of dredged materials.

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APPENDICES

APPENDIX A: Atterberg Limit Tests Results

APPENDIX B: Compaction Tests Results

APPENDIX C: Unconfined Compression Test Results

APPENDIX A

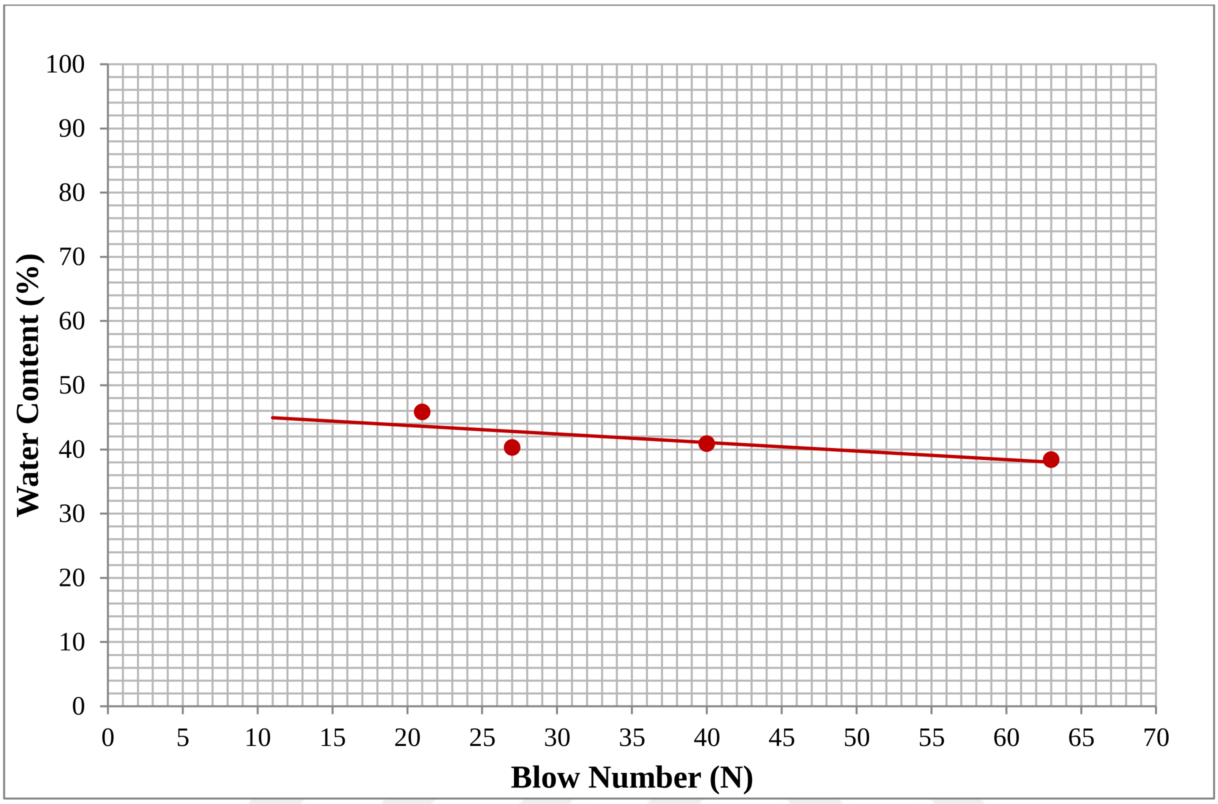

Figure A.1 : Result of liquid limit test of raw Dtm-1.

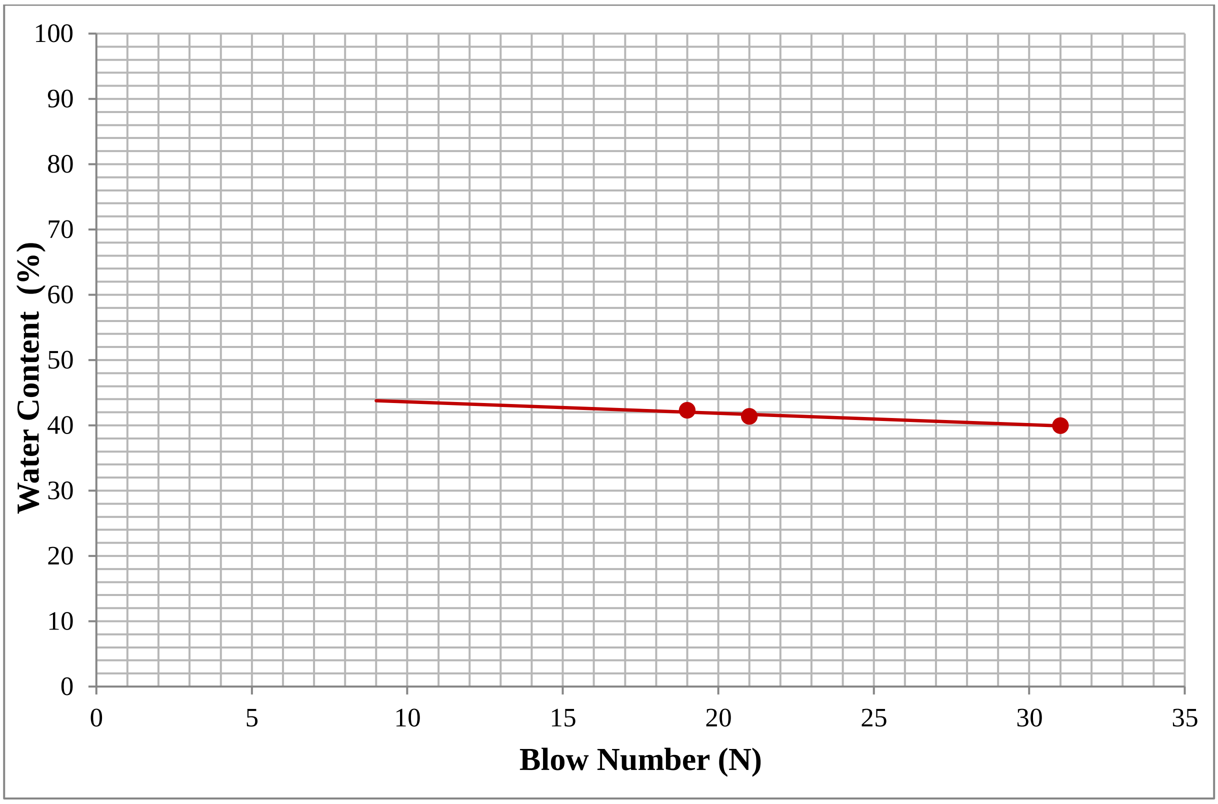

Figure A.2 : Result of liquid limit test of Dtm-1 mixed with 2% lime by weight.

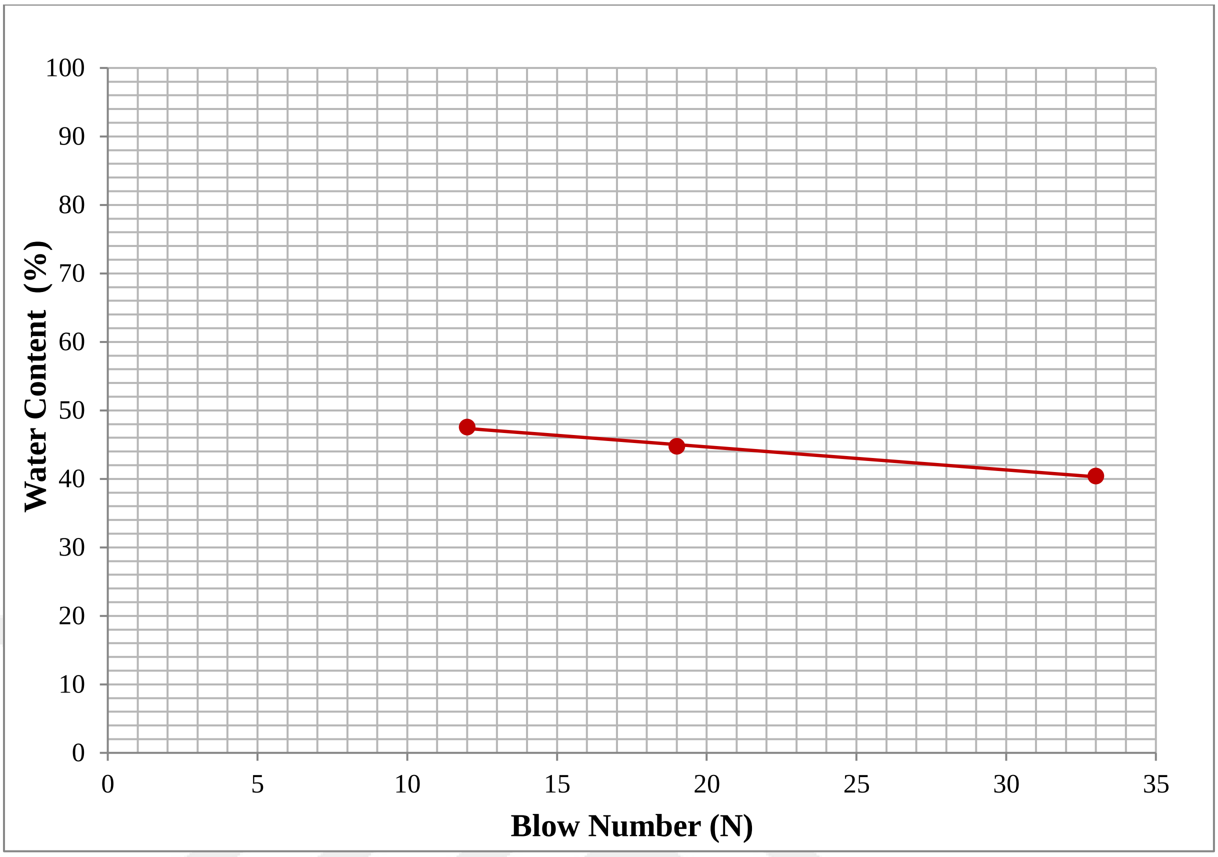

Figure A.3 : Result of liquid limit test of Dtm-1 mixed with 4% lime by weight.

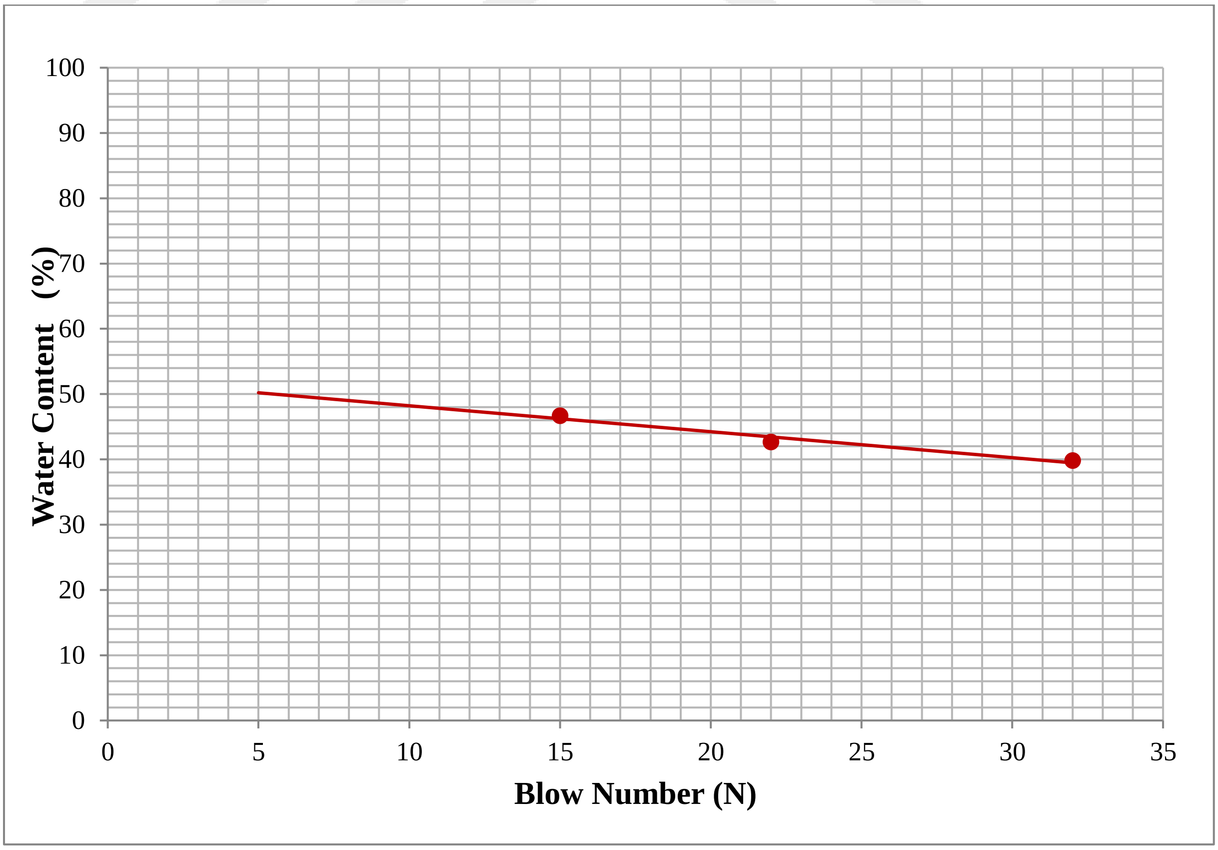

Figure A.4 : Result of liquid limit test of Dtm-1 mixed with 6% lime by weight.

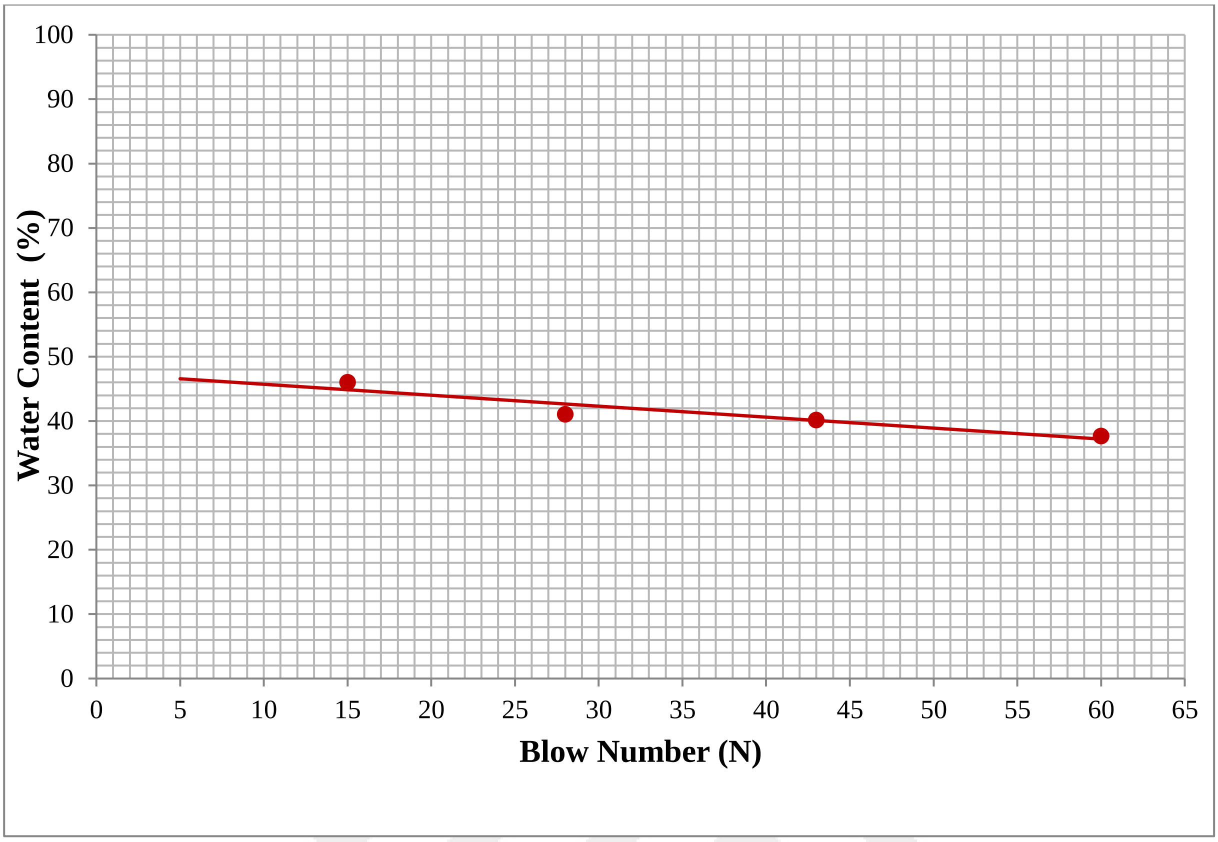

Figure A.5 : Result of liquid limit test of Dtm-1 mixed with 5% cement by weight.

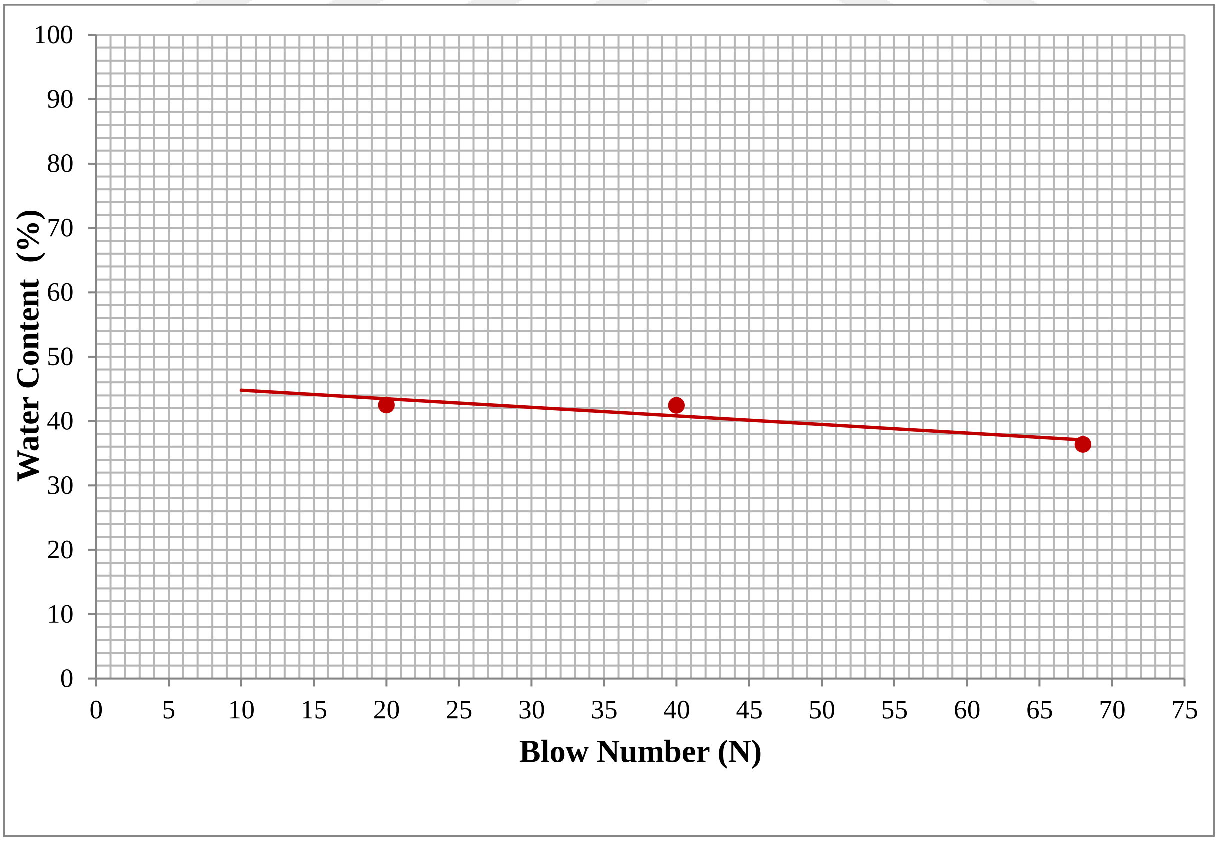

Figure A.6 : Result of liquid limit test of Dtm-1 mixed with 10% cement by weight.

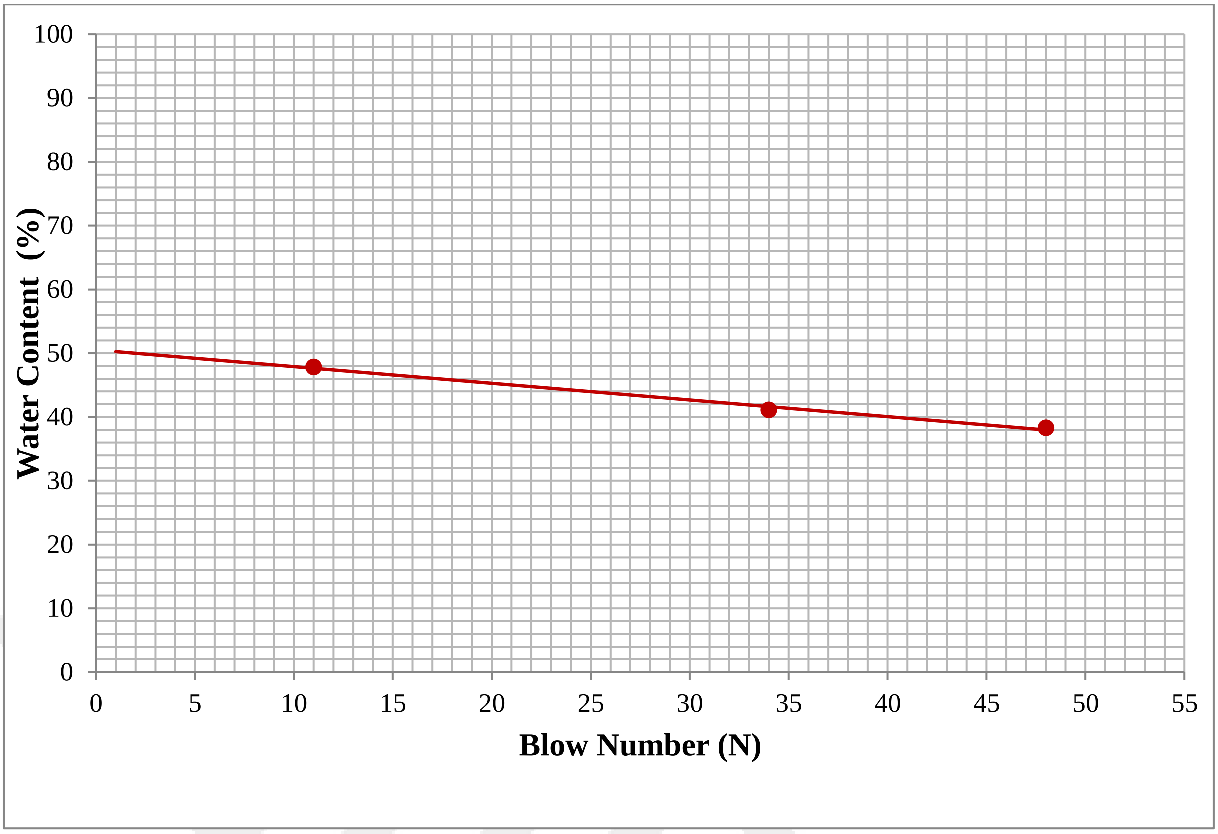

Figure A.7 : Result of liquid limit test of Dtm-1 mixed with 15% cement by weight.

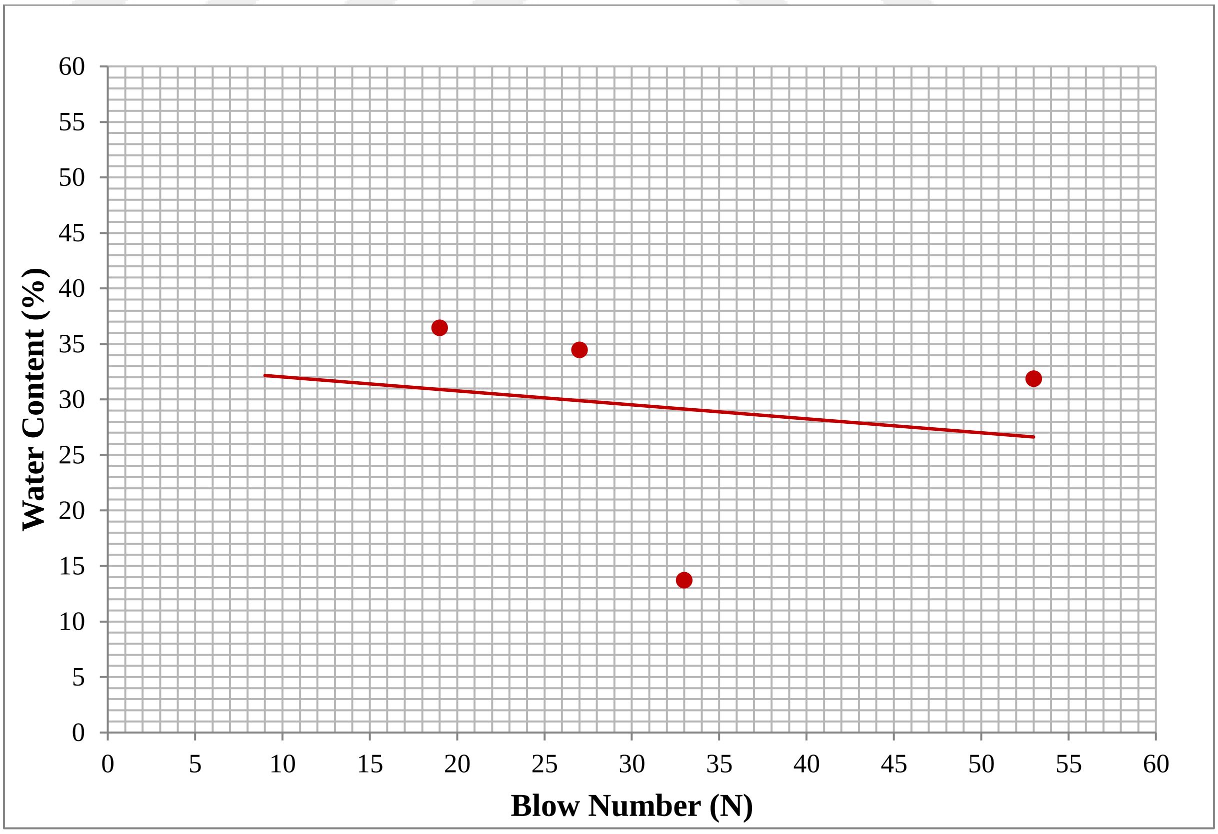

Figure A.8 : Result of liquid limit test of raw Dtm-10.

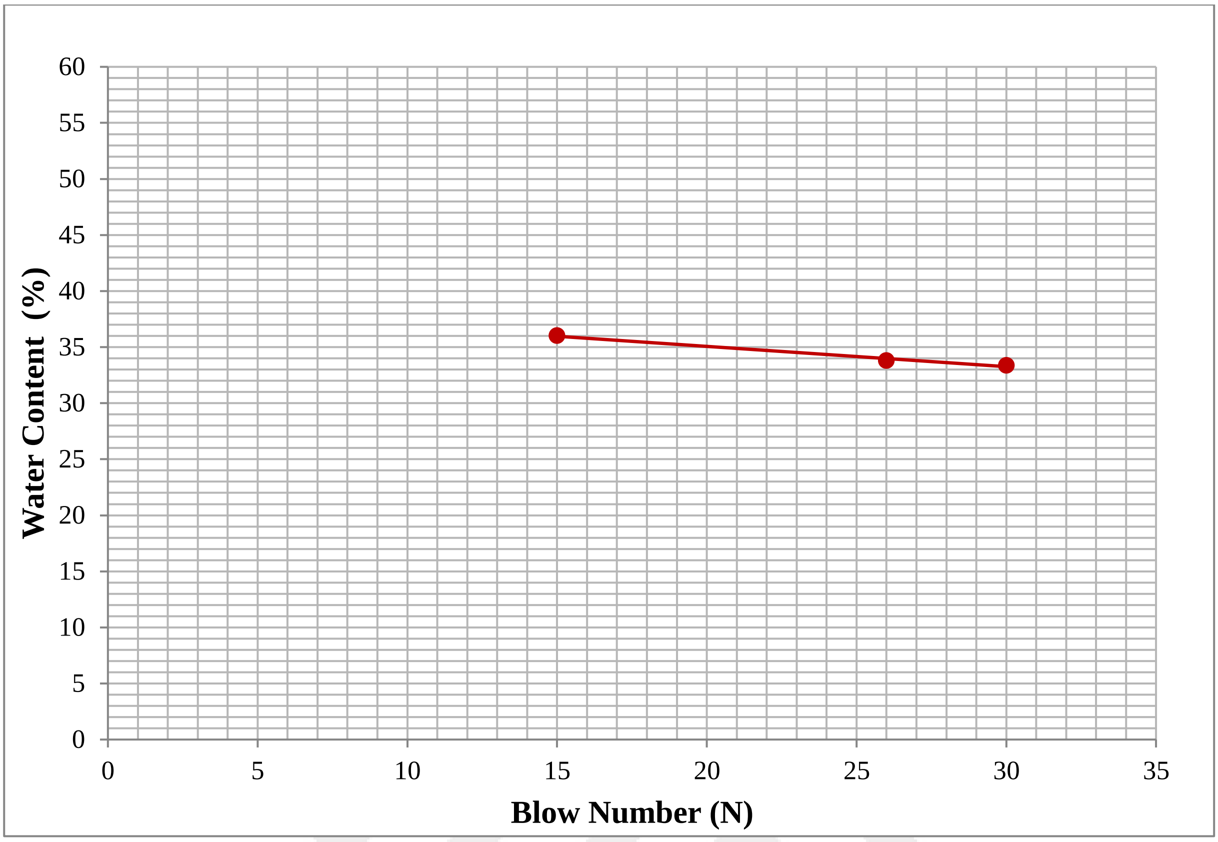

Figure A.9 : Result of liquid limit test of Dtm-10 mixed with 2% lime by weight.

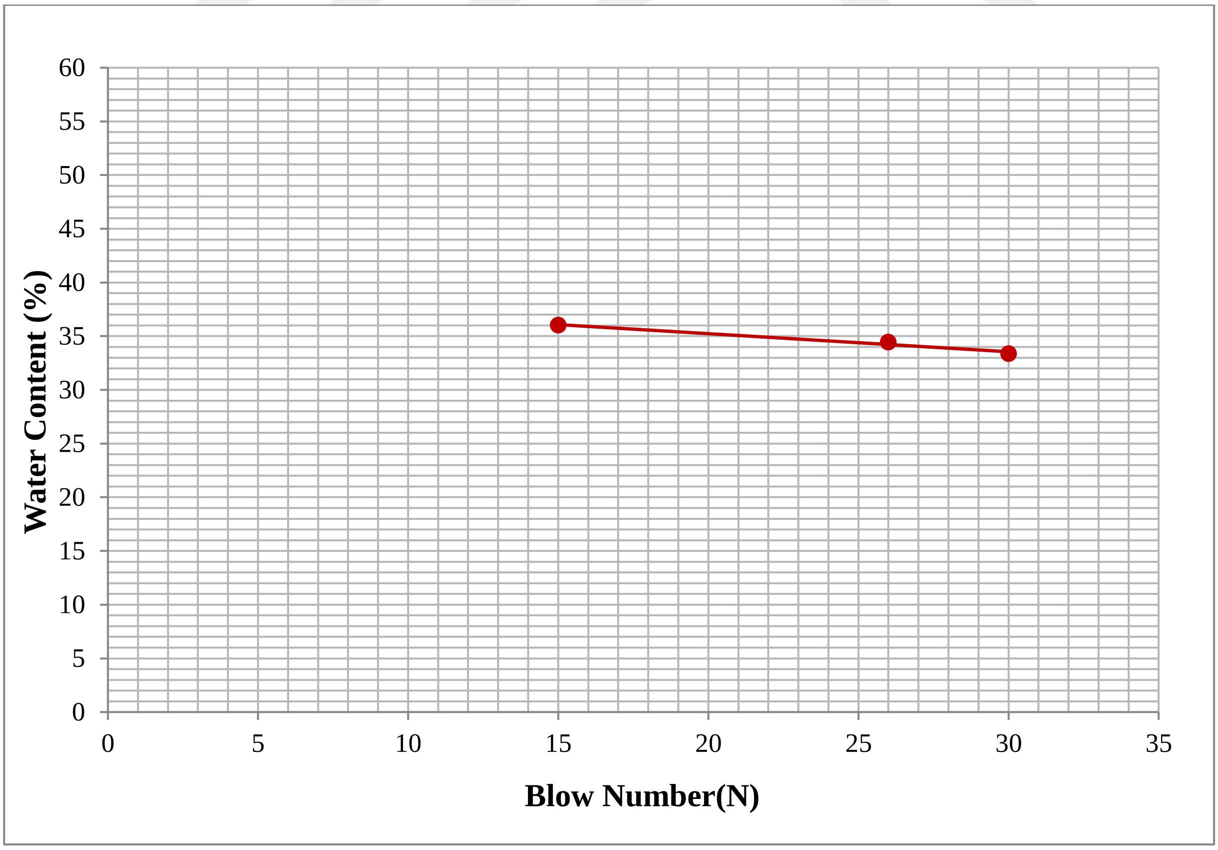

Figure A.10 : Result of liquid limit test of Dtm-10 mixed with 4% lime by weight.

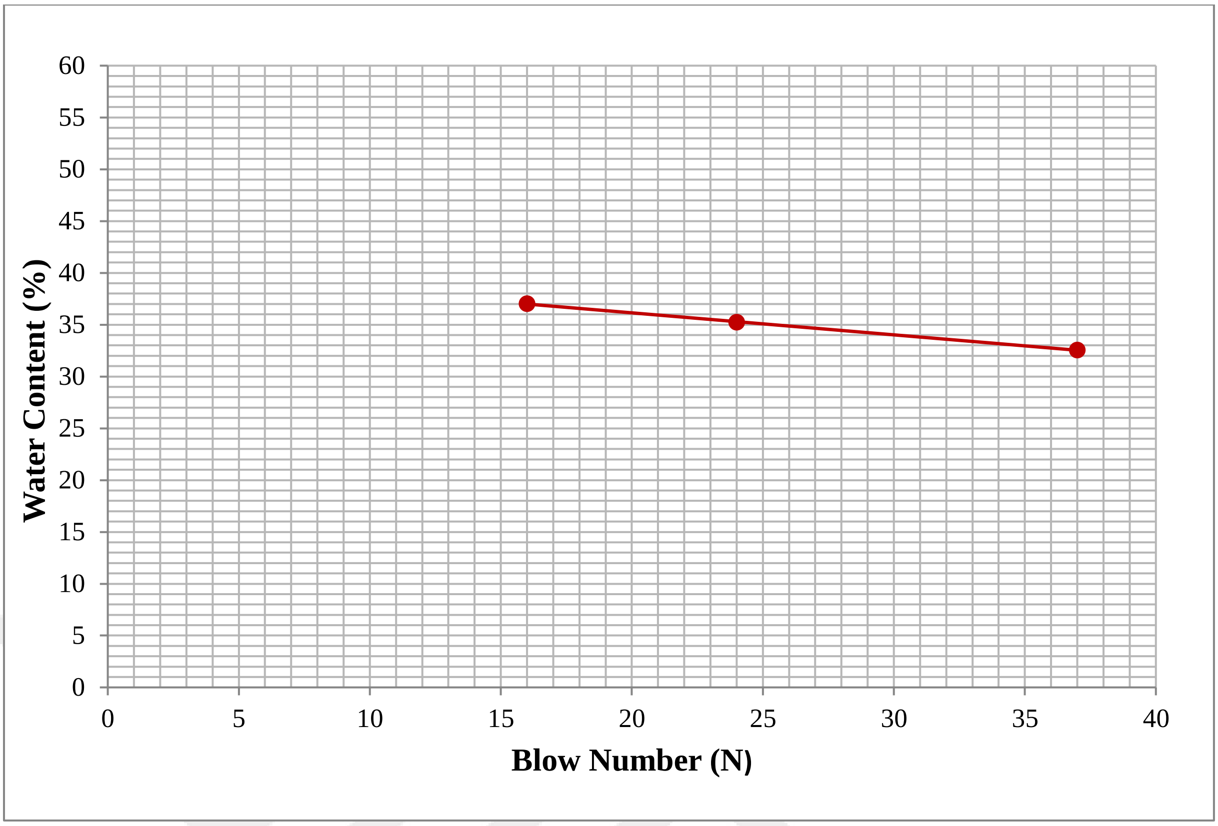

Figure A.11 : Result of liquid limit test of Dtm-10 mixed with 6% lime by weight.

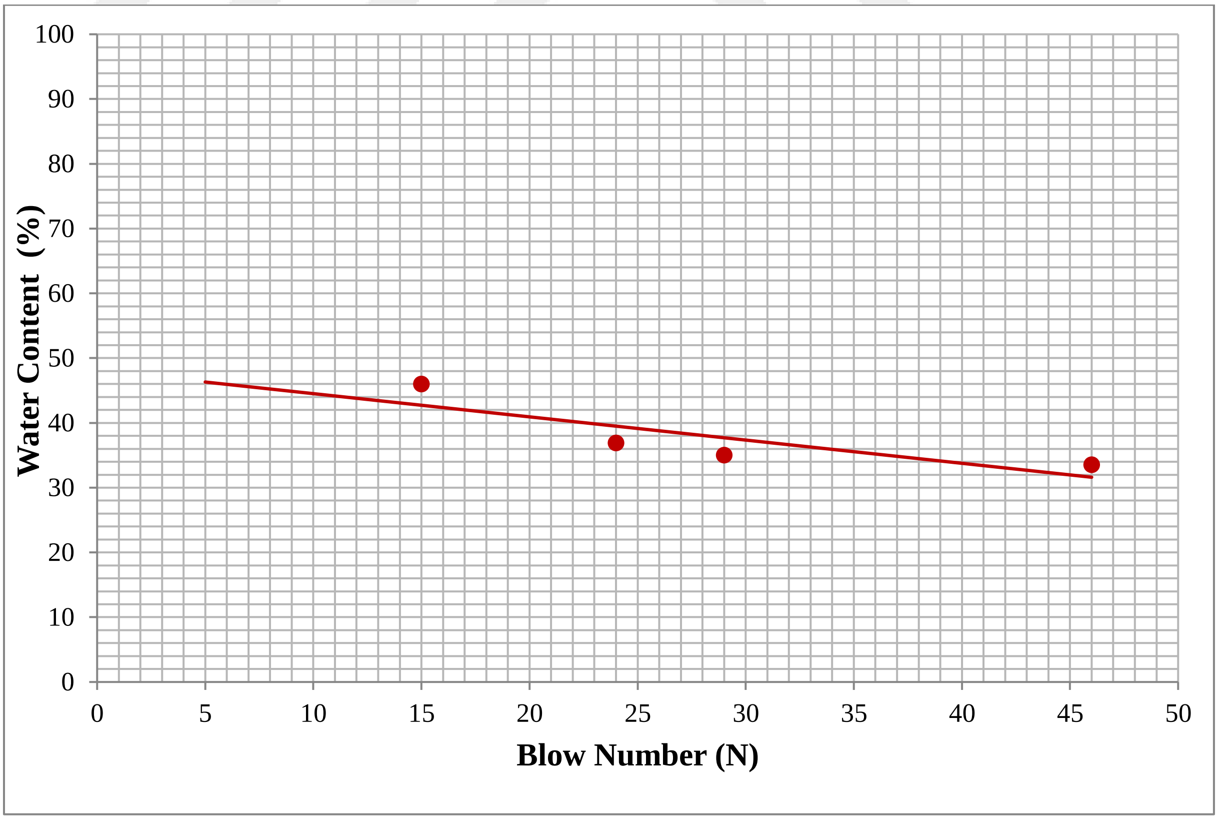

Figure A.12 : Result of liquid limit test of Dtm-10 mixed with 5% cement by weight.

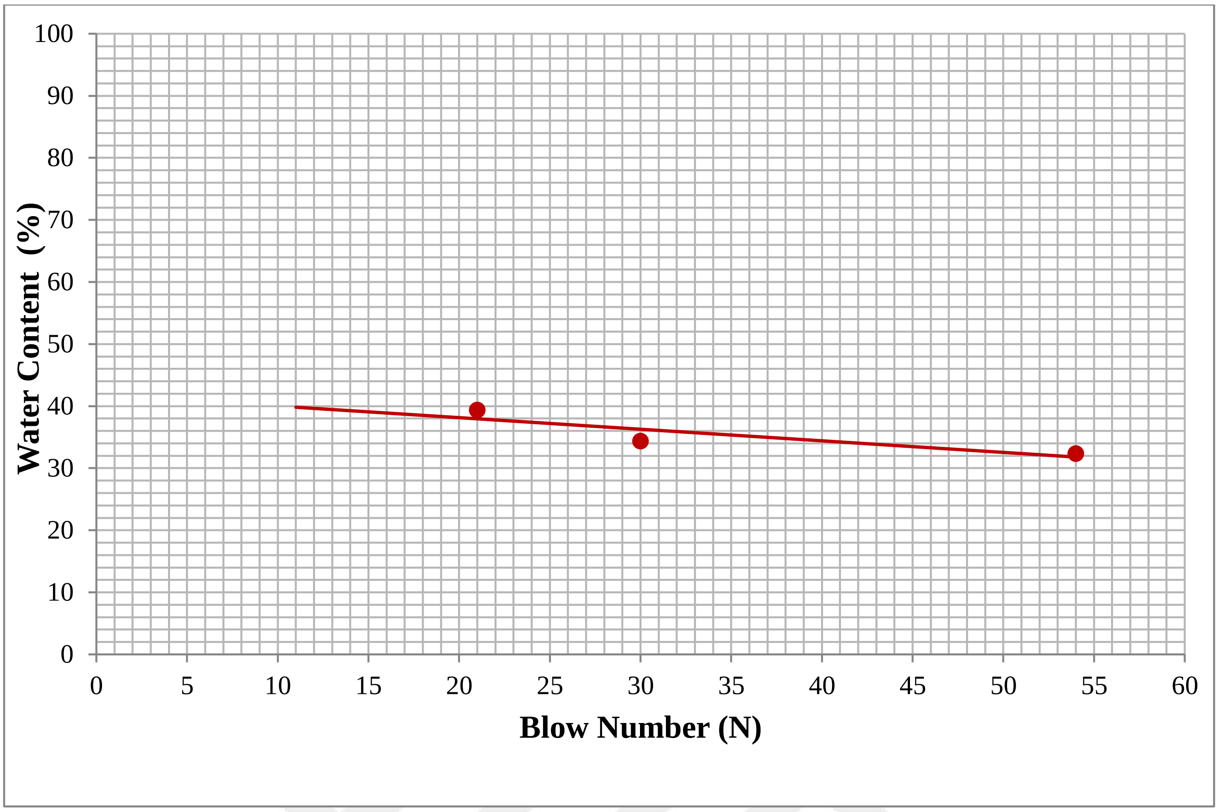

Figure A.13 : Result of liquid limit test of Dtm-10 mixed with 10% cement by weight.

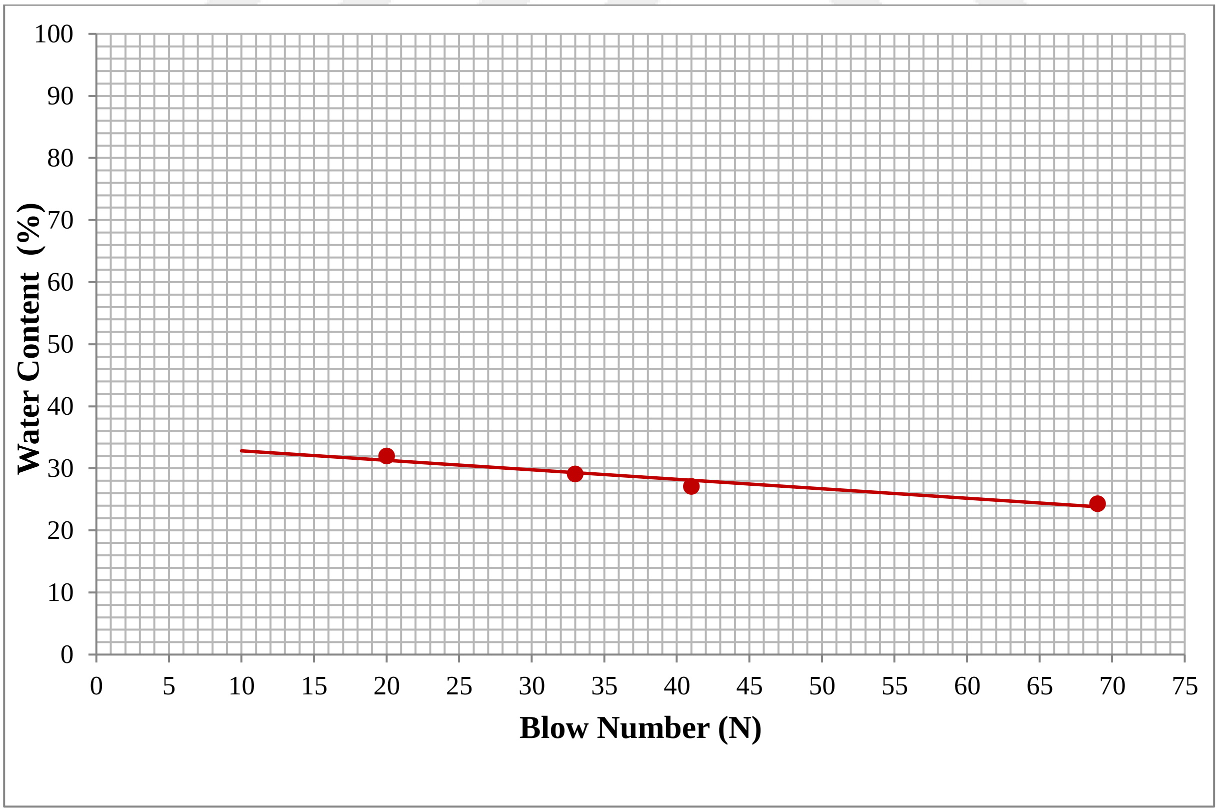

Figure A.14 : Result of liquid limit test of Dtm-10 mixed with 15% cement by weight.

APPENDIX B

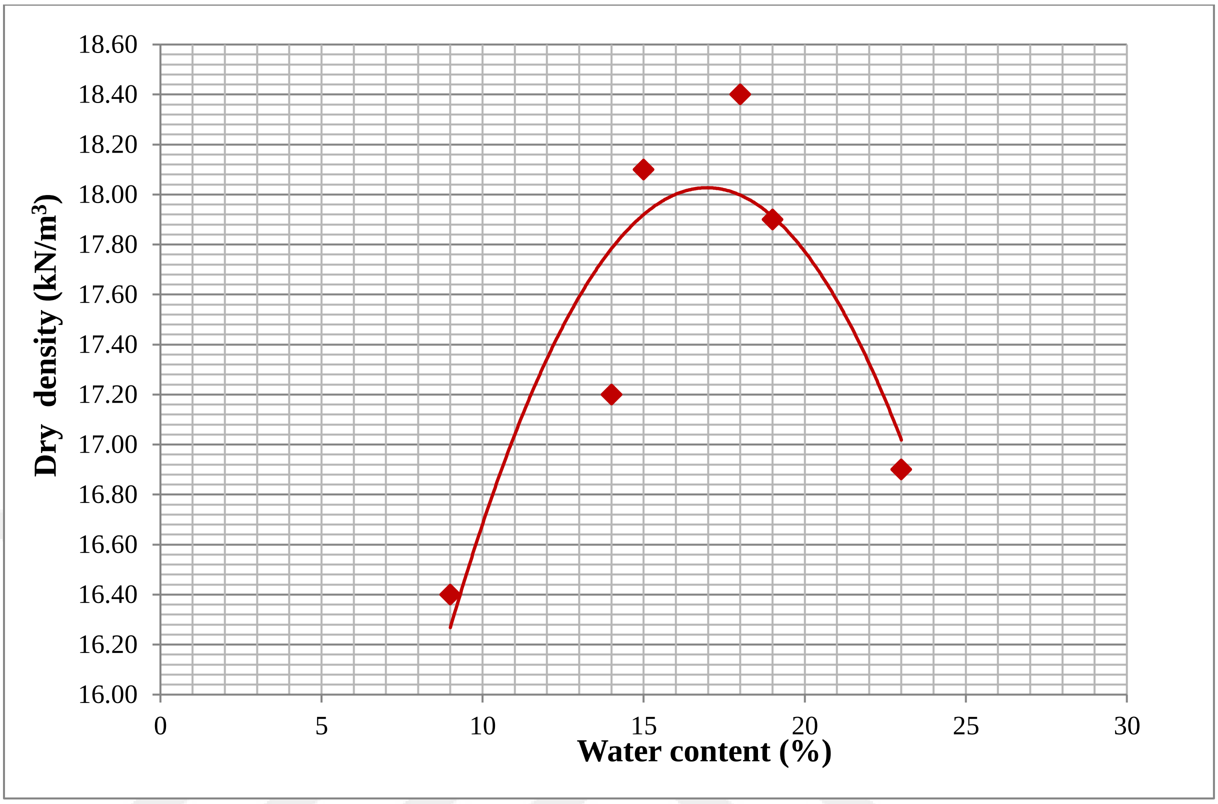

Figure B.1 : Result of the standard Proctor compaction test of Dtm-1.

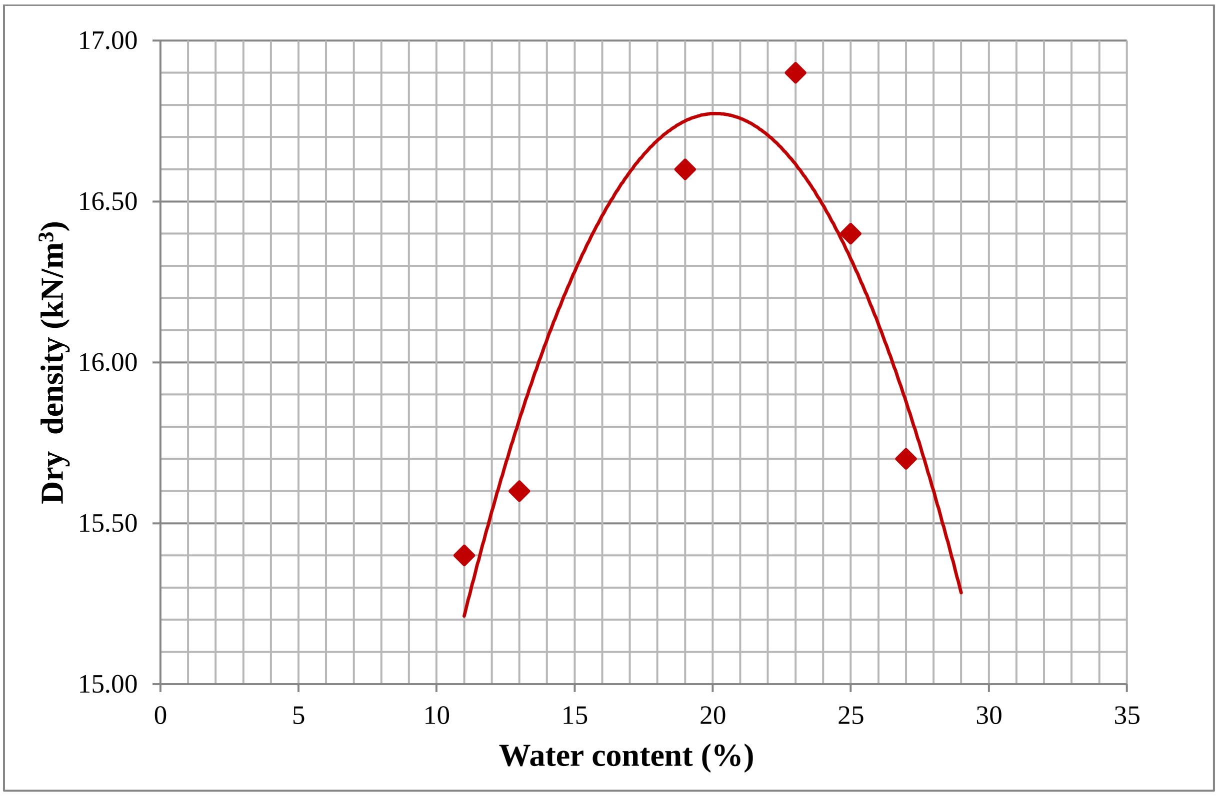

Figure B.2 : Result of the miniature compaction test of Dtm-1.

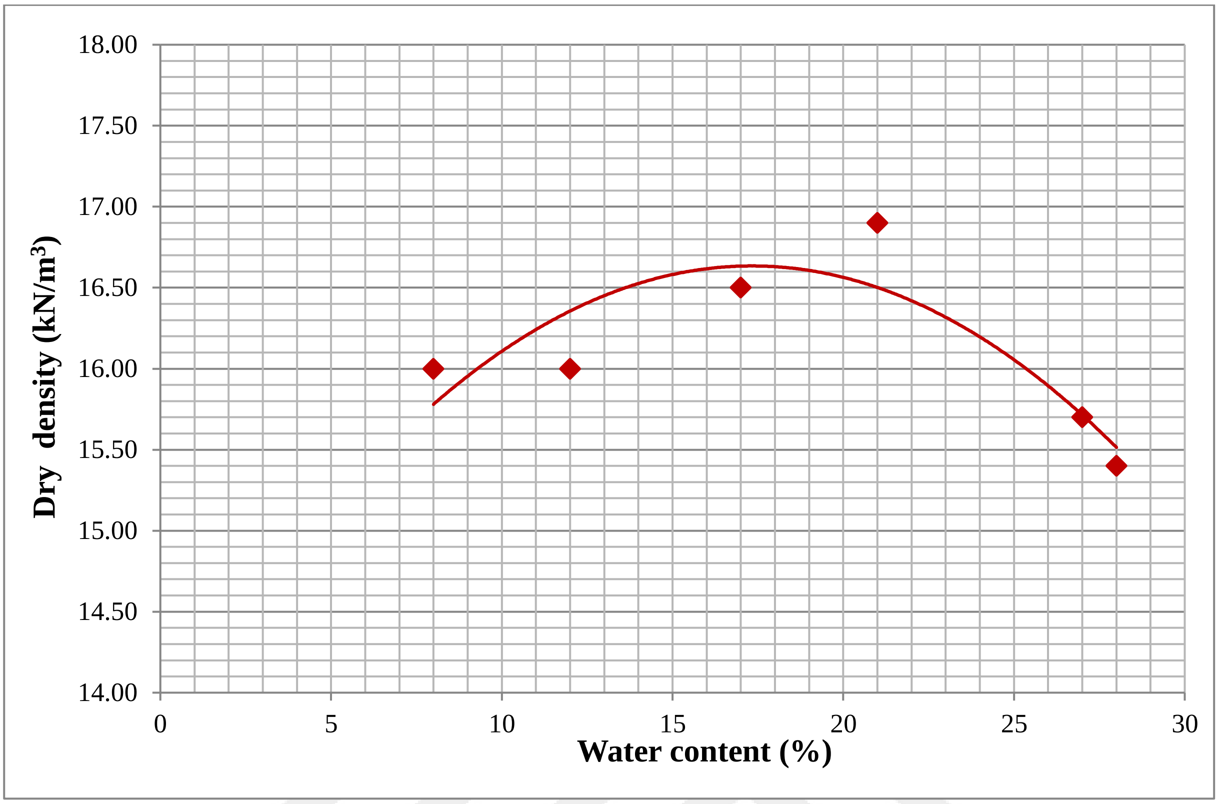

Figure B.3 : Result of the miniature compaction test of Dtm-1 mixed with 2% lime by weight.

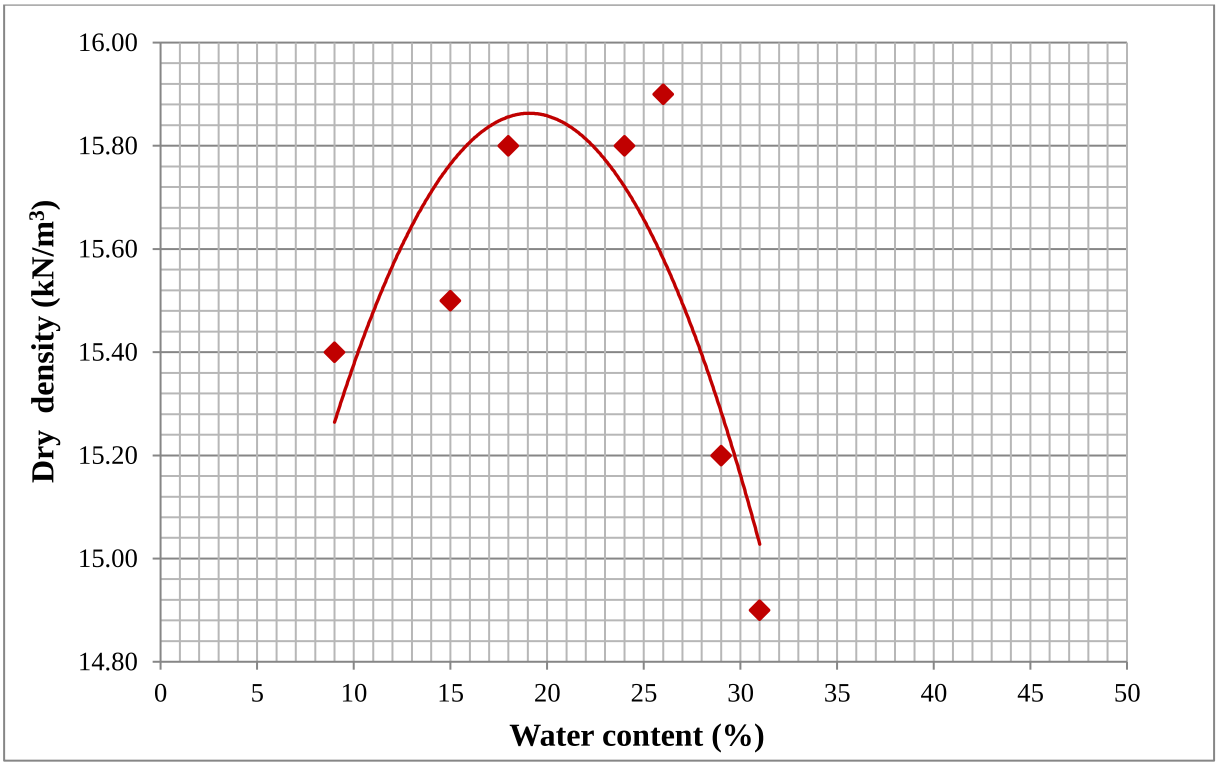

Figure B.4 : Result of the miniature compaction test of Dtm-1 mixed with 4% lime by weight.

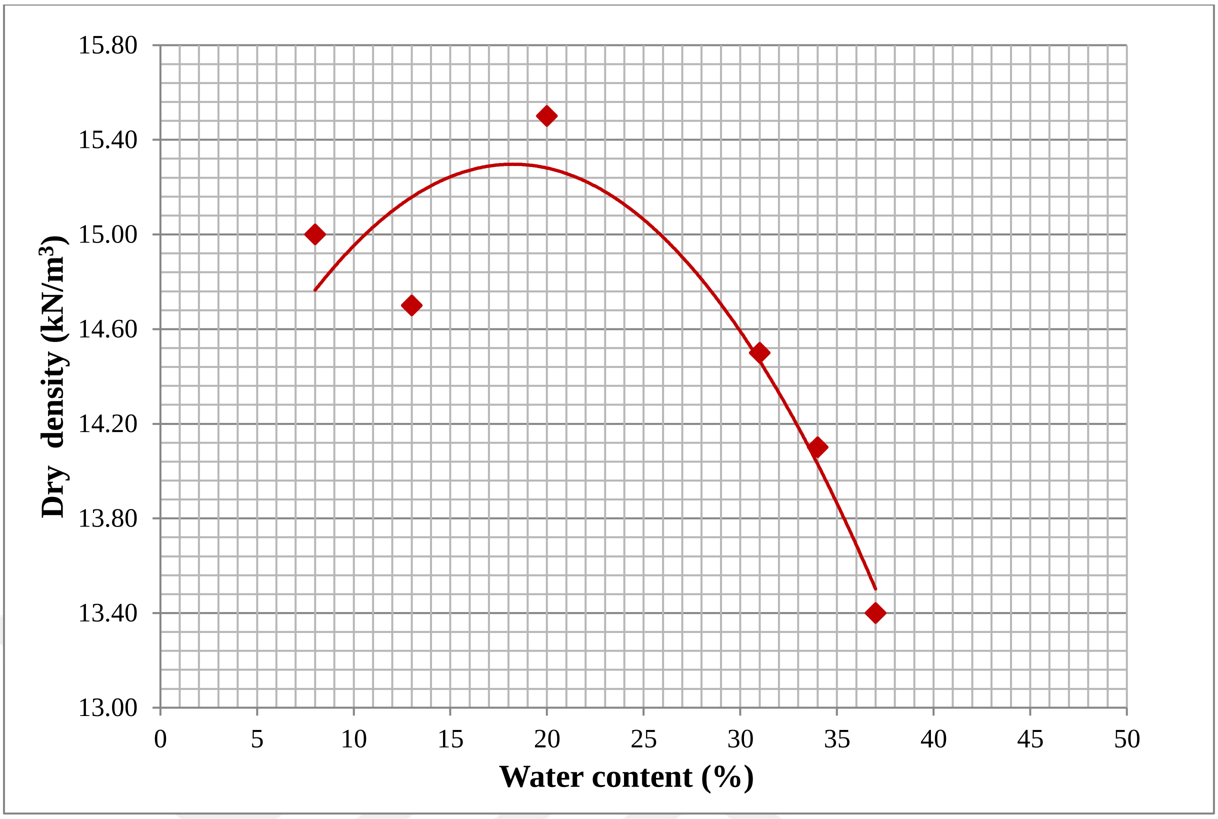

Figure B.5 : Result of the miniature compaction test of Dtm-1 mixed with 6% lime by weight.

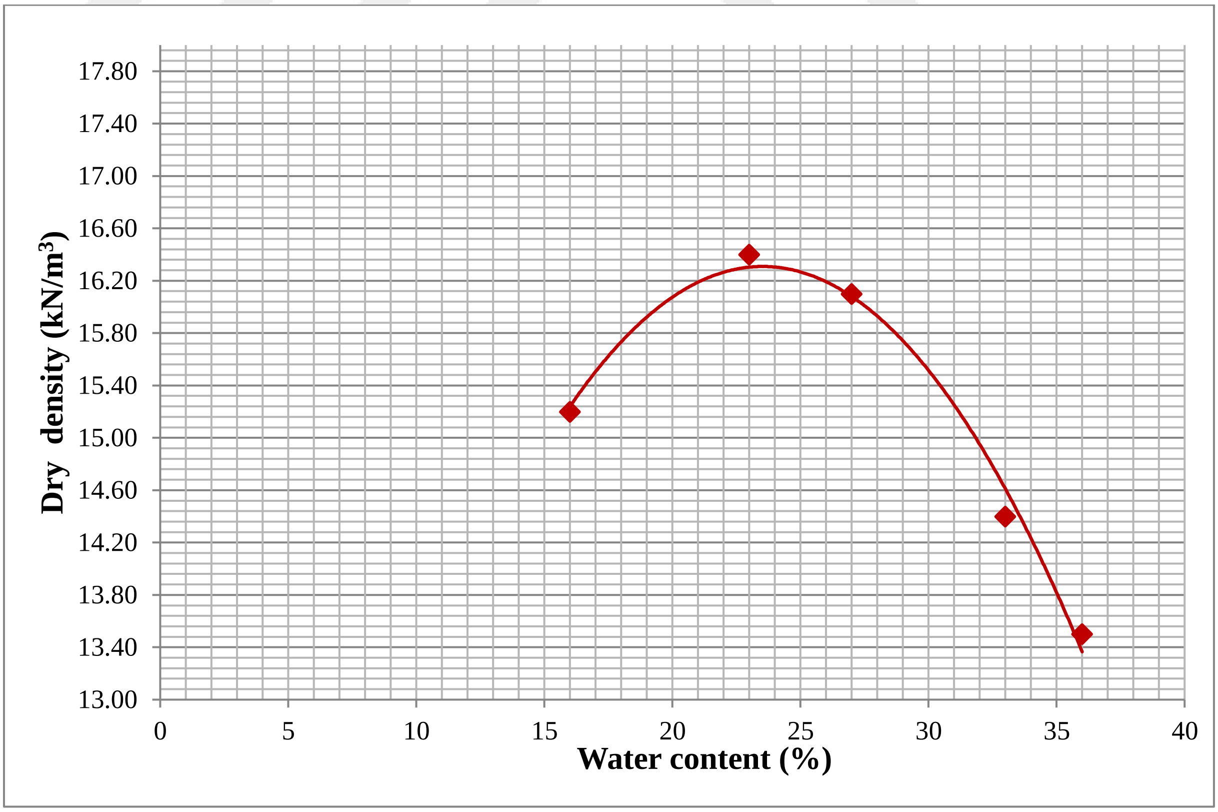

Figure B.6 : Result of the miniature compaction test of Dtm-1 mixed with 5% cement by weight.

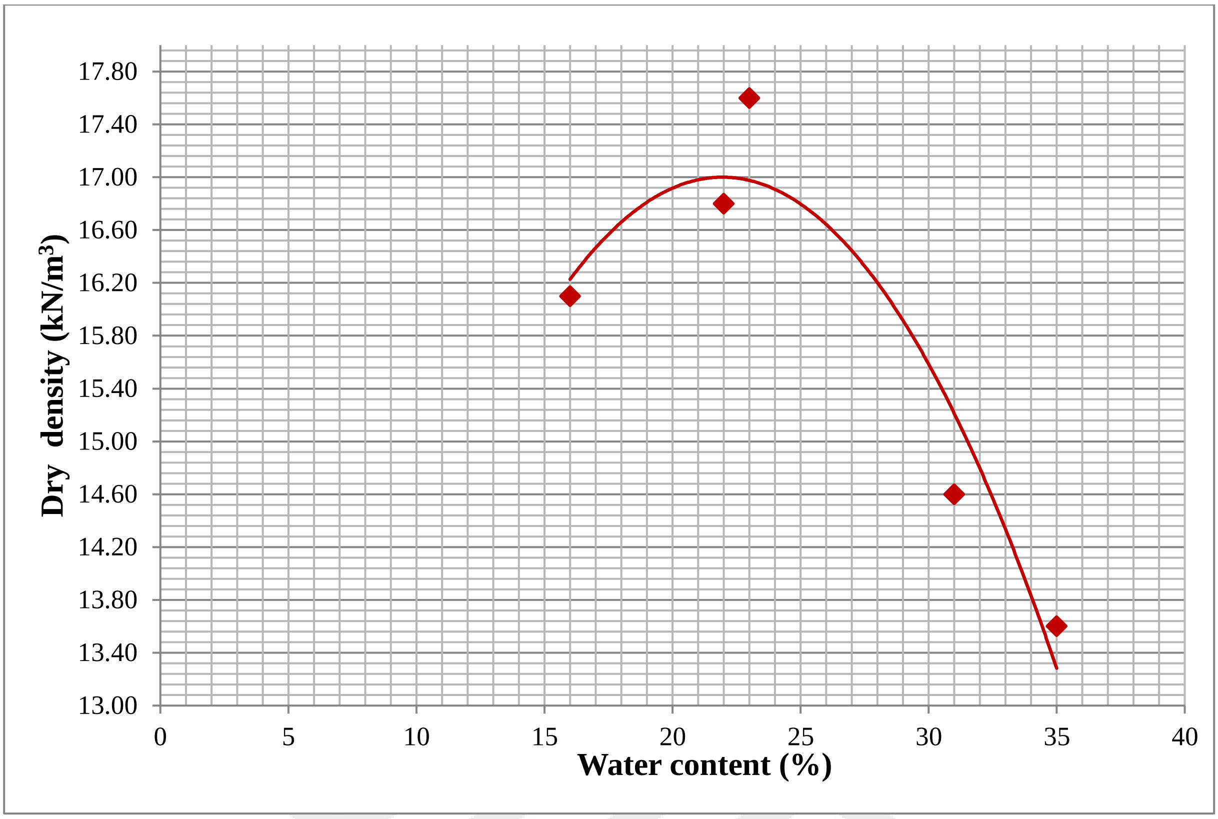

Figure B.7 : Result of the miniature compaction test of Dtm-1 mixed with 10% cement by weight.

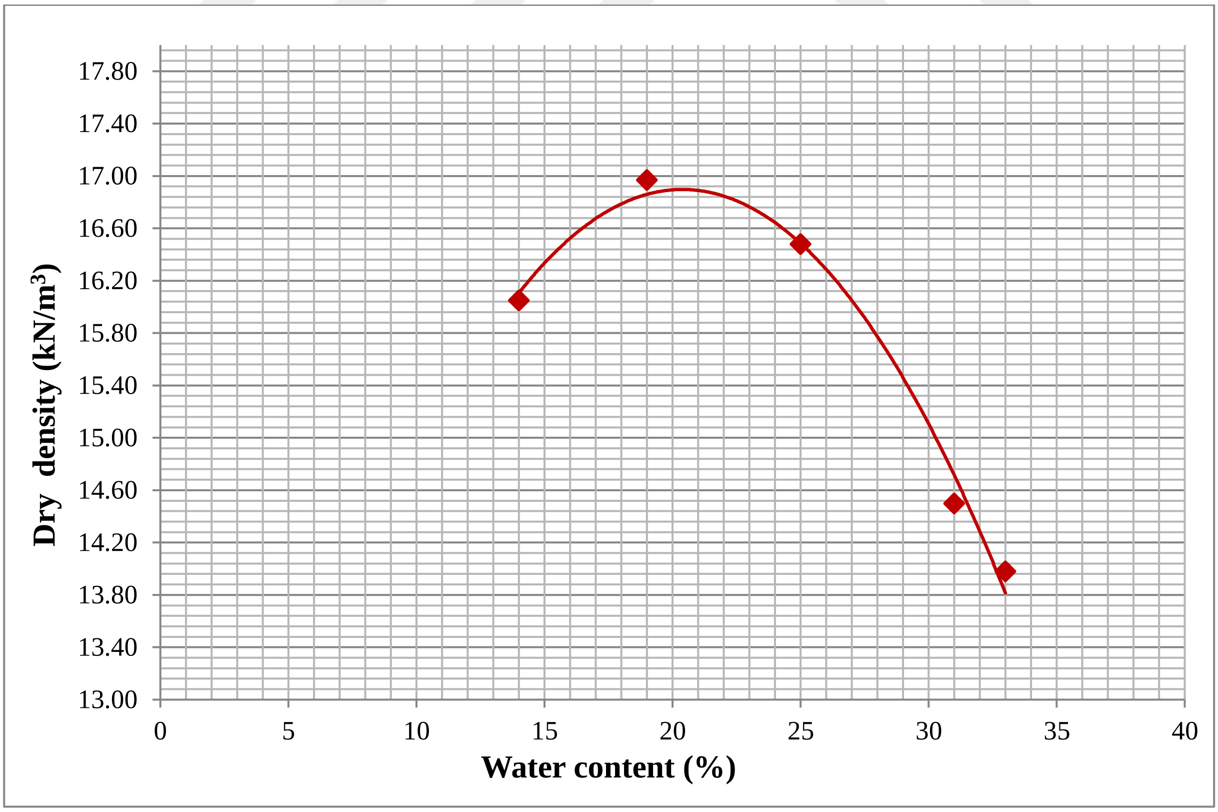

Figure B.8 : Result of the miniature compaction test of Dtm-1 mixed with 15% cement by weight.

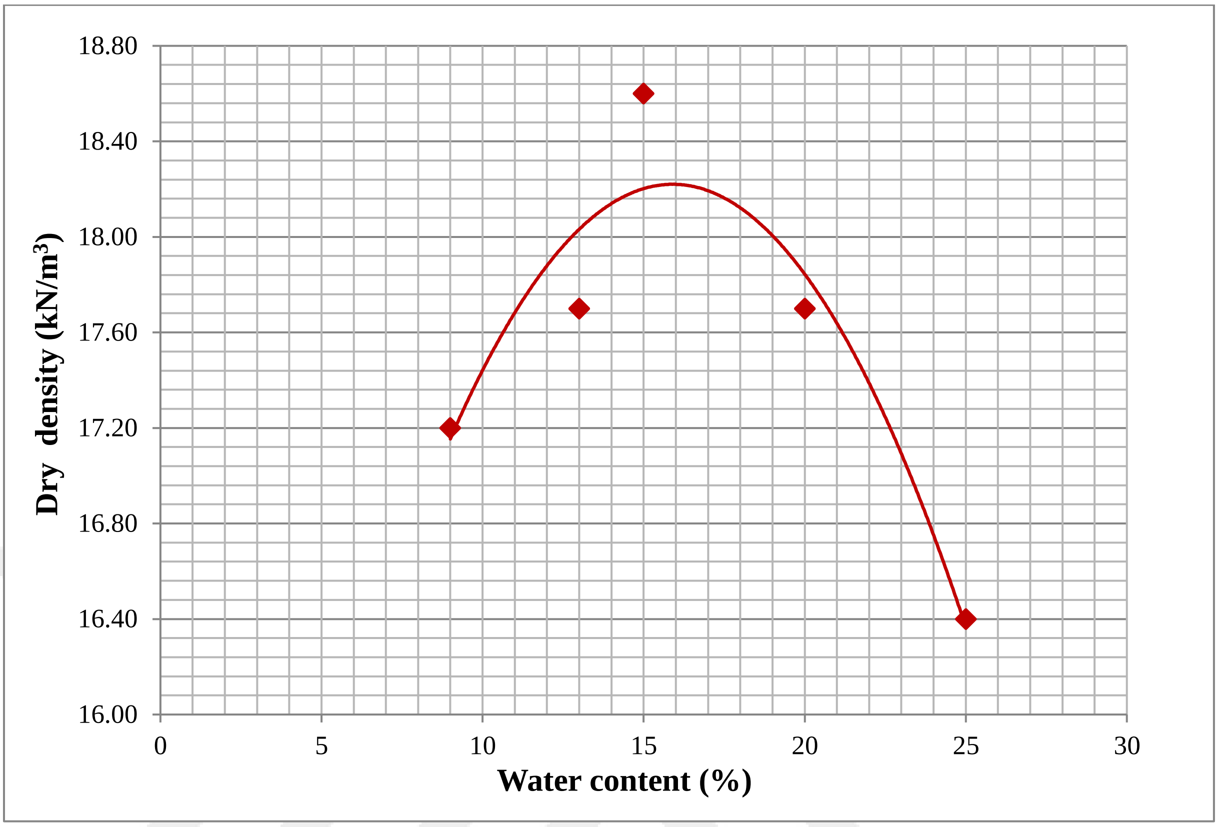

Figure B.9 : Result of the standard Proctor compaction test of Dtm-10.

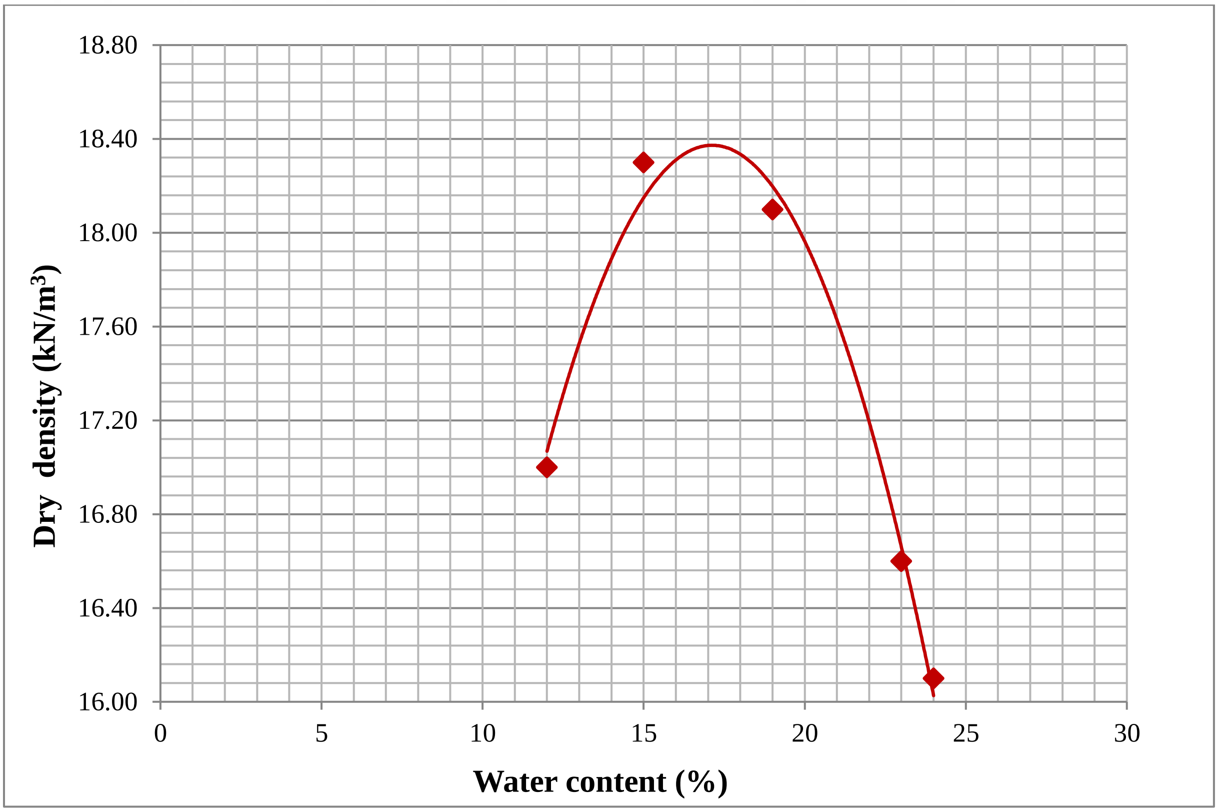

Figure B.10 : Result of the miniature compaction test of Dtm-10.

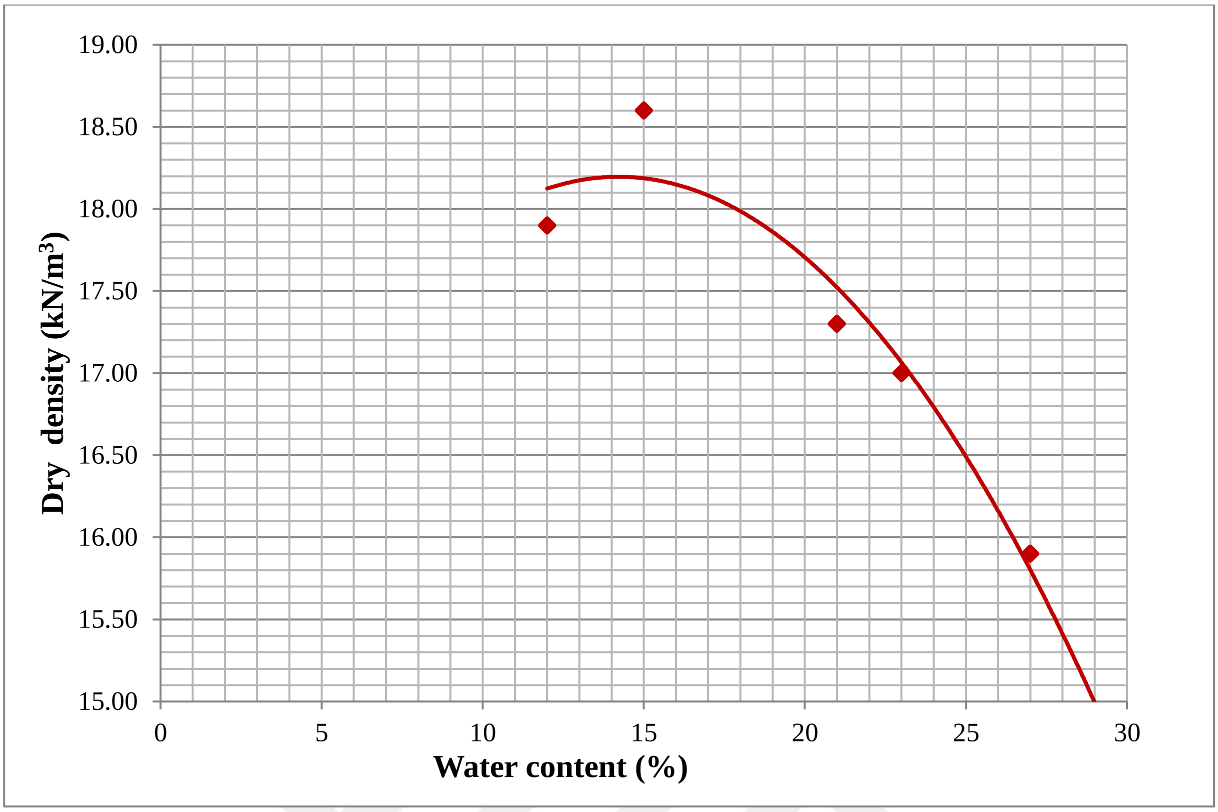

Figure B.11 : Result of the miniature compaction test of Dtm-10 mixed with 2% lime by weight.

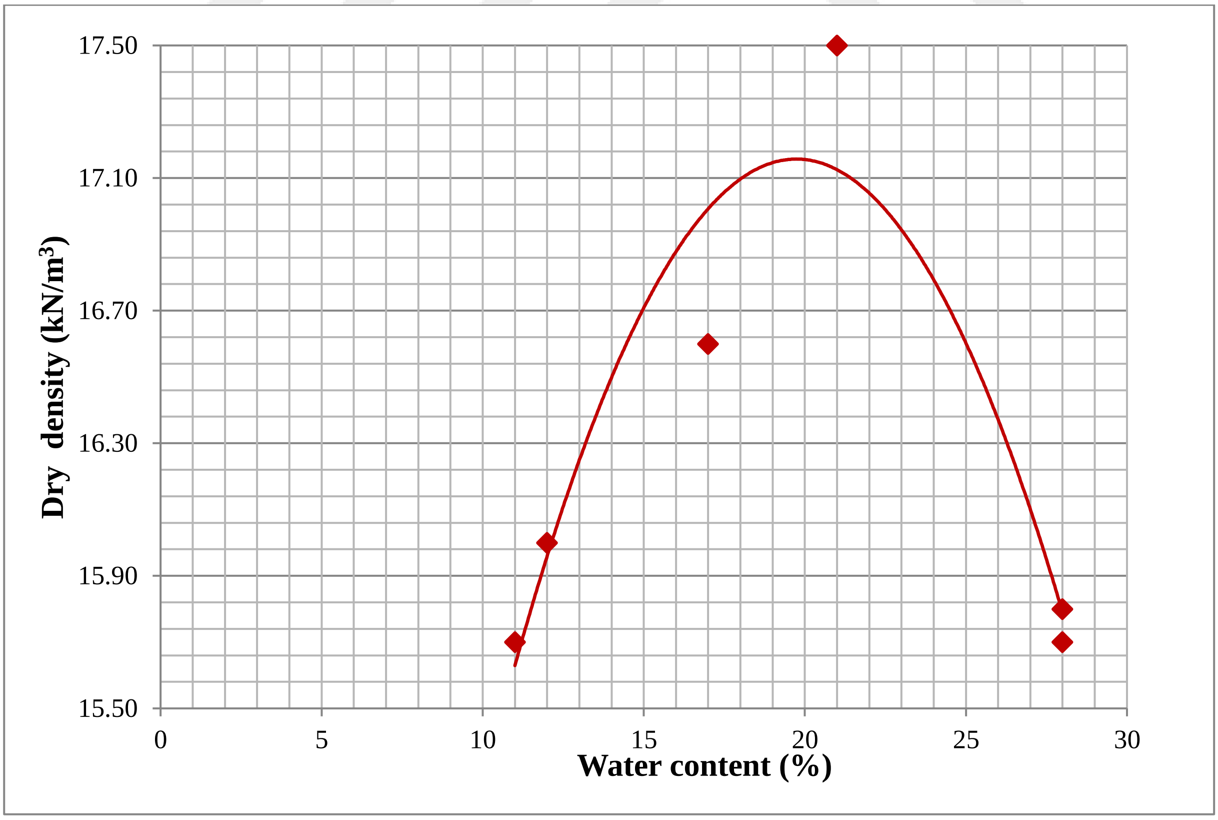

Figure B.12 : Result of the miniature compaction test of Dtm-10 mixed with 4% lime by weight.

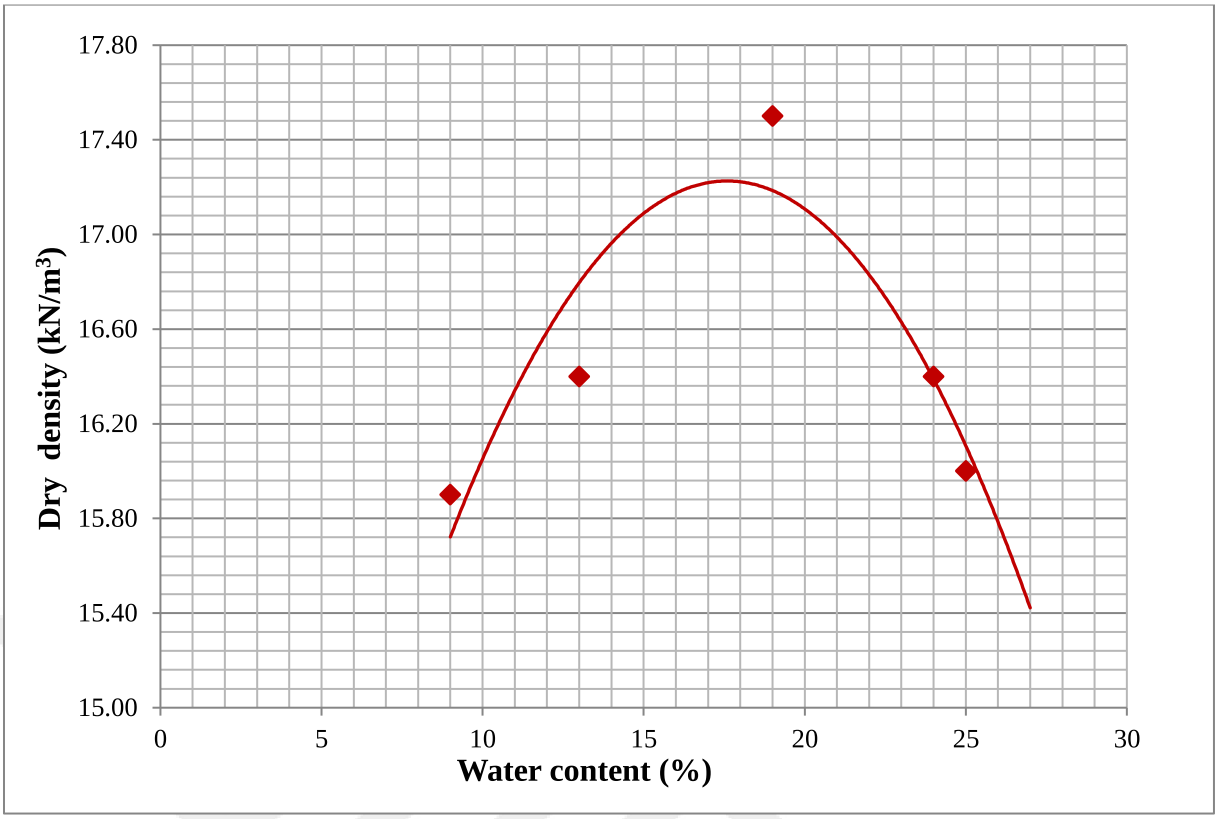

Figure B.13 : Result of the miniature compaction test of Dtm-10 mixed with 6% lime by weight.

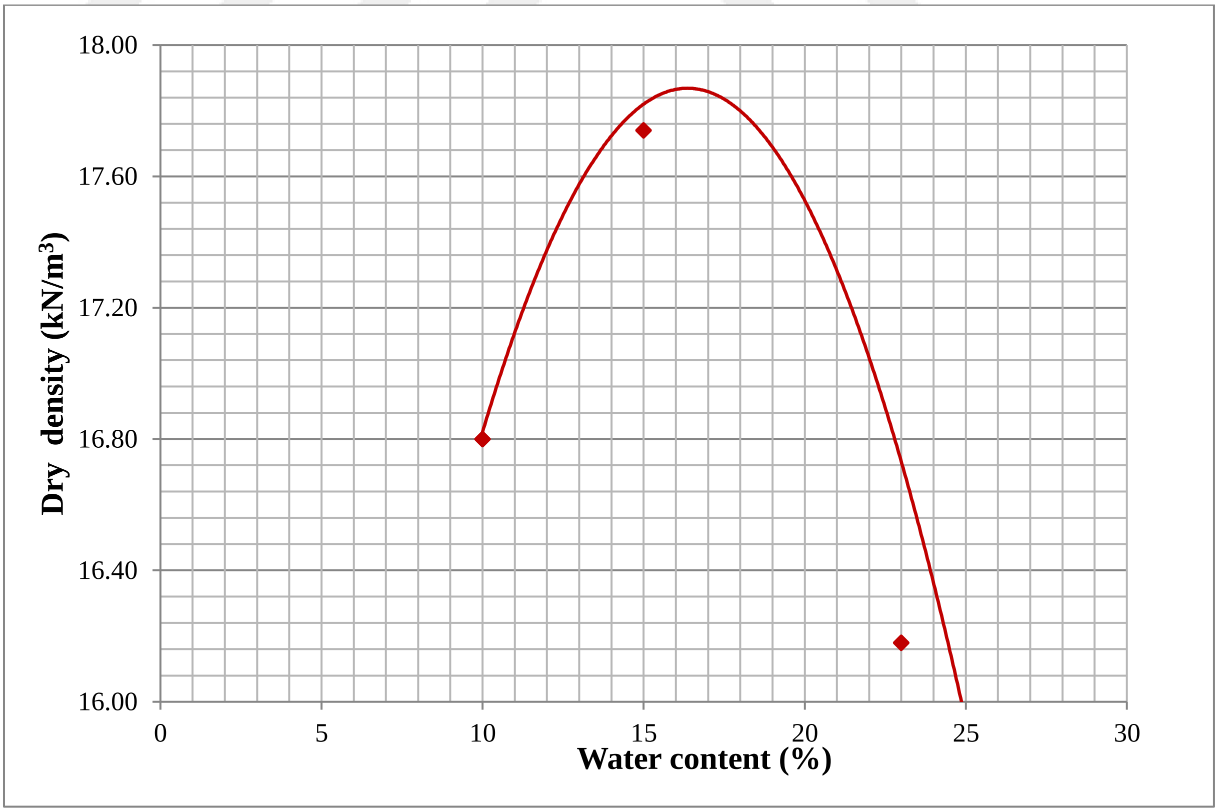

Figure B.14 : Result of the miniature compaction test of Dtm-10 mixed with 5% cement by weight.

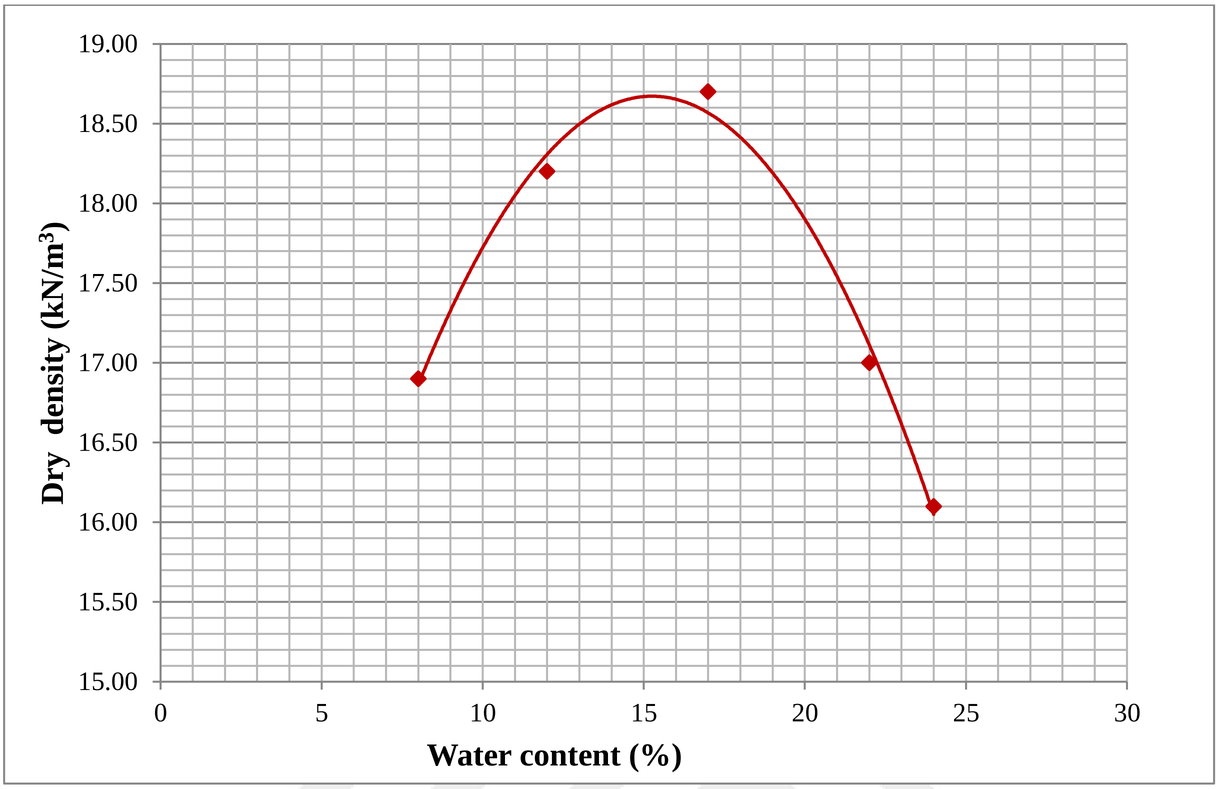

Figure B.15 : Result of the miniature compaction test of Dtm-10 mixed with 10% cement by weight.

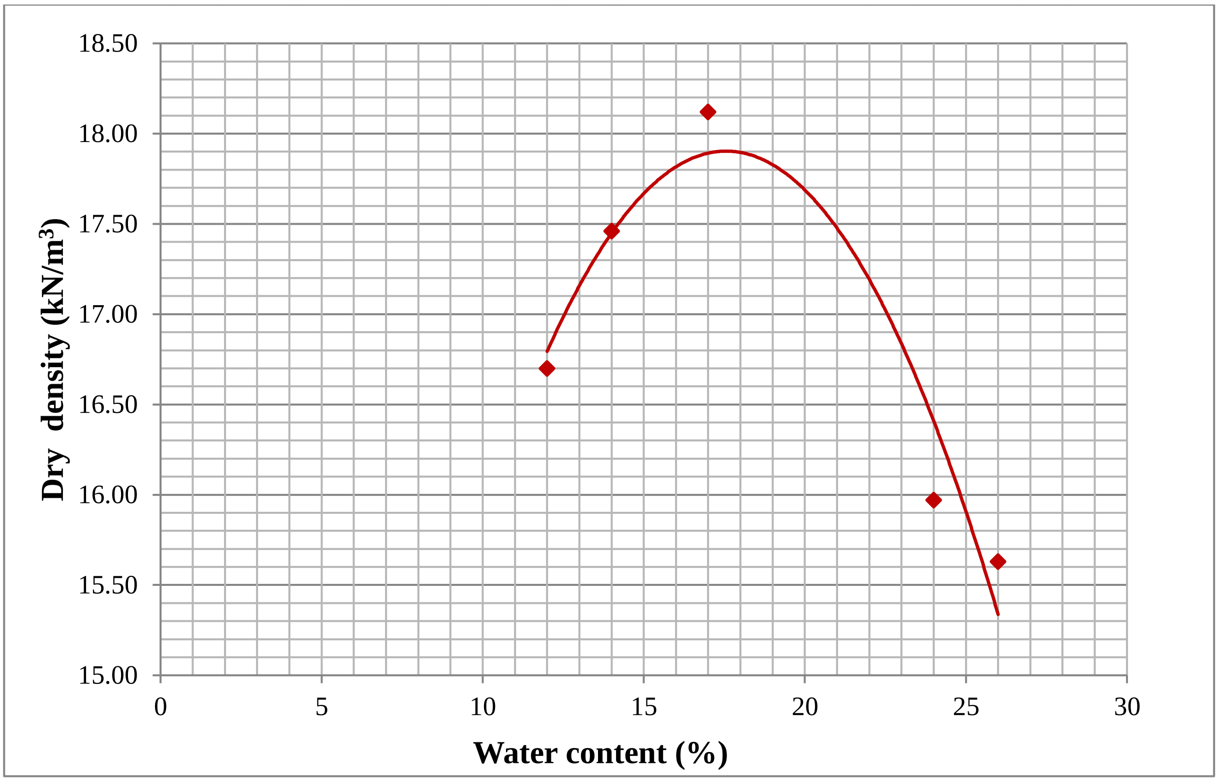

Figure B.16 : Result of the miniature compaction test of Dtm-10 mixed with 15% cement by weight.

APPENDIX C

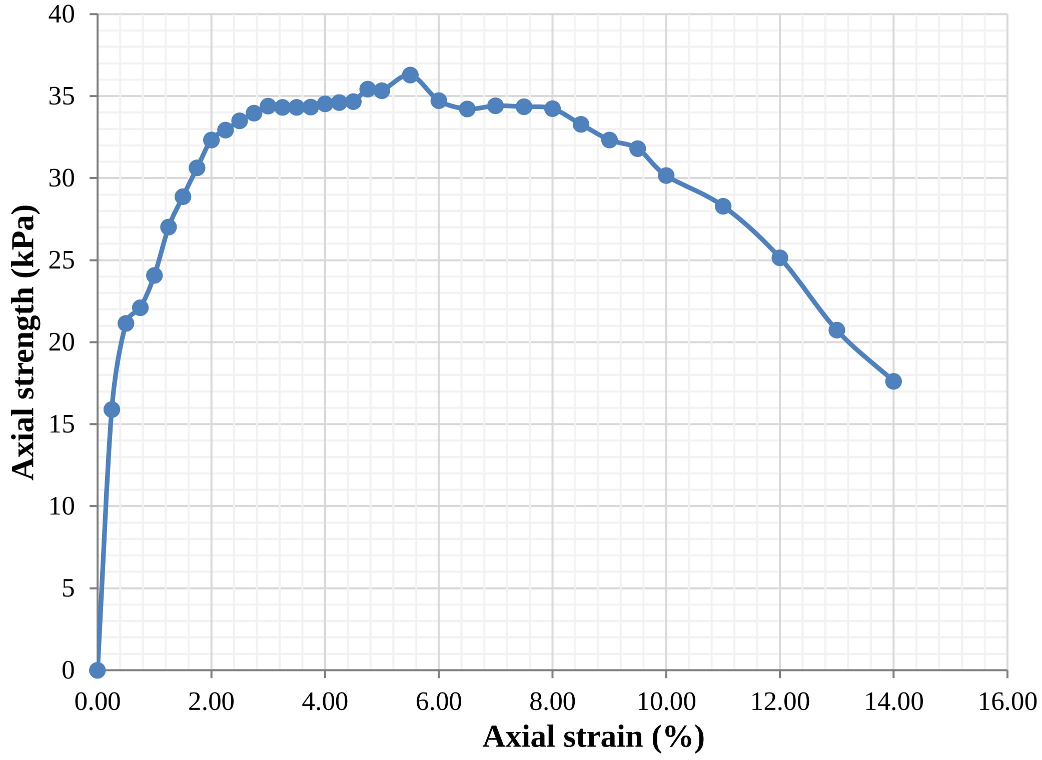

Figure C.1 : Result of the unconfined compression test of raw Dtm-1 (Sample 1).

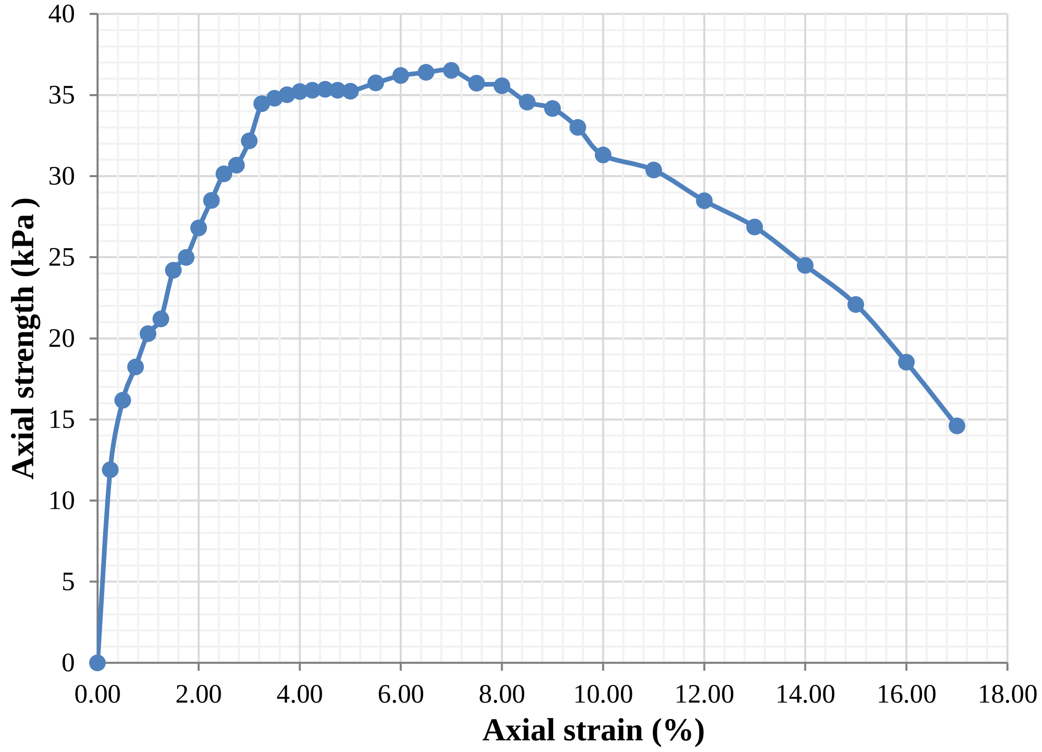

Figure C.2 : Result of the unconfined compression test of raw Dtm-1 (Sample 2).

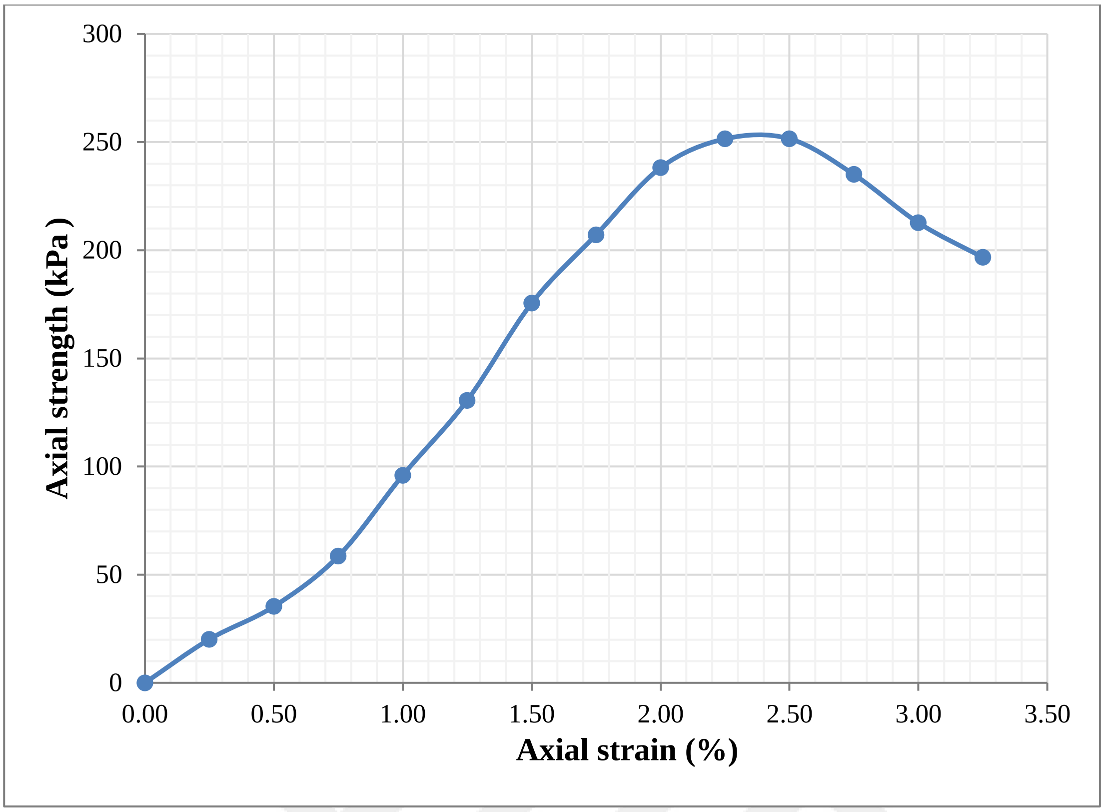

Figure C.3 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 1 day curing (Sample 1).

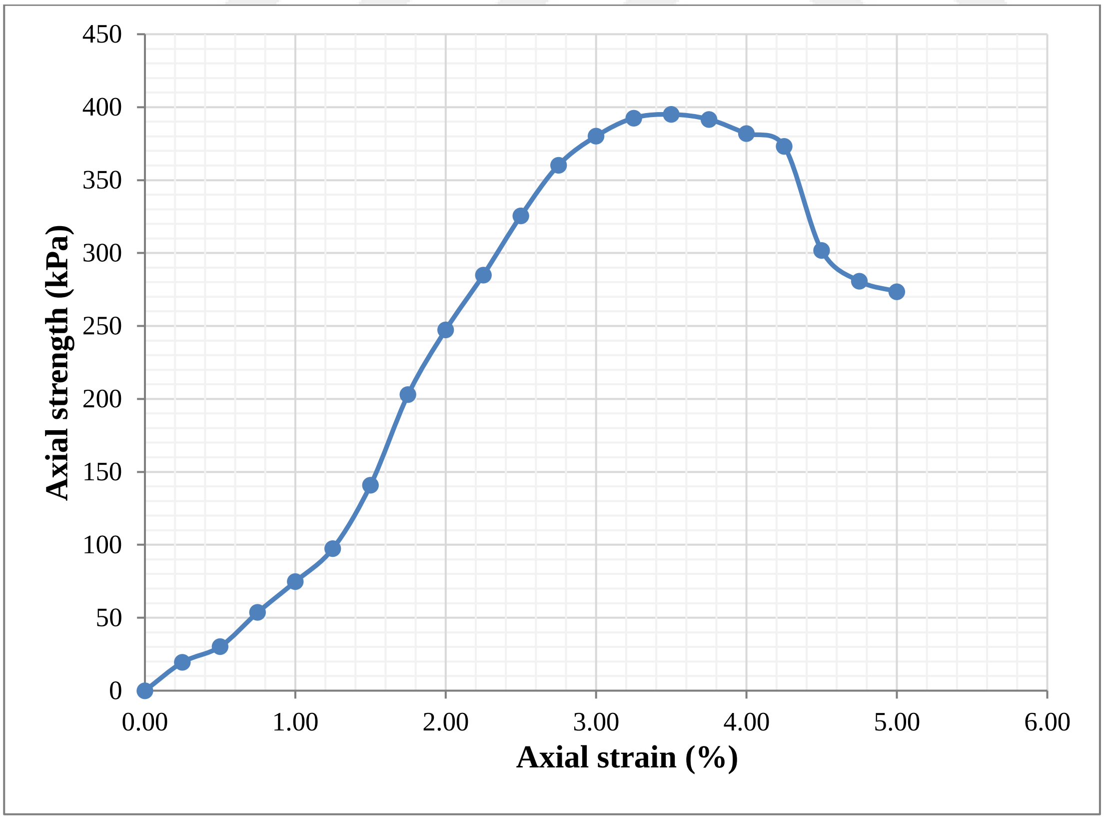

Figure C.4 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 1 day curing (Sample 2).

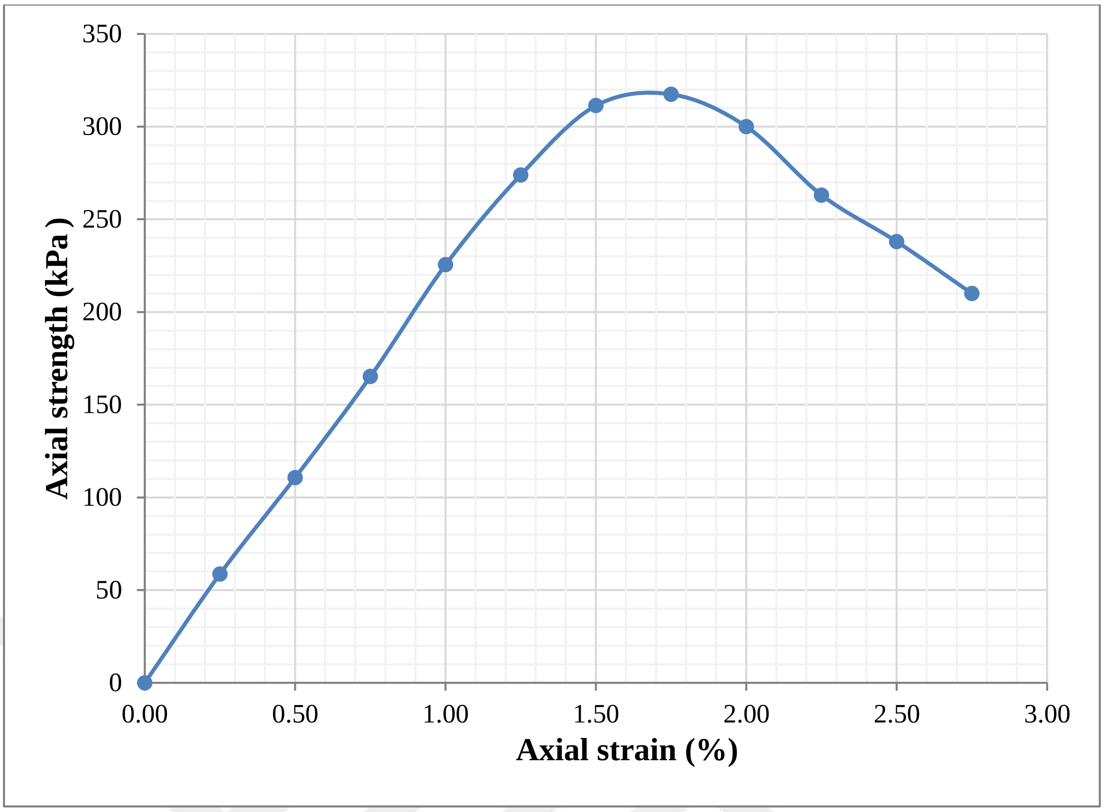

Figure C.5 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 7 days curing (Sample 1).

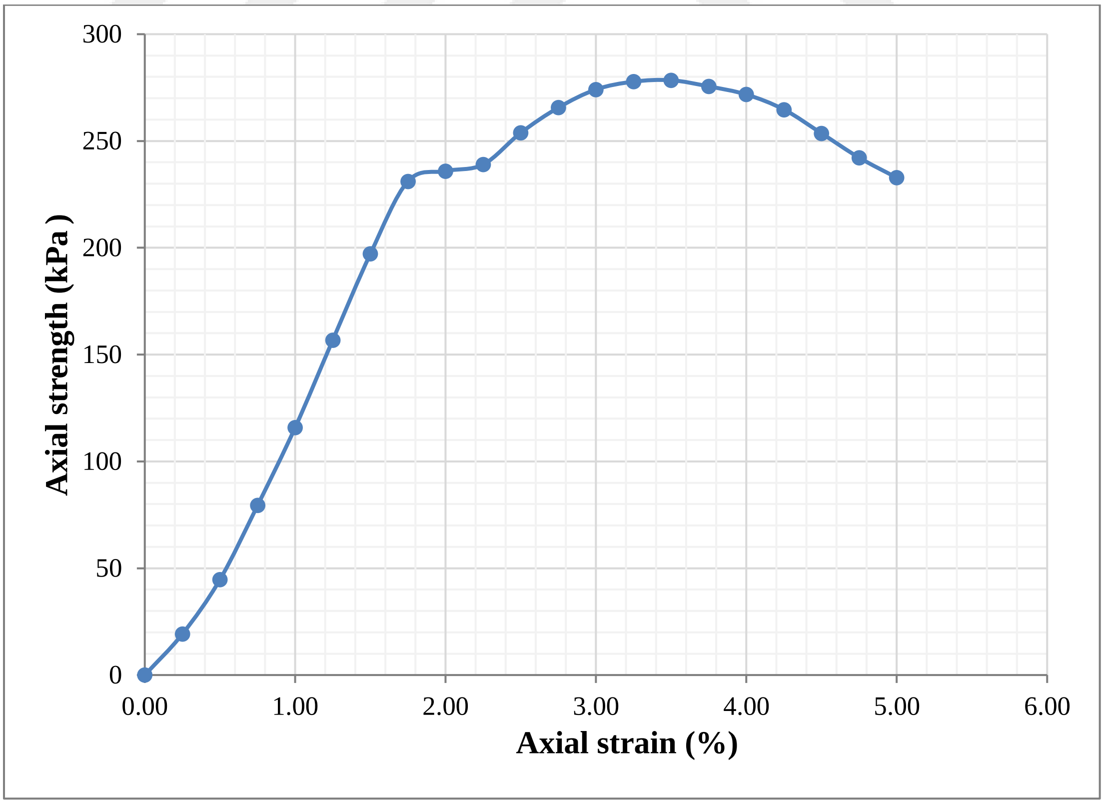

Figure C.6 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 7 days curing (Sample 2).

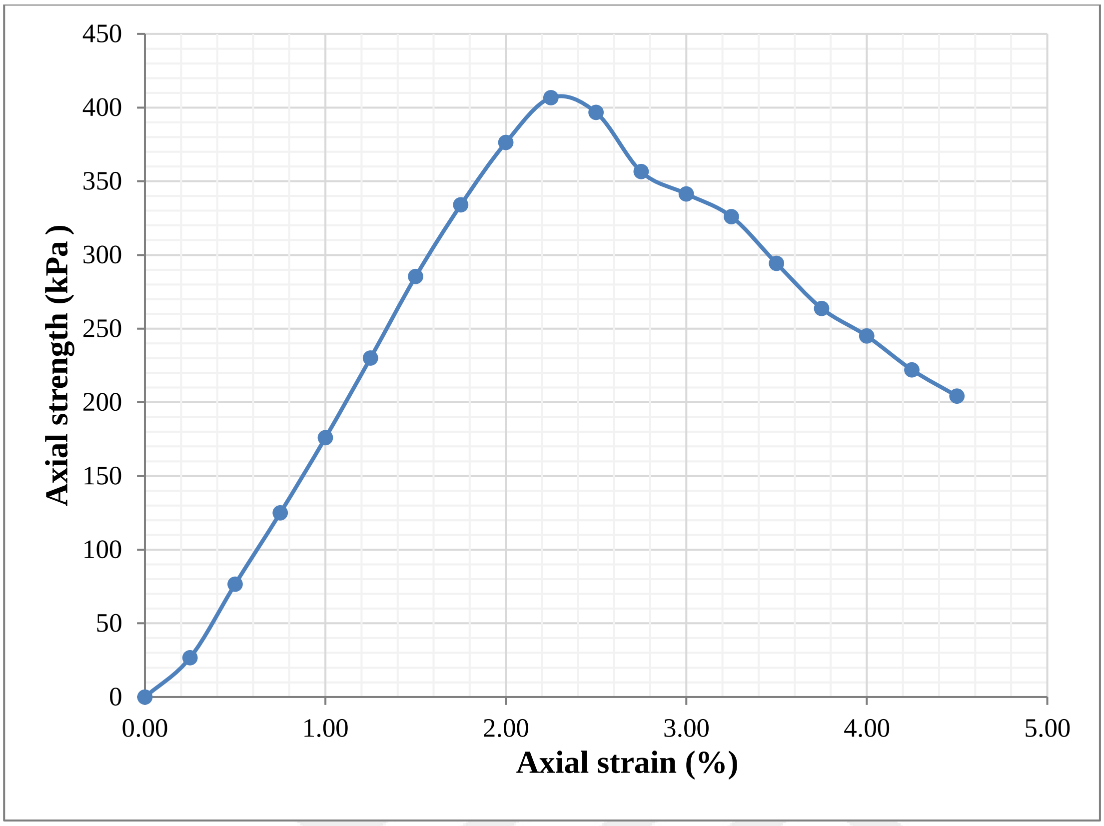

Figure C.7 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 28 days curing (Sample 1).

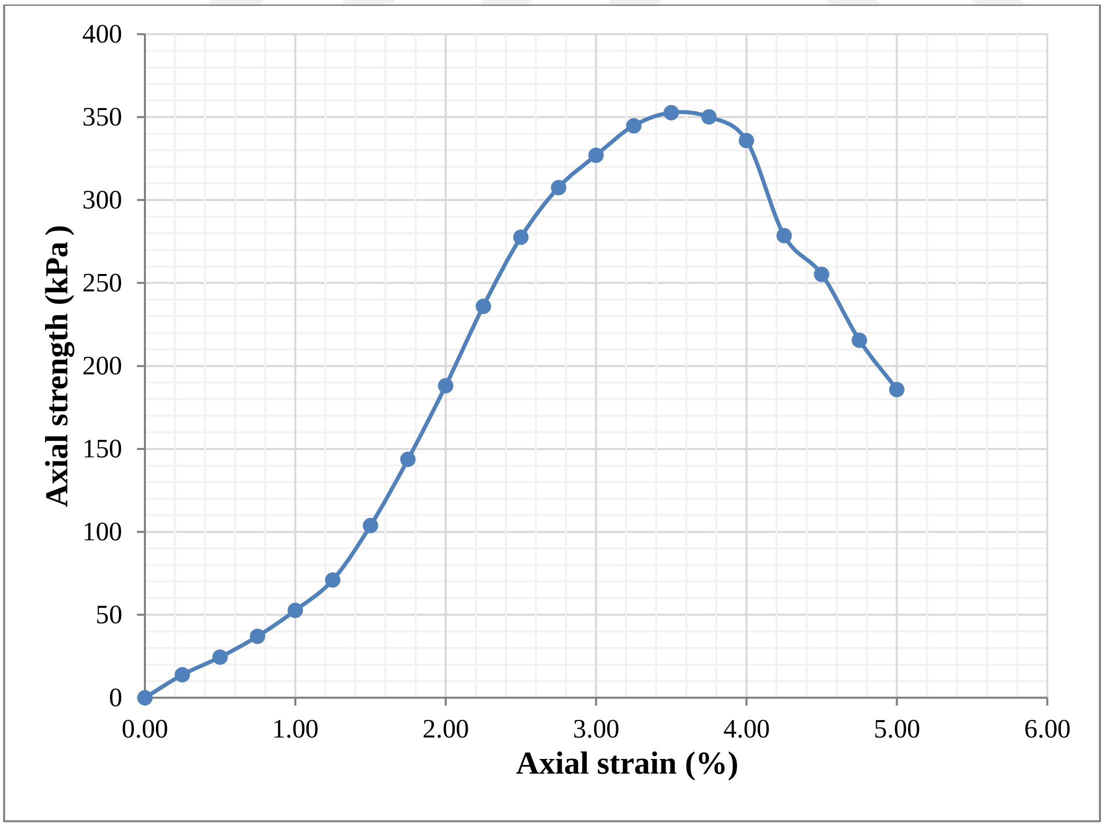

Figure C.8 : Result of the unconfined compression test of Dtm-1 mixed with 2% lime after 28 days curing (Sample 2).

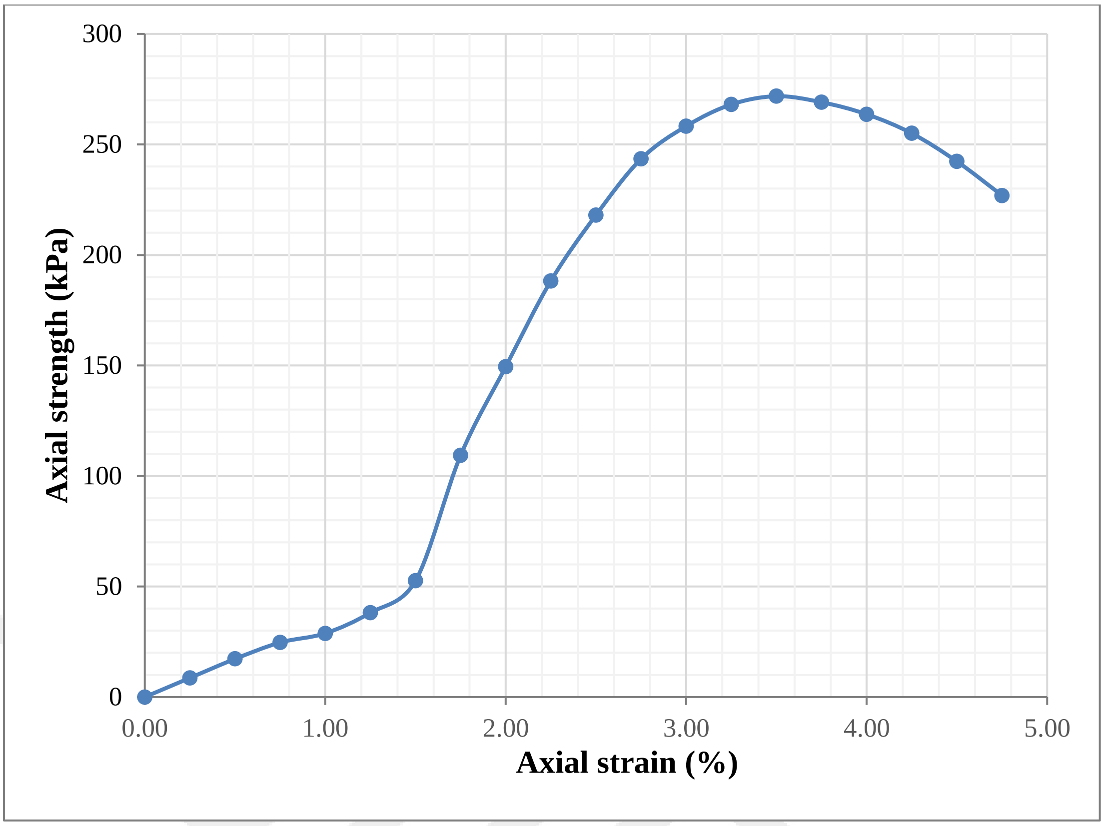

Figure C.9 : Result of the unconfined compression test of Dtm-1 mixed with 4% lime after 1 day curing (Sample 1).

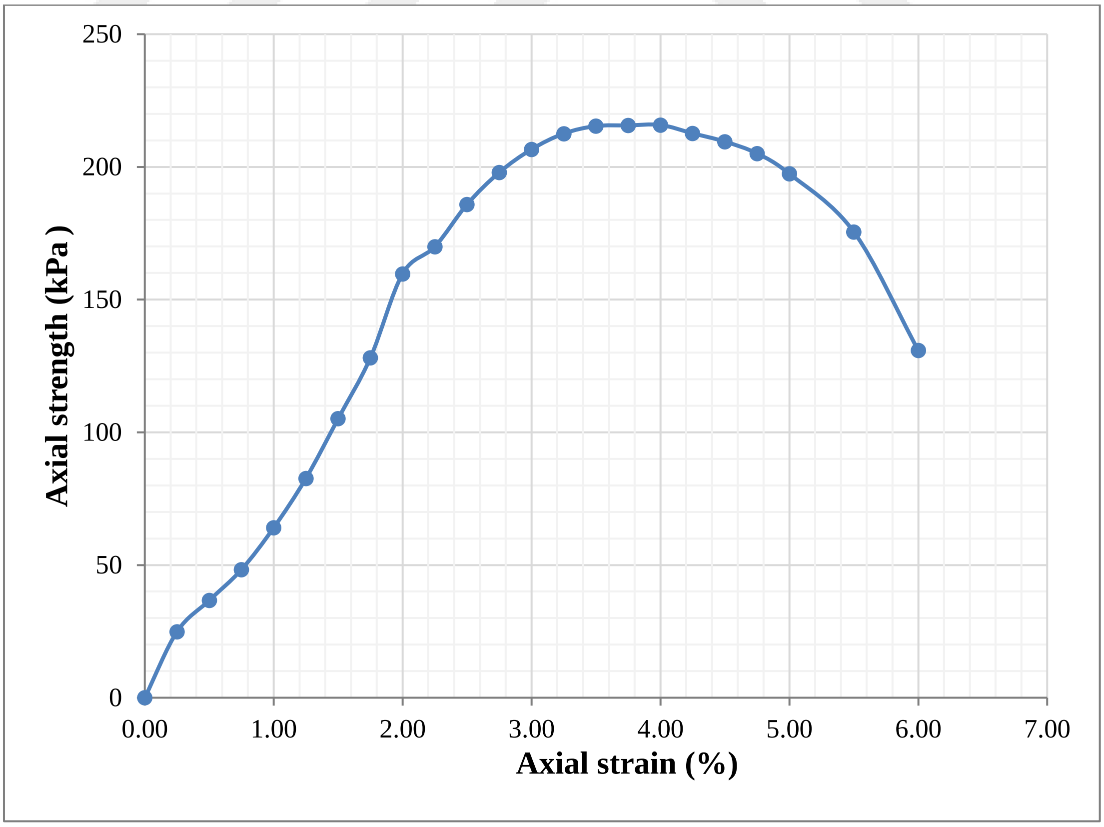

Figure C.10 : Result of the unconfined compression test of Dtm-1 mixed with 4% lime after 1 day curing (Sample 2).

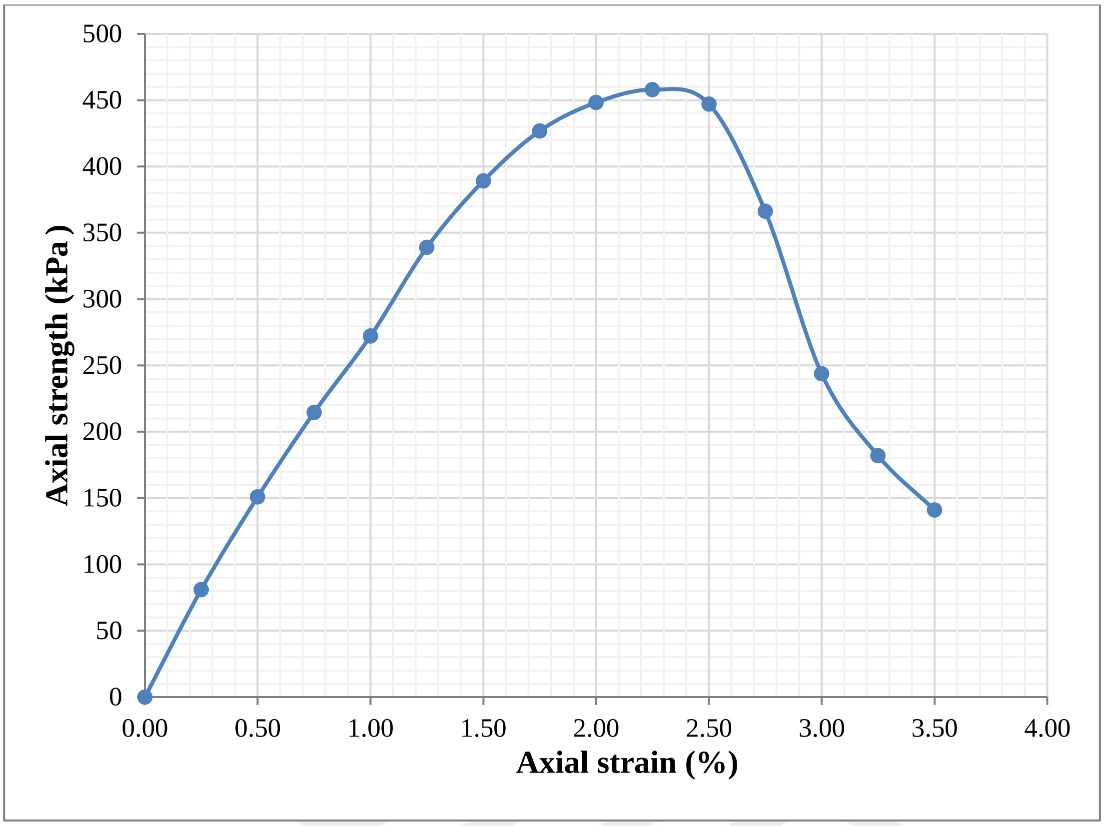

Figure C.11 : Result of the unconfined compression test of Dtm-1 mixed with 4% lime after 7 days curing (Sample 1).

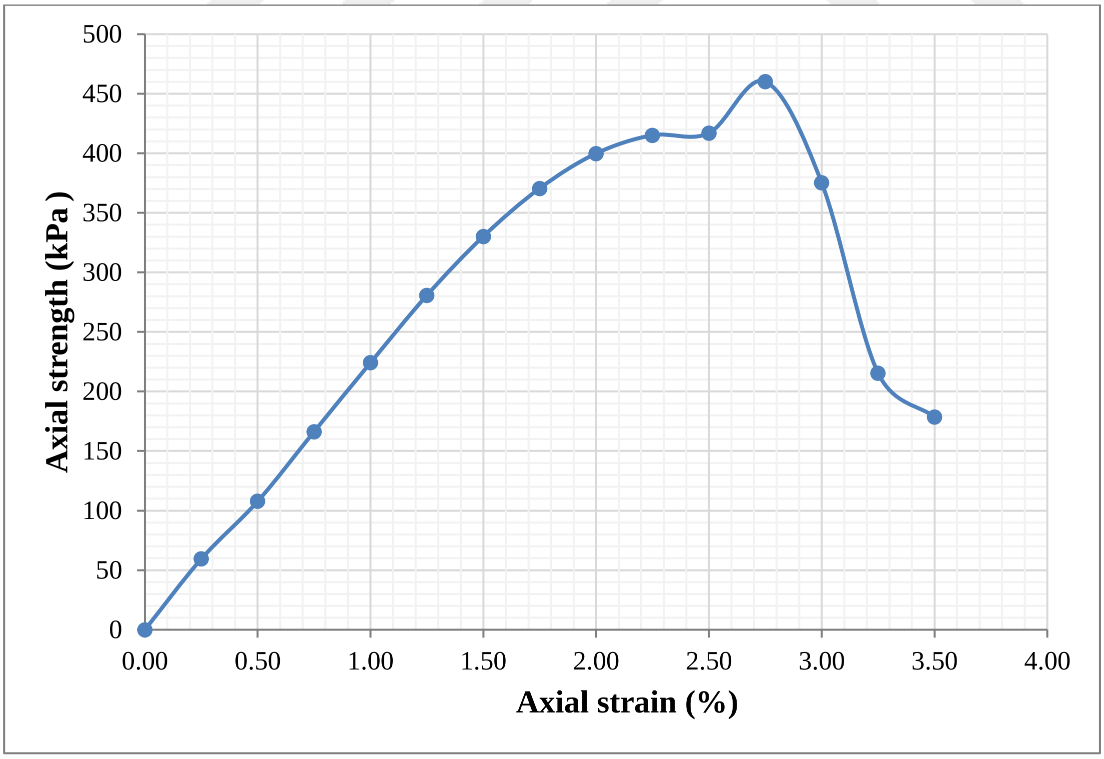

Figure C.12 : Result of the unconfined compression test of Dtm-1 mixed with 4% lime after 7 days curing (Sample 2).

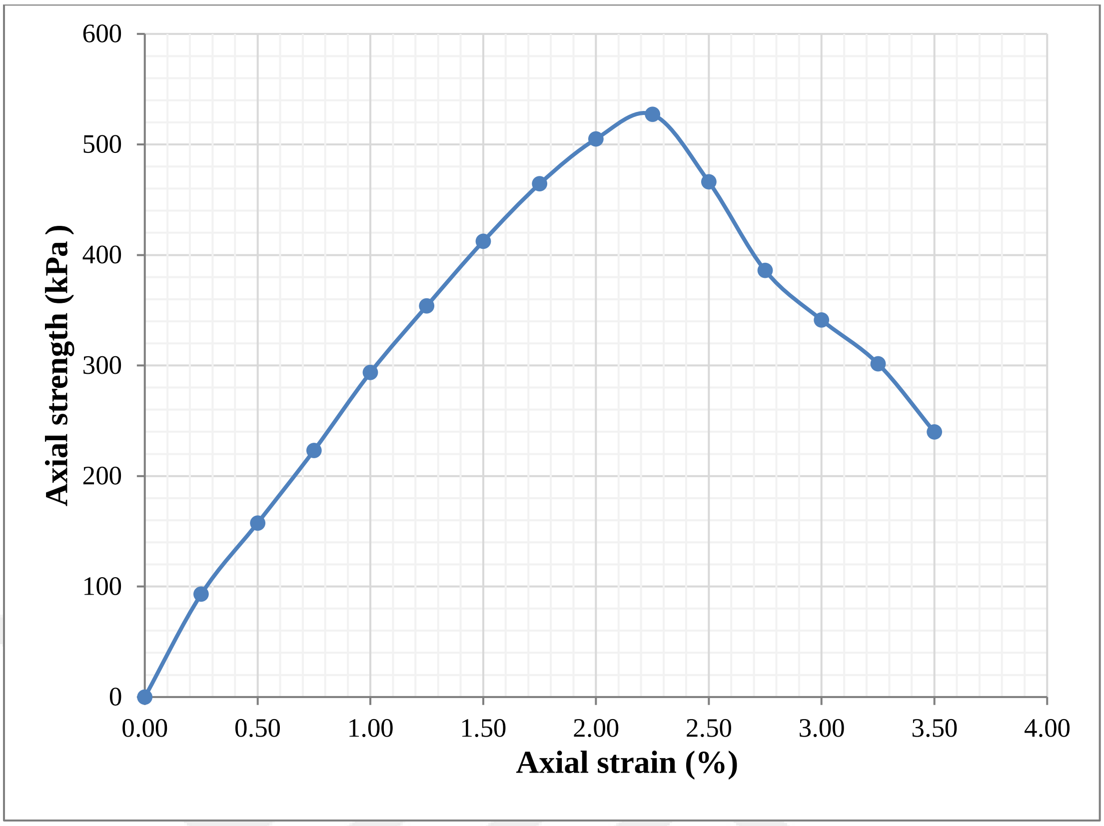

Figure C.13 : Result of the unconfined compression test of Dtm-1 mixed with 4% lime after 28 days curing (Sample 1).

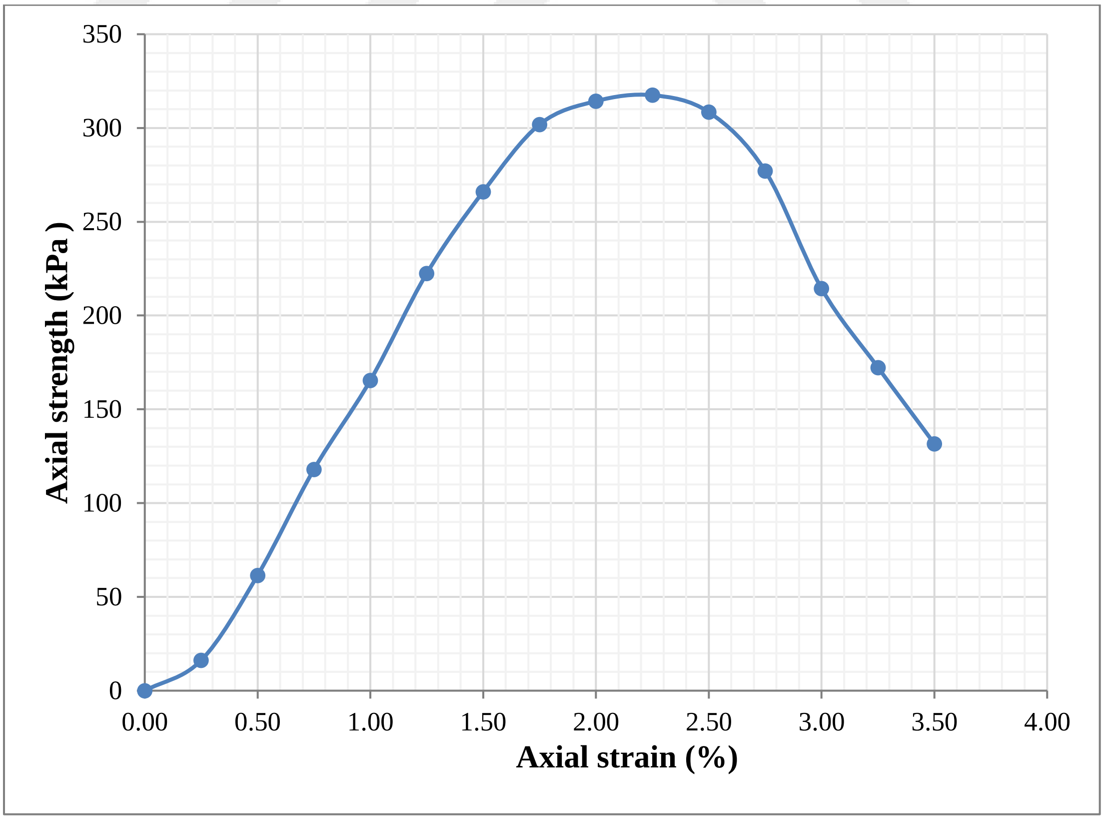

Figure C.14 : Result of the unconfined compression test of Dtm-1 mixed with 6% lime after 1 day curing (Sample 1).

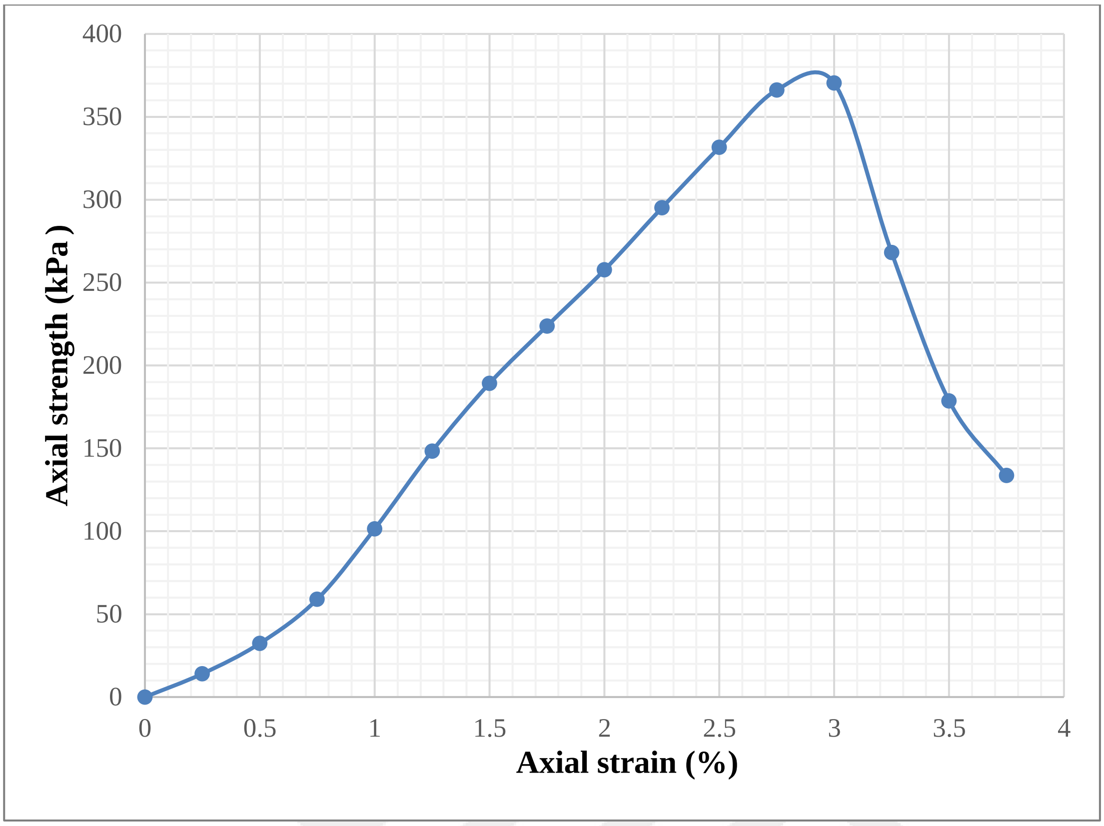

Figure C.15 : Result of the unconfined compression test of Dtm-1 mixed with 6% lime after 7 days curing (Sample 1).

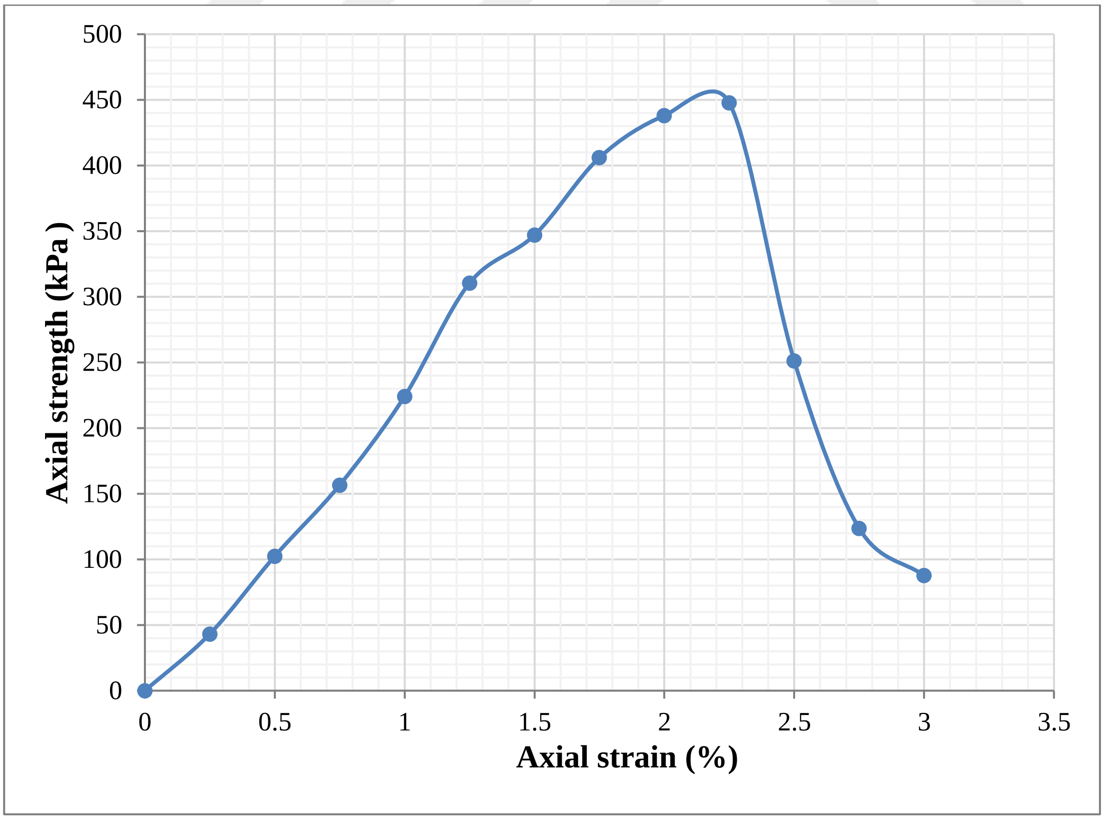

Figure C.16 : Result of the unconfined compression test of Dtm-1 mixed with 6% lime after 7 days curing (Sample 2).

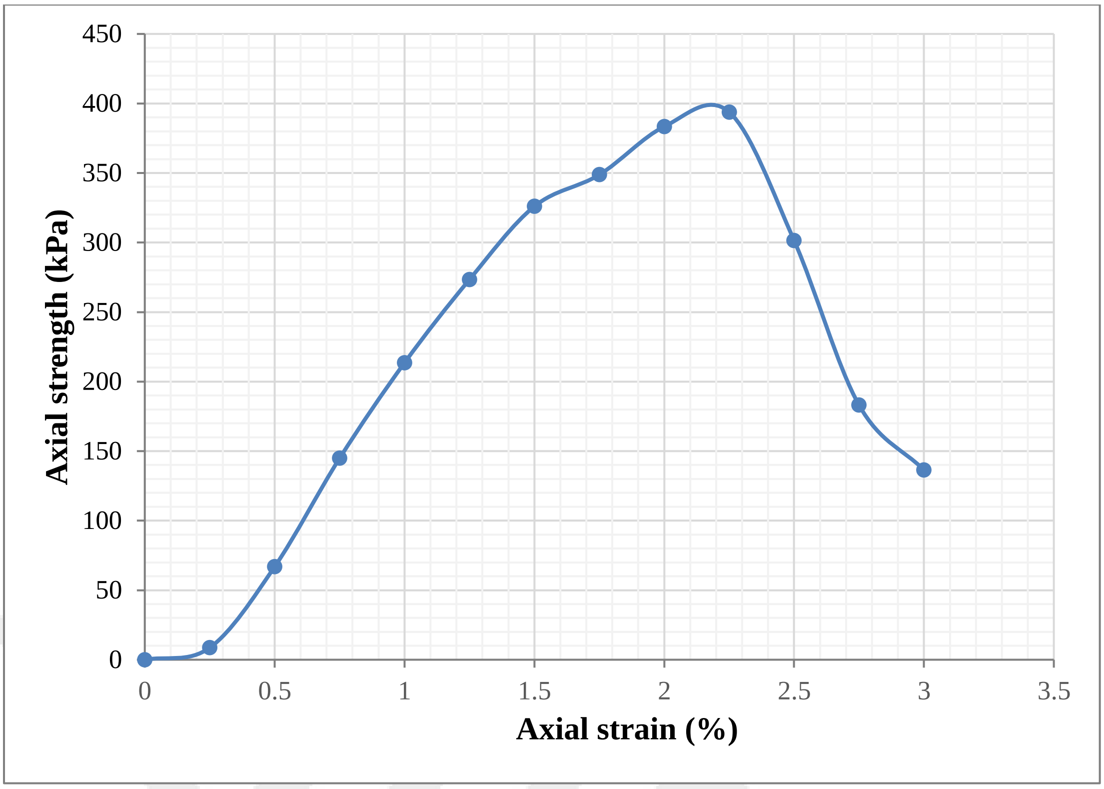

Figure C.17 : Result of the unconfined compression test of Dtm-1 mixed with 6% lime after 28 days curing (Sample 1).

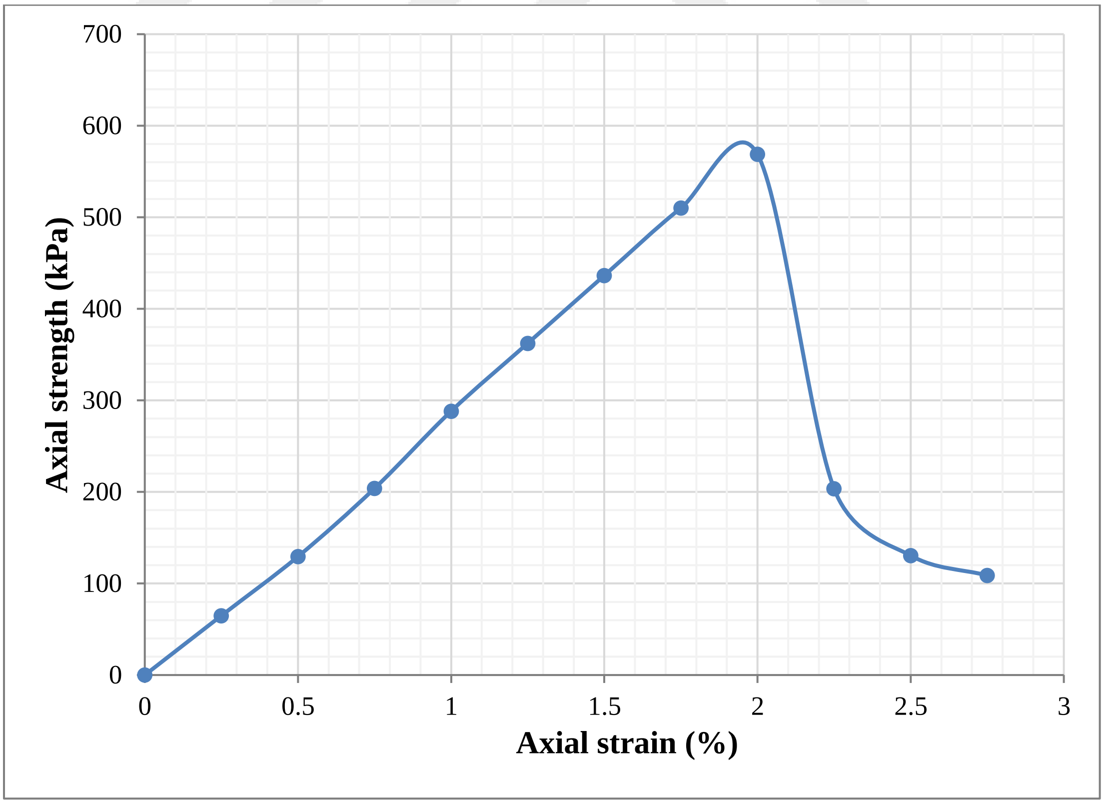

Figure C.18 : Result of the unconfined compression test of Dtm-1 mixed with 6% lime after 28 days curing (Sample 2).

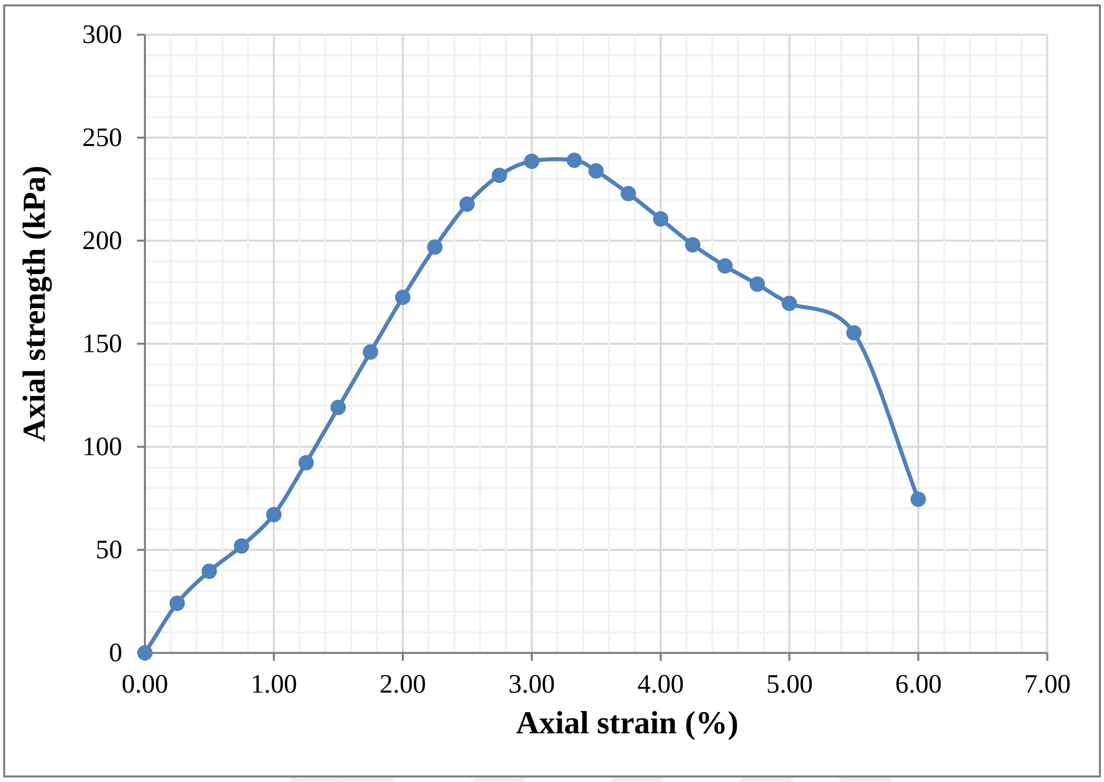

Figure C.19 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 1 day curing (Sample 1).

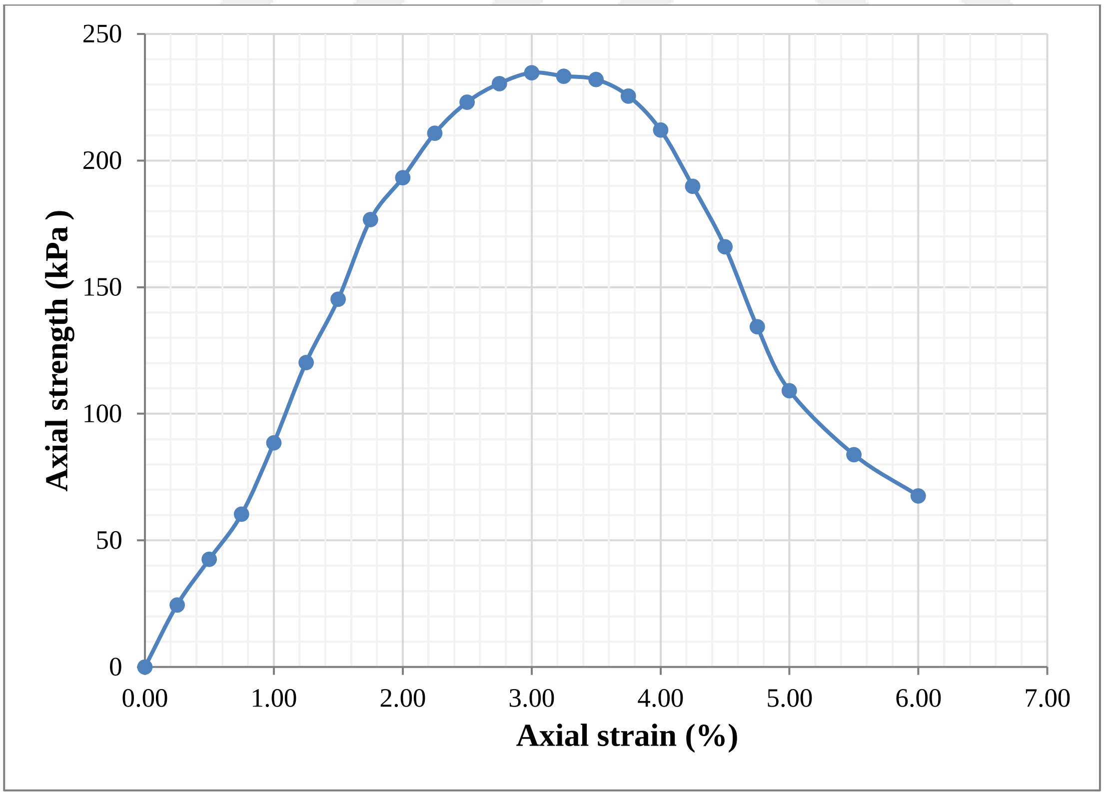

Figure C.20 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 1 day curing (Sample 2).

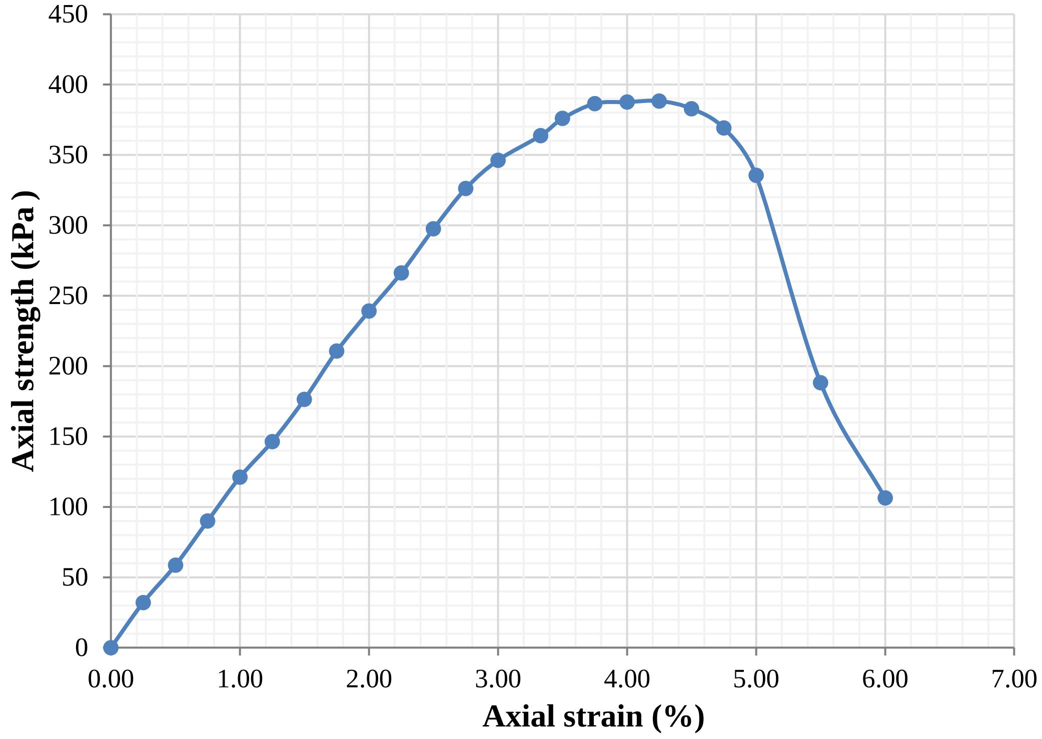

Figure C.21 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 7 days curing (Sample 1).

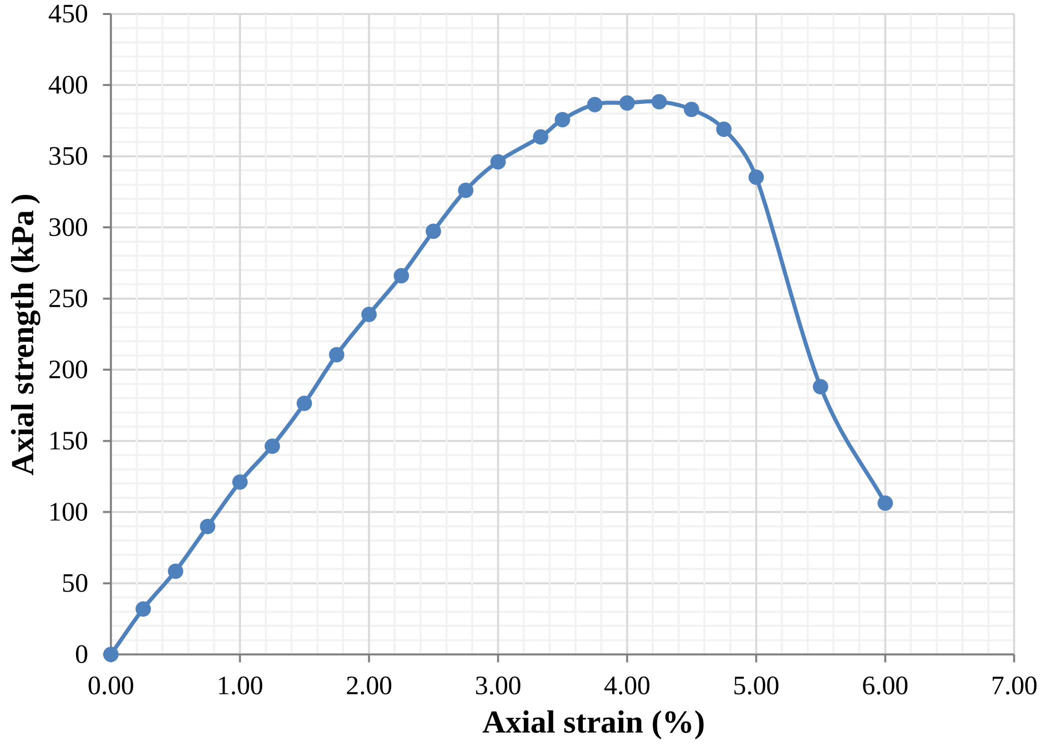

Figure C.22 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 7 days curing (Sample 2).

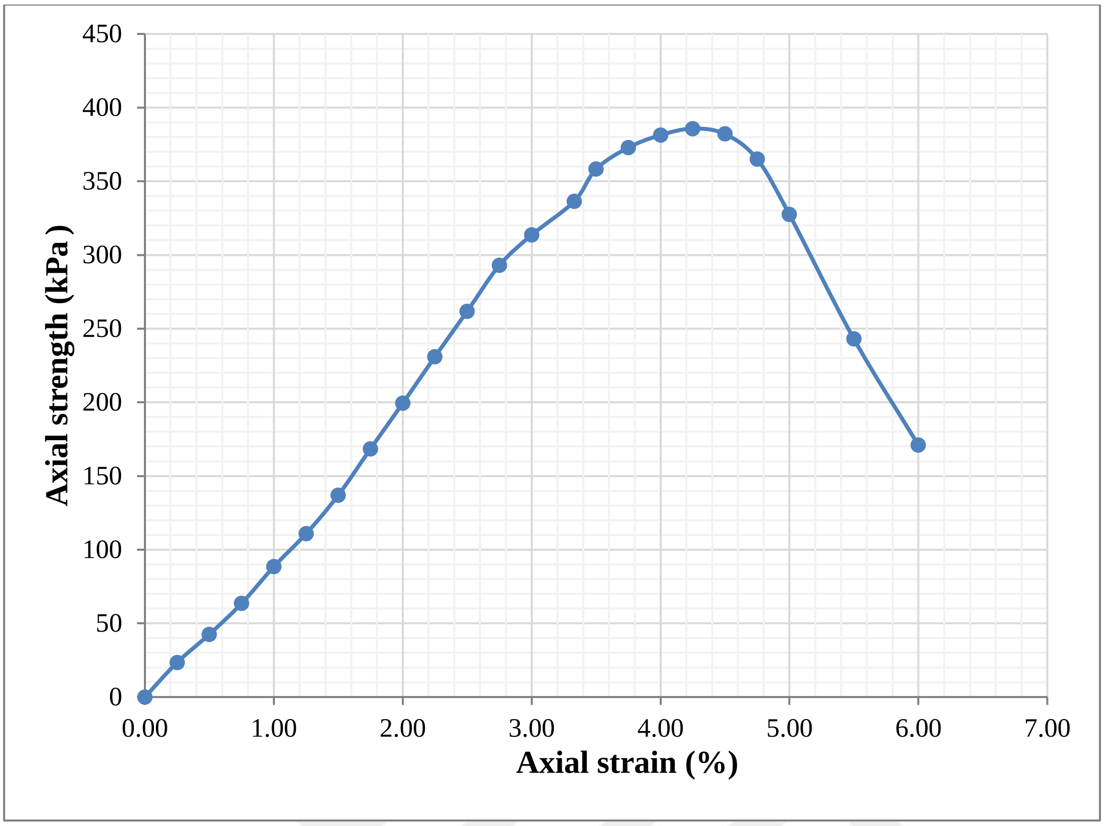

Figure C.23 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 28 days curing (Sample 1).

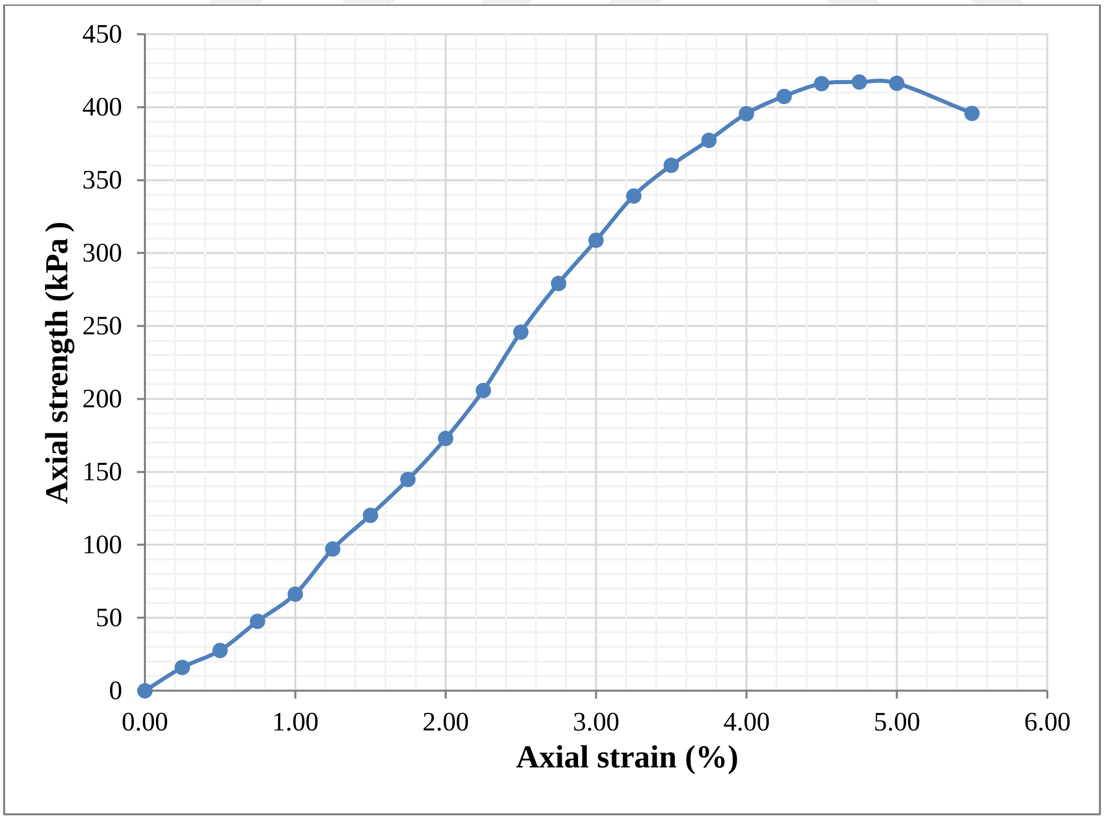

Figure C.24 : Result of the unconfined compression test of Dtm-1 mixed with 5% cement after 28 days curing (Sample 2).

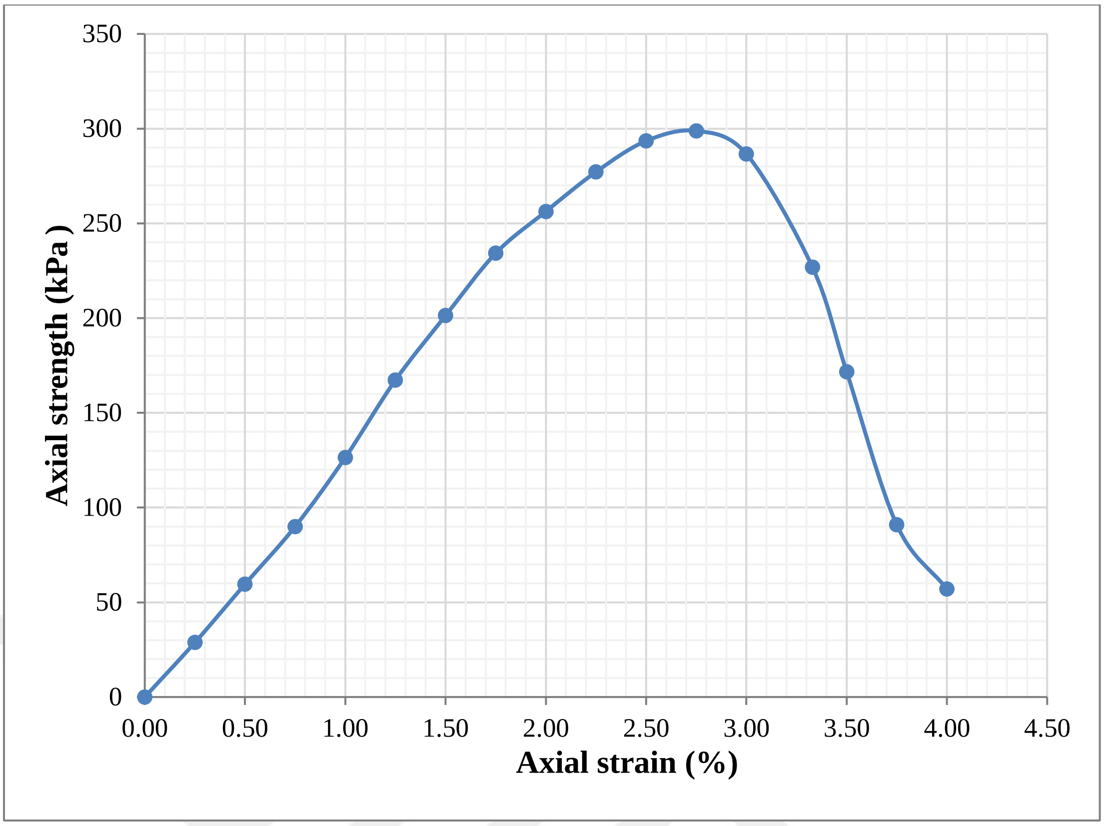

Figure C.25 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 1 day curing (Sample 1).

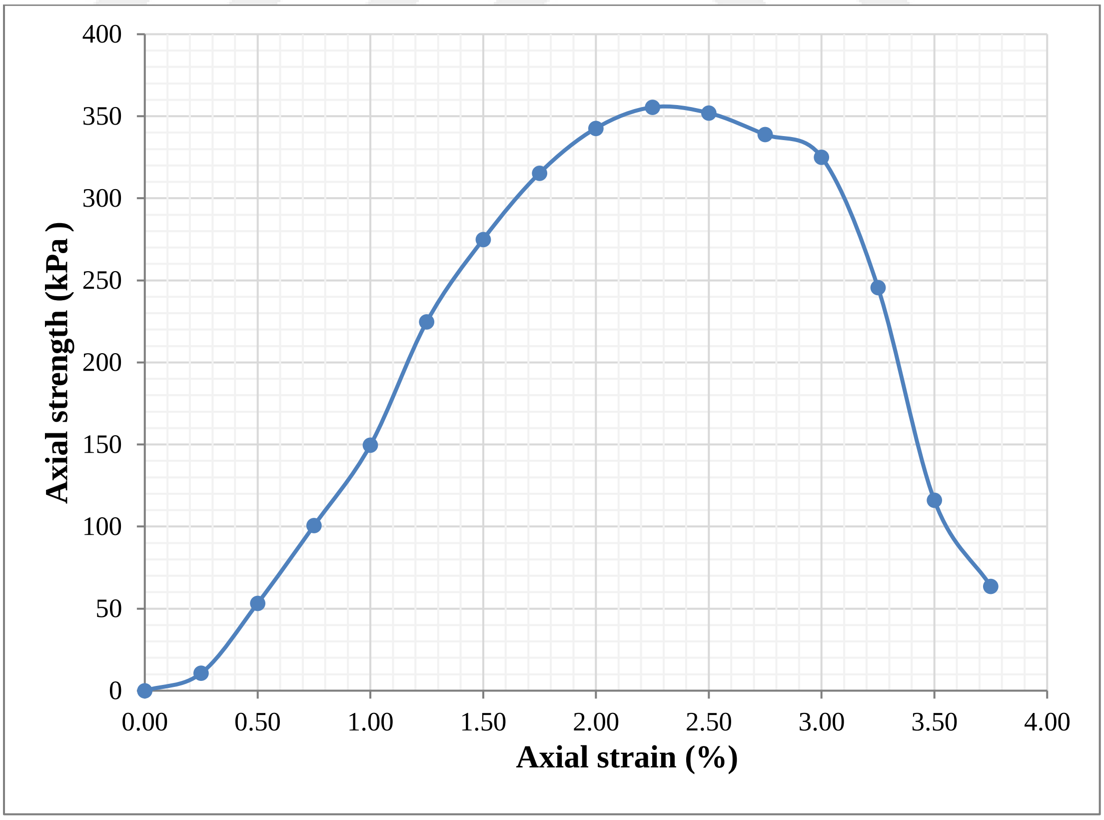

Figure C.26 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 1 day curing (Sample 2).

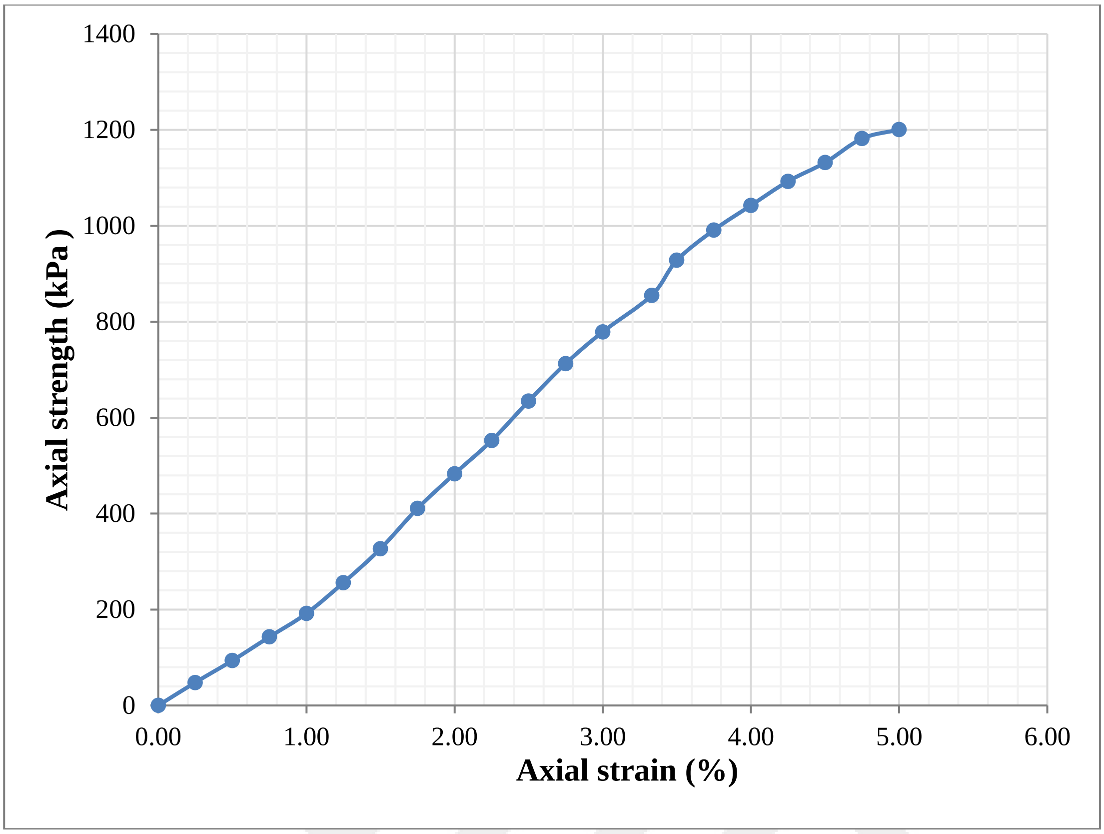

Figure C.27 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 7 days curing (Sample 1).

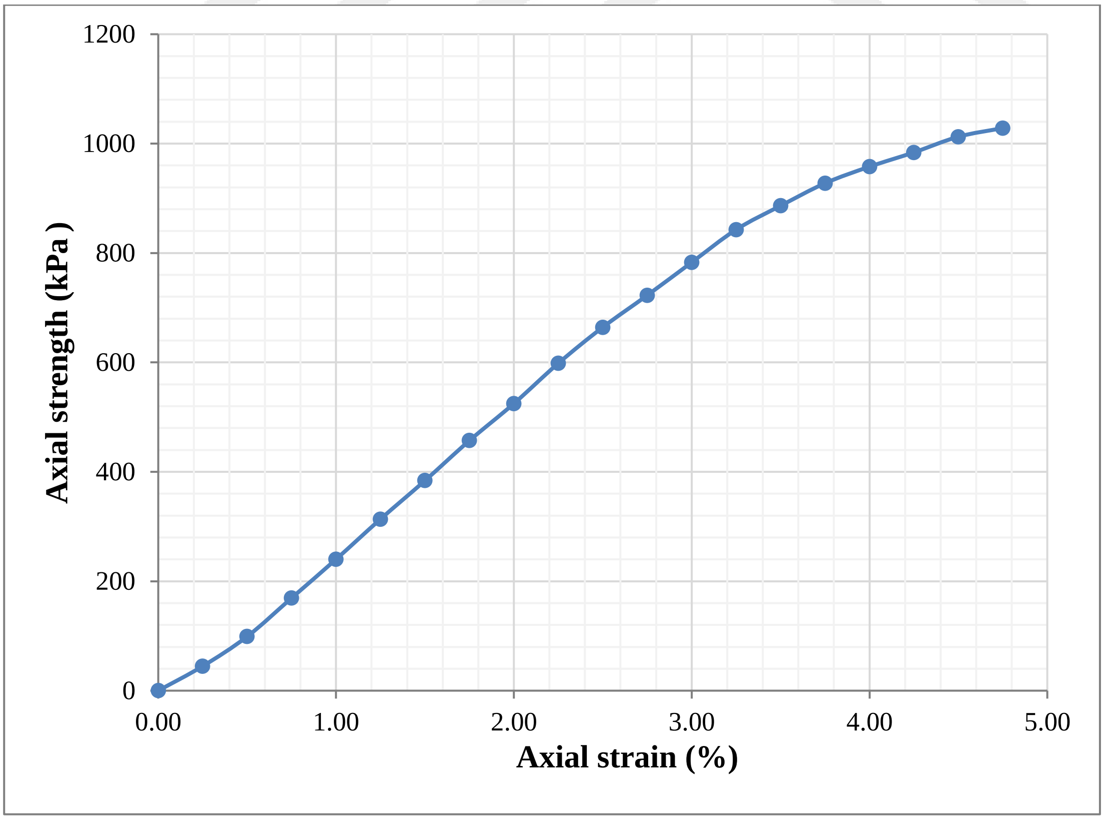

Figure C.28 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 7 days curing (Sample 2).

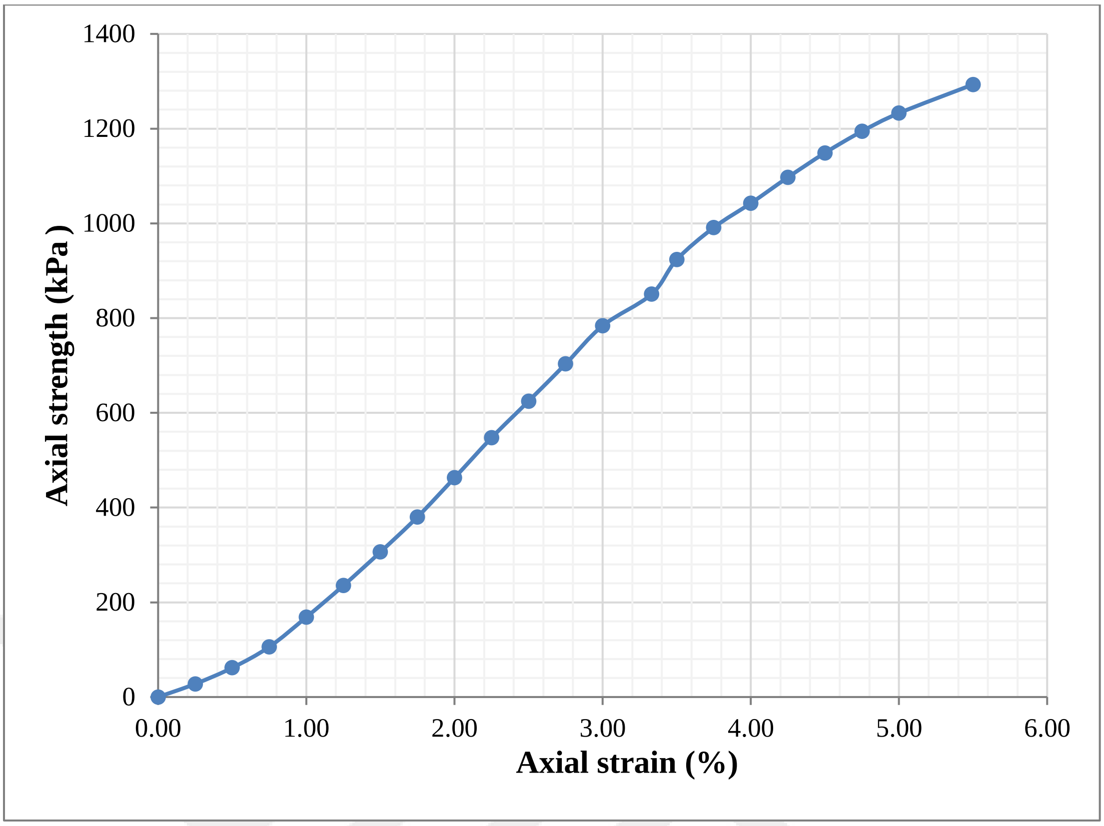

Figure C.29 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 28 days curing (Sample 1).

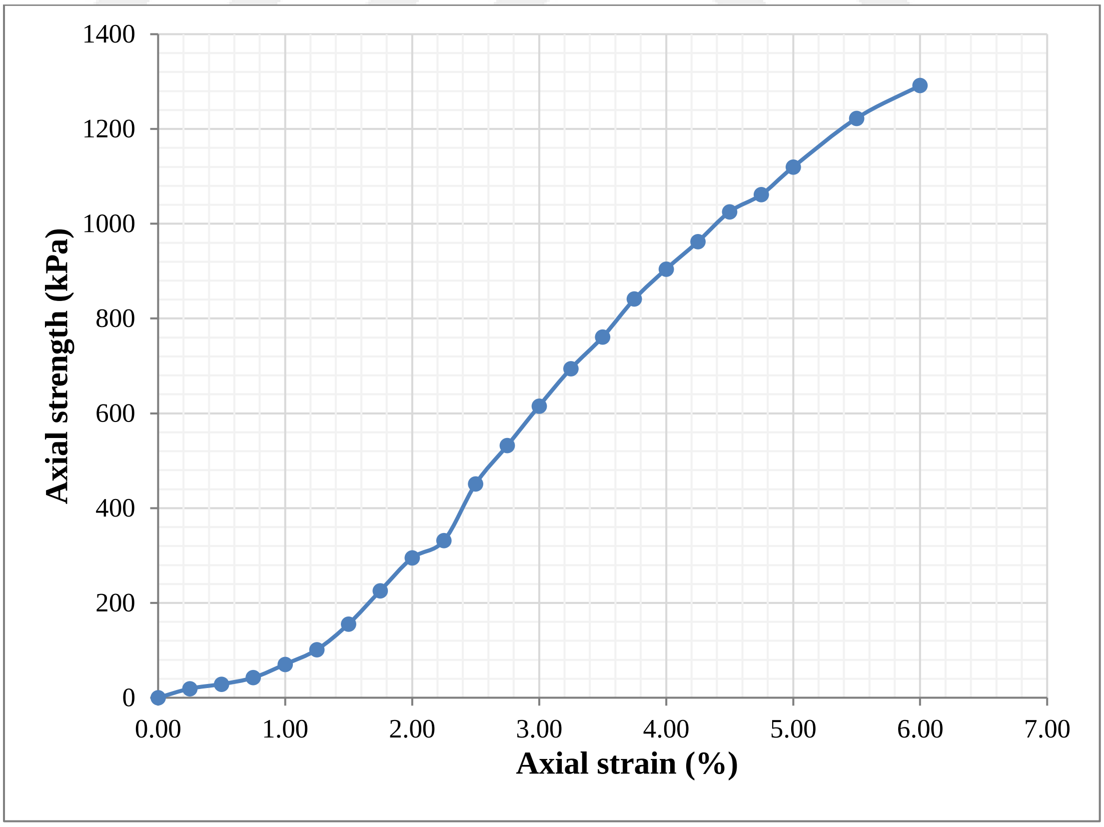

Figure C.30 : Result of the unconfined compression test of Dtm-1 mixed with 10% cement after 28 days curing (Sample 2).

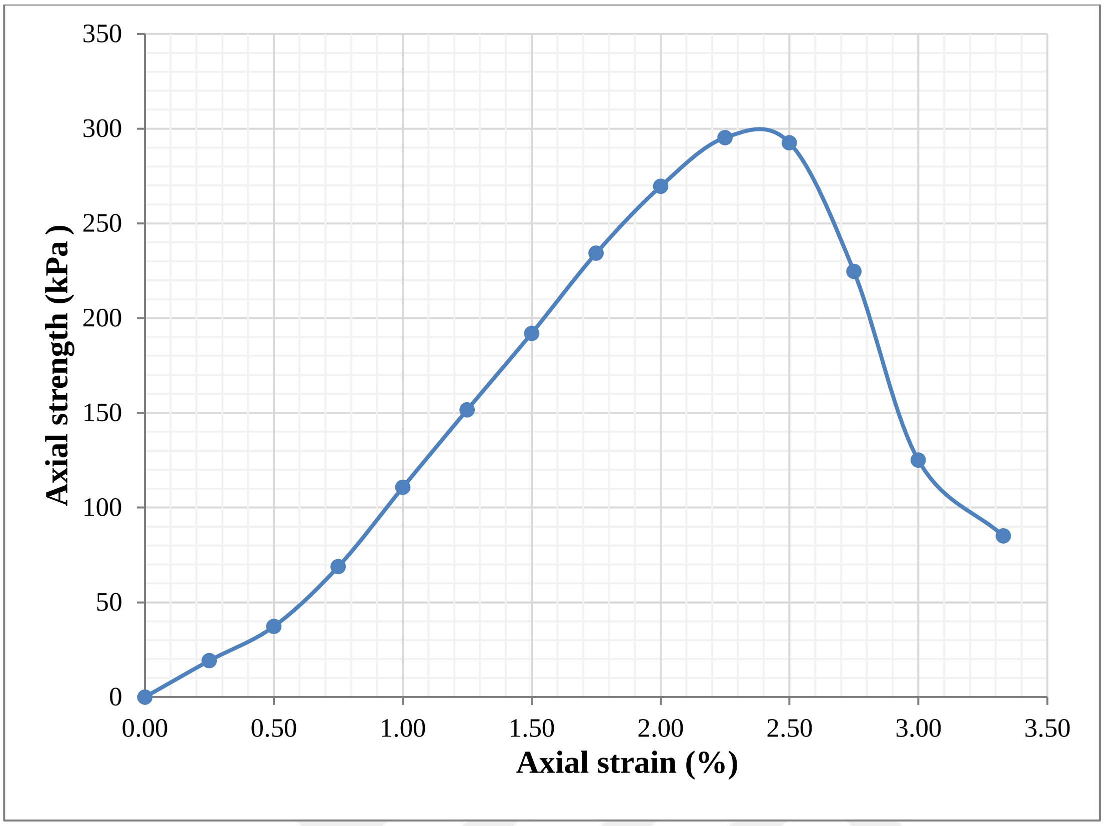

Figure C.31 : Result of the unconfined compression test of Dtm-1 mixed with 15% cement after 1 day curing (Sample 1).

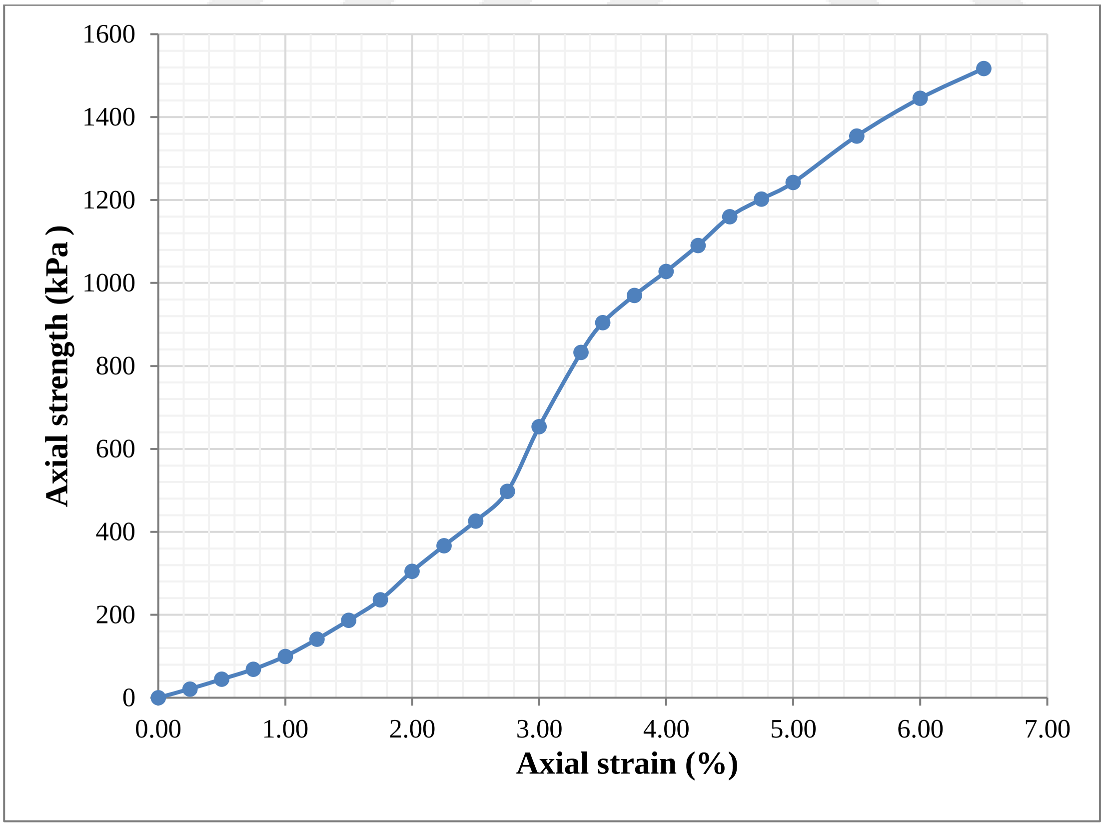

Figure C.32 : Result of the unconfined compression test of Dtm-1 mixed with 15% cement after 7 days curing (Sample 1).

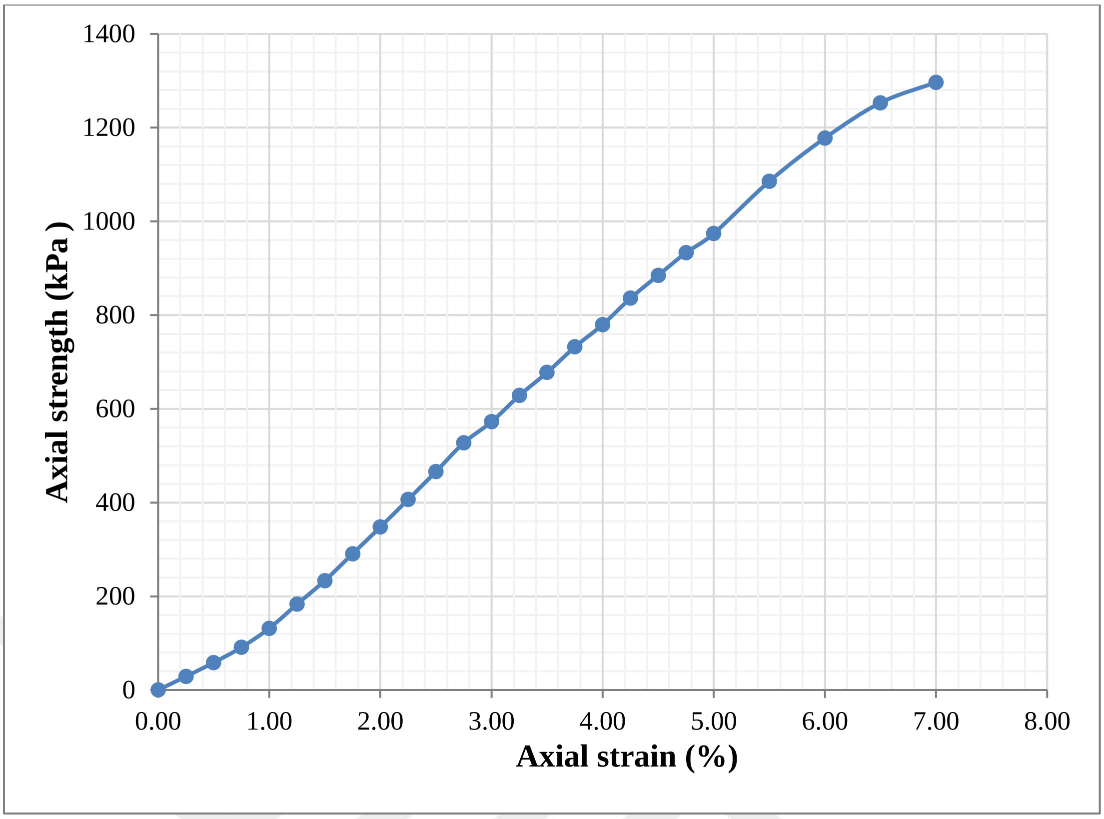

Figure C.33 : Result of the unconfined compression test of Dtm-1 mixed with 15% cement after 7 days curing (Sample 2).

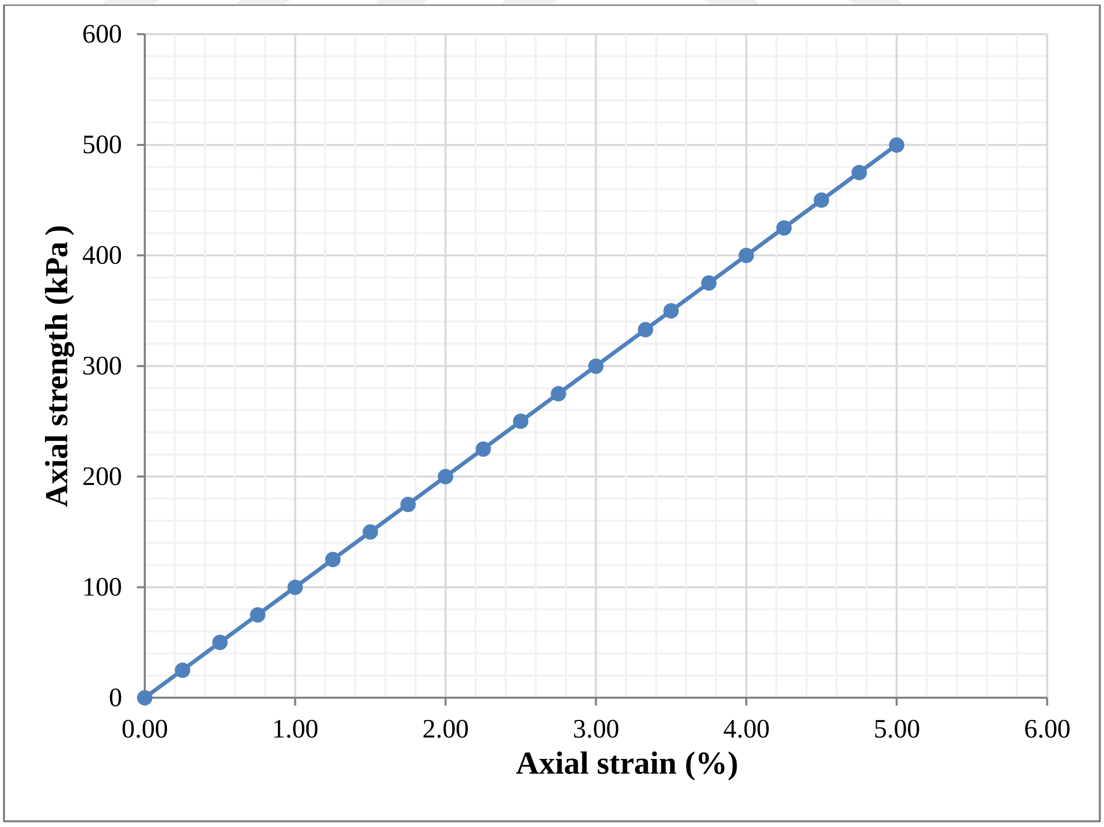

Figure C.34 : Result of the unconfined compression test of Dtm-1 mixed with 15% cement after 28 days curing (Sample 1).

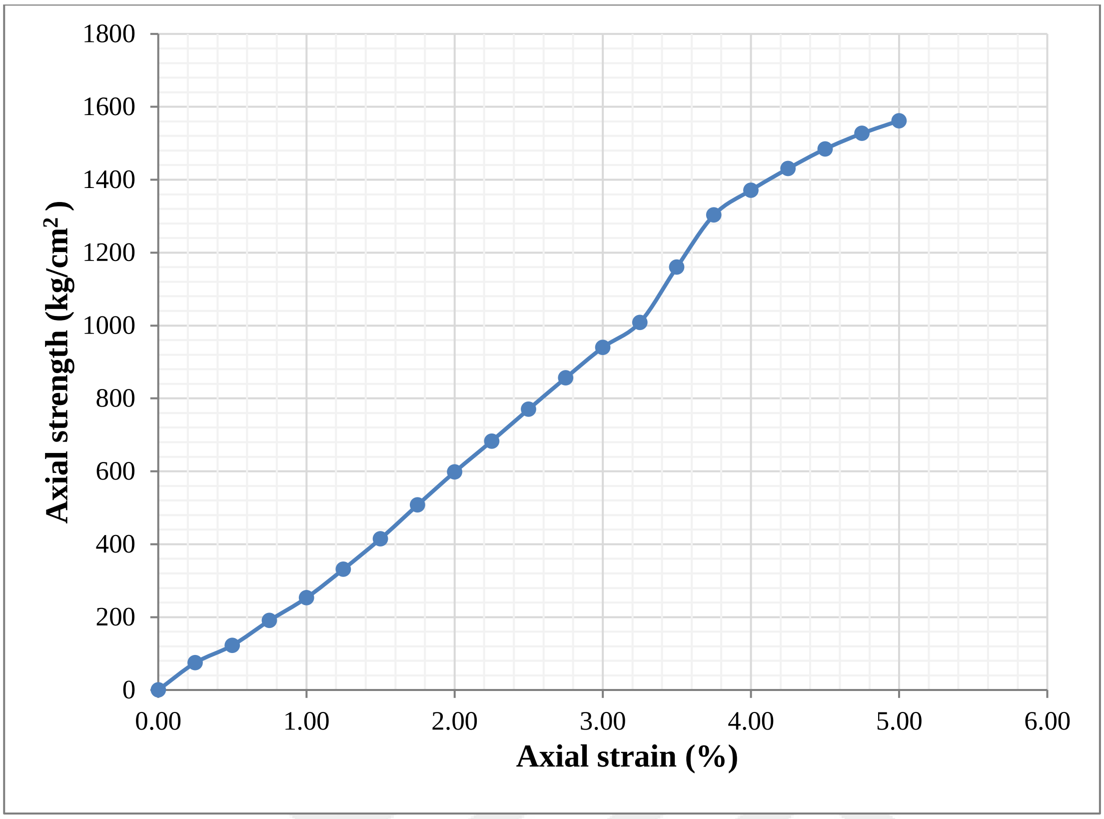

Figure C.35 : Result of the unconfined compression test of Dtm-1 mixed with 15% cement after 28 days curing (Sample 2).

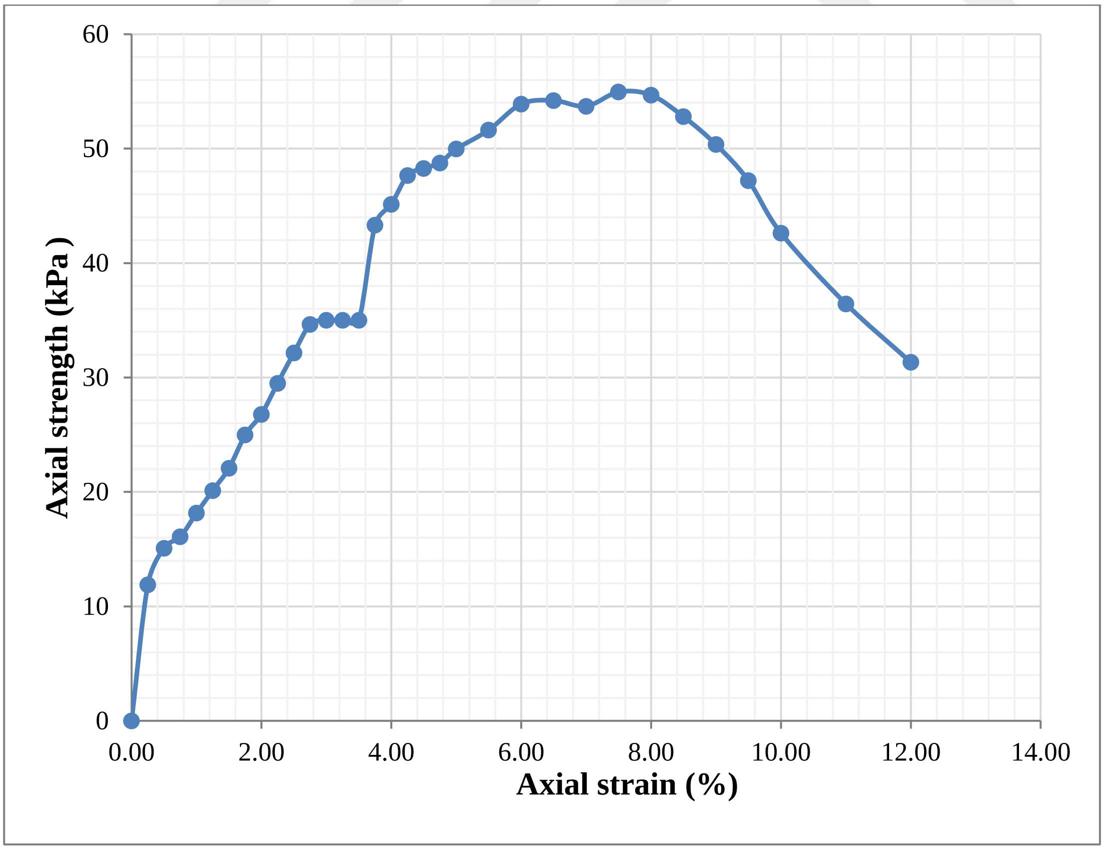

Figure C.36 : Result of the unconfined compression test of raw Dtm-10 (Sample 1).

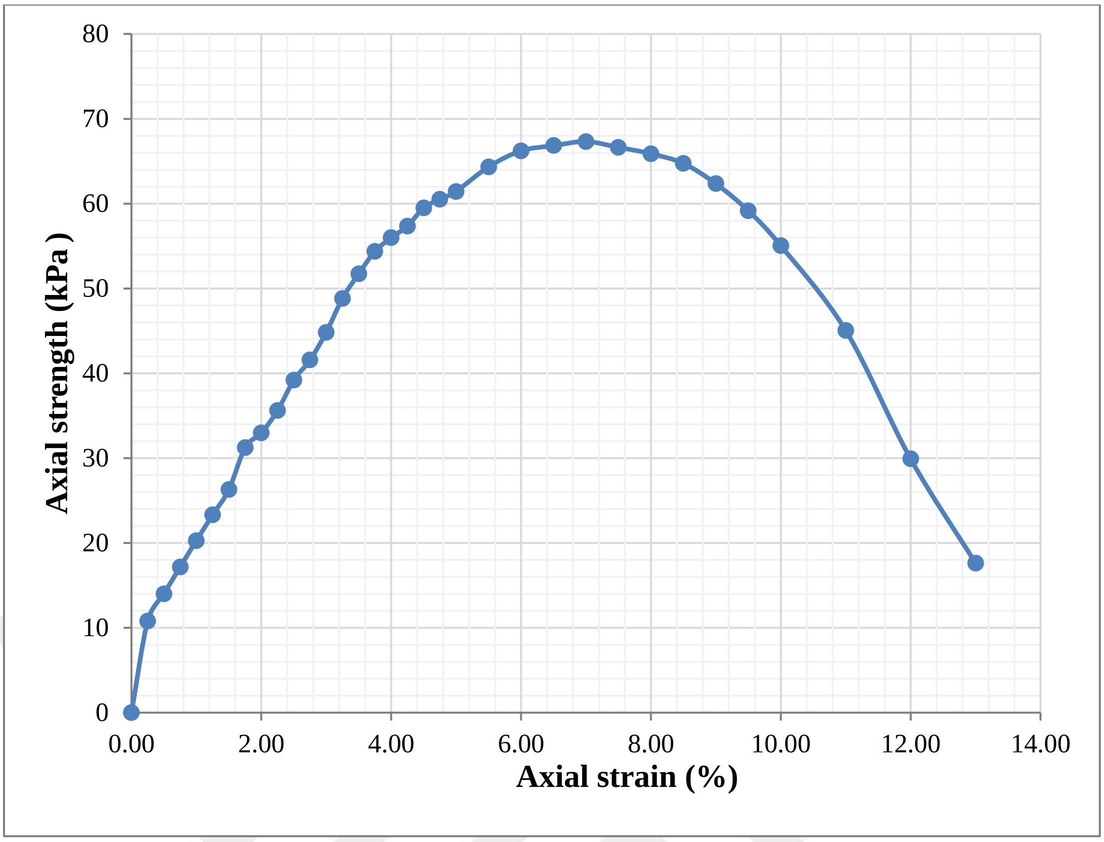

Figure C.37 : Result of the unconfined compression test of raw Dtm-10 (Sample 2).

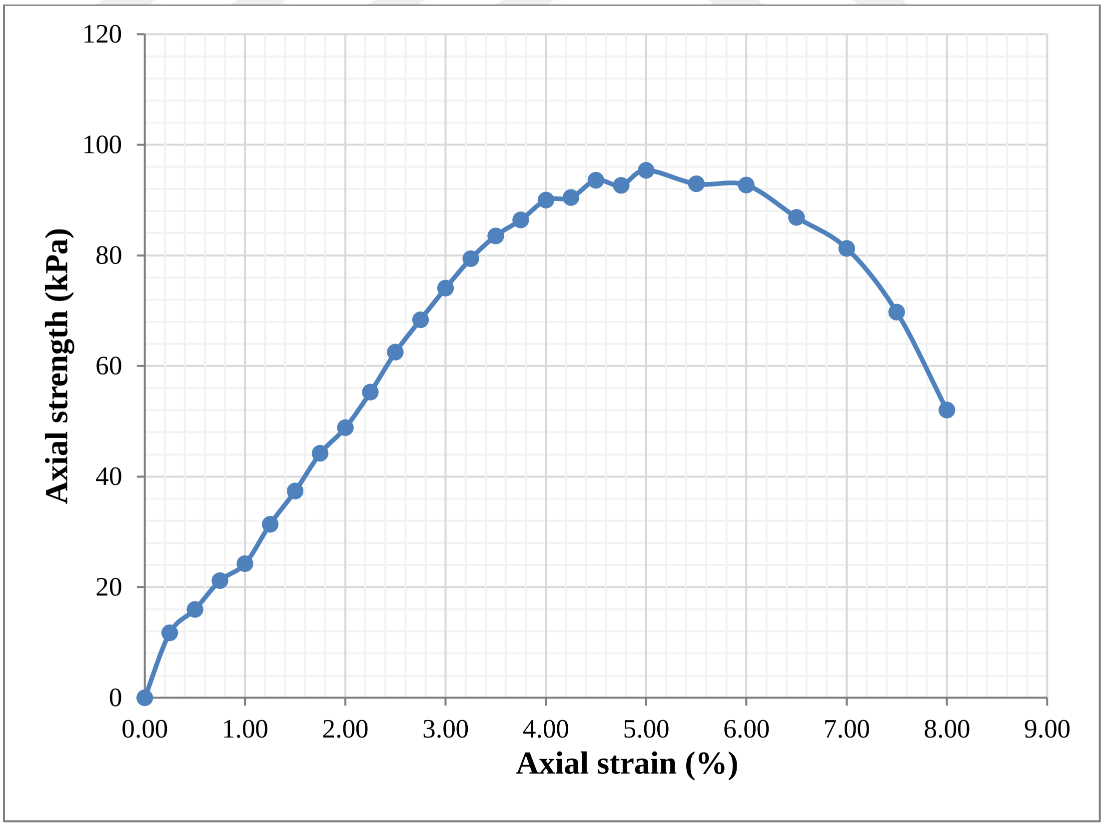

Figure C.38 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 1 day curing (Sample 1).

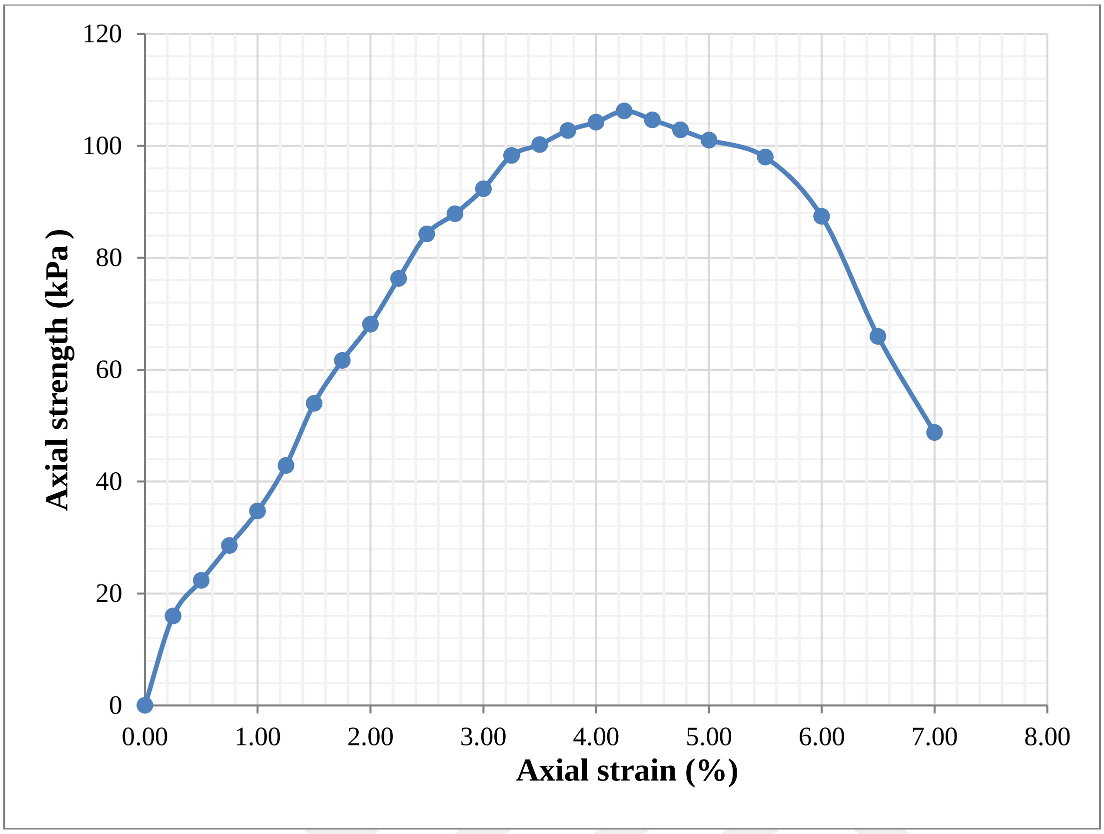

Figure C.39 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 1 day curing (Sample 2).

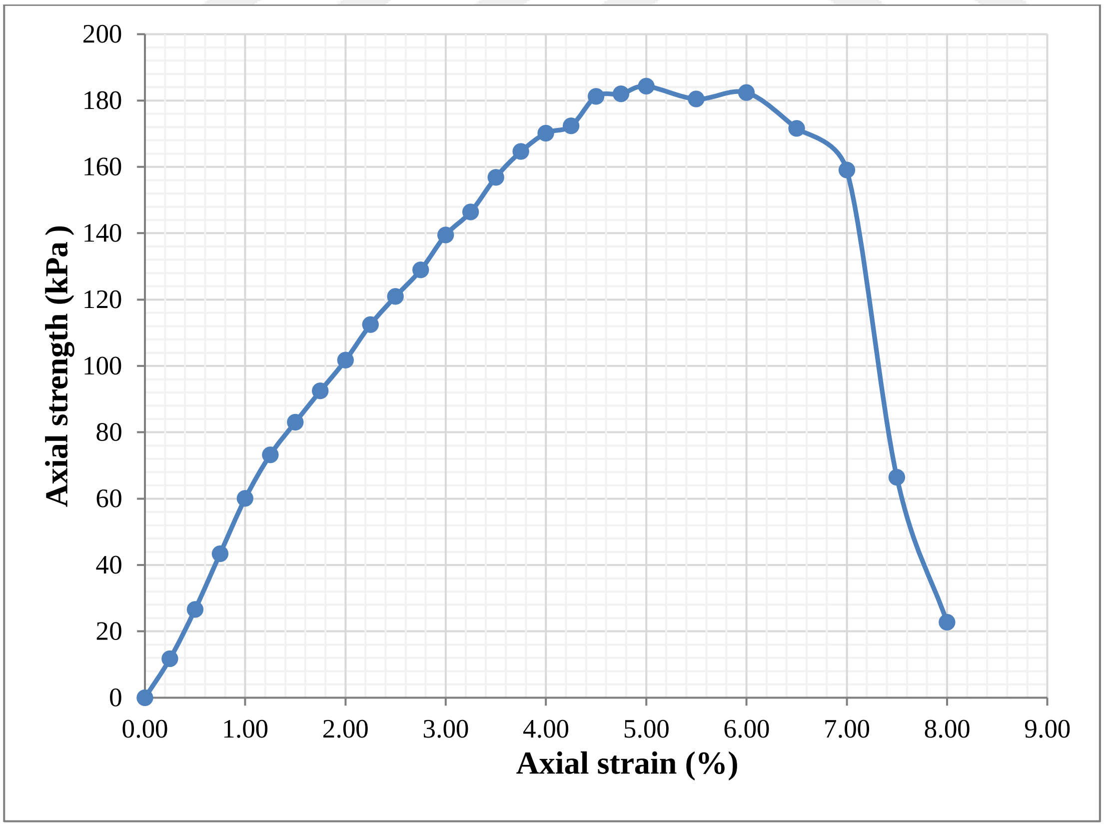

Figure C.40 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 7 days curing (Sample 1).

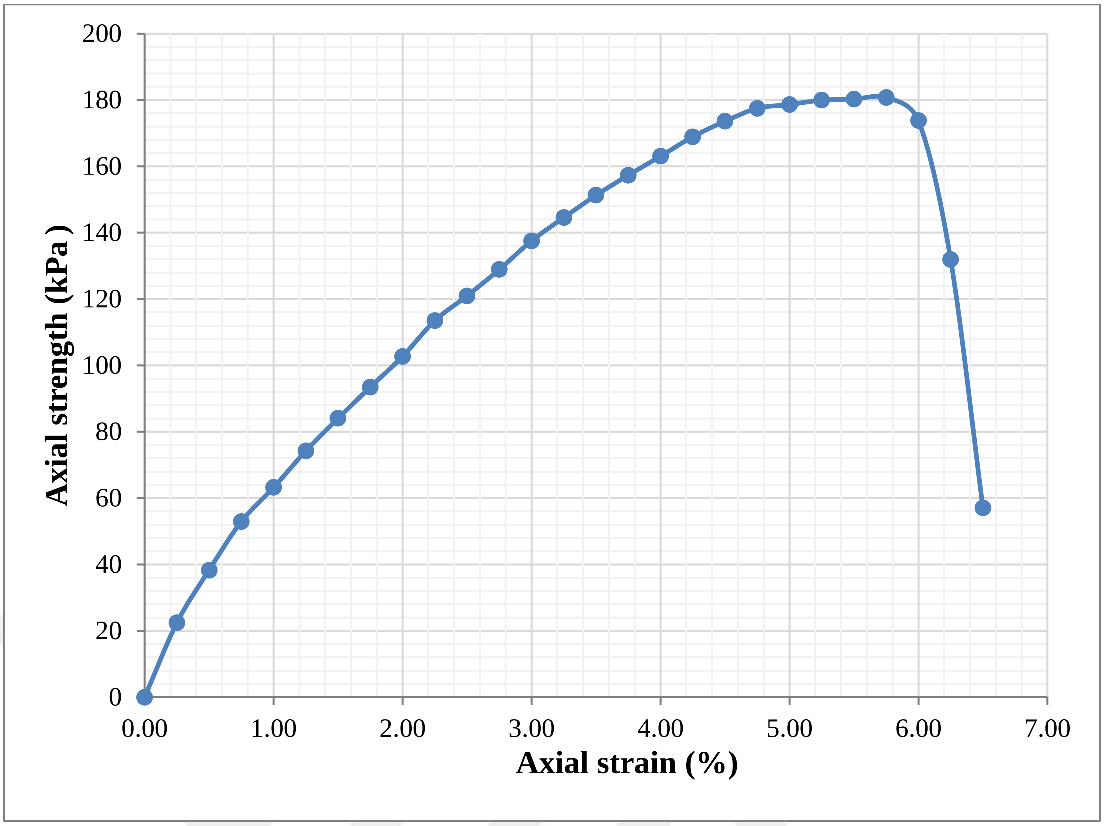

Figure C.41 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 7 days curing (Sample 2).

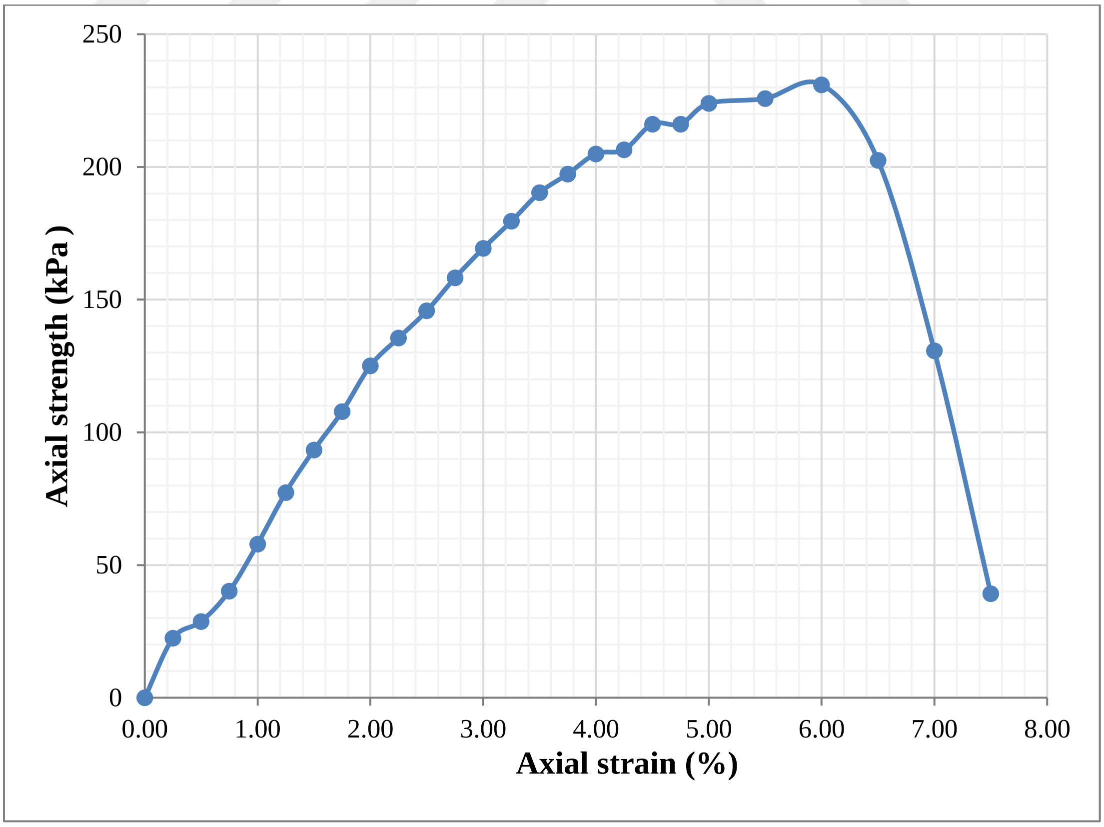

Figure C.42 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 28 days curing (Sample 1).

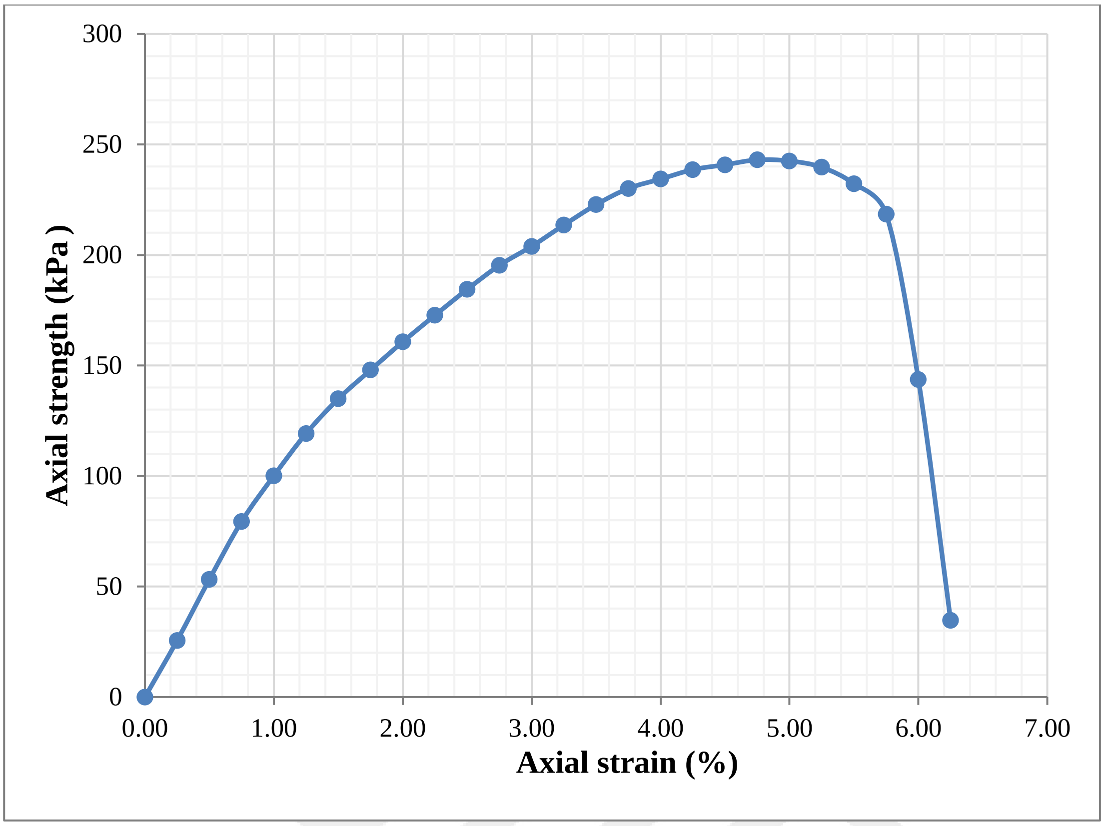

Figure C.43 : Result of the unconfined compression test of Dtm-10 mixed with 2% lime after 28 days curing (Sample 2).

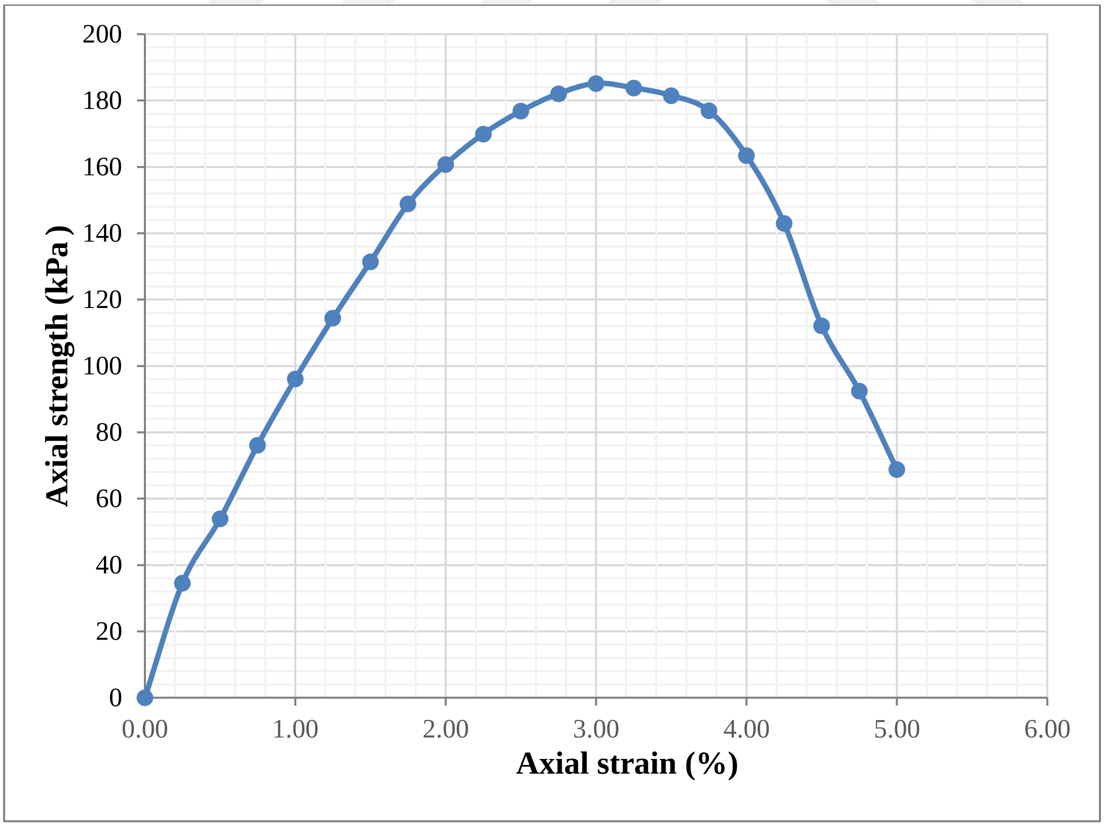

Figure C.44 : Result of the unconfined compression test of Dtm-10 mixed with 4% lime after 1 day curing (Sample 1).

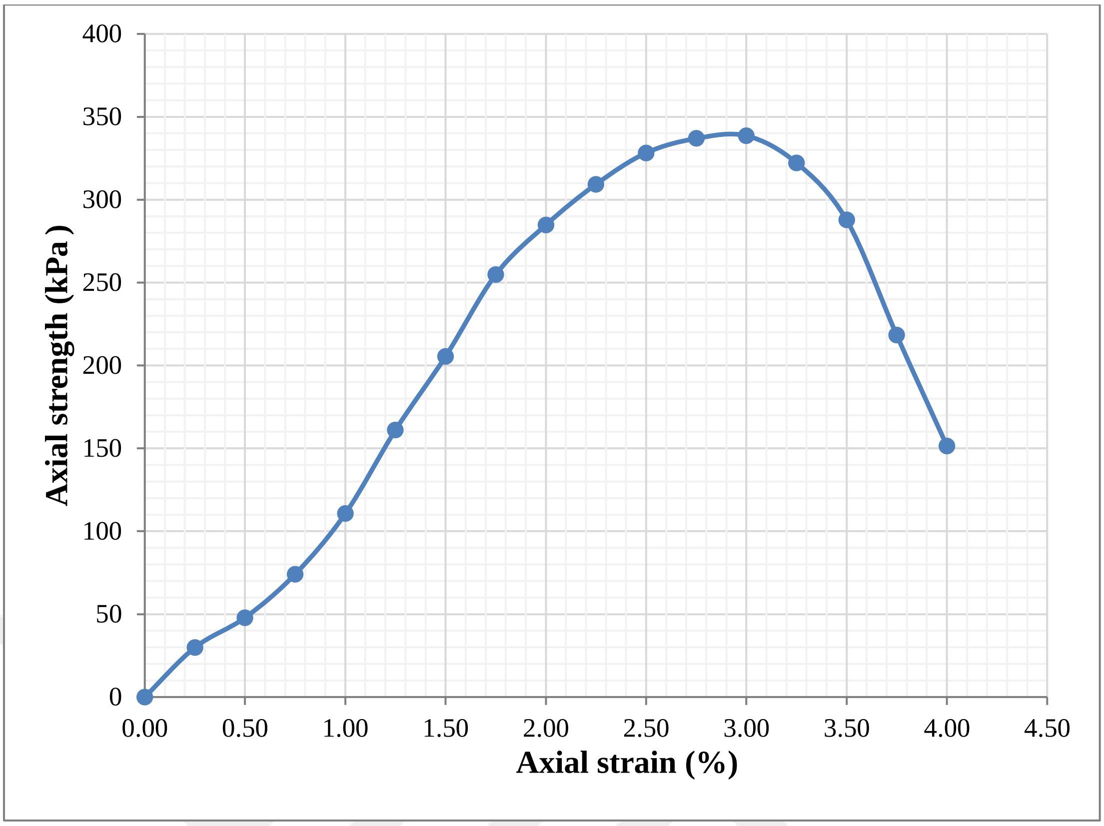

Figure C.45 : Result of the unconfined compression test of Dtm-10 mixed with 4% lime after 7 days curing (Sample 1).

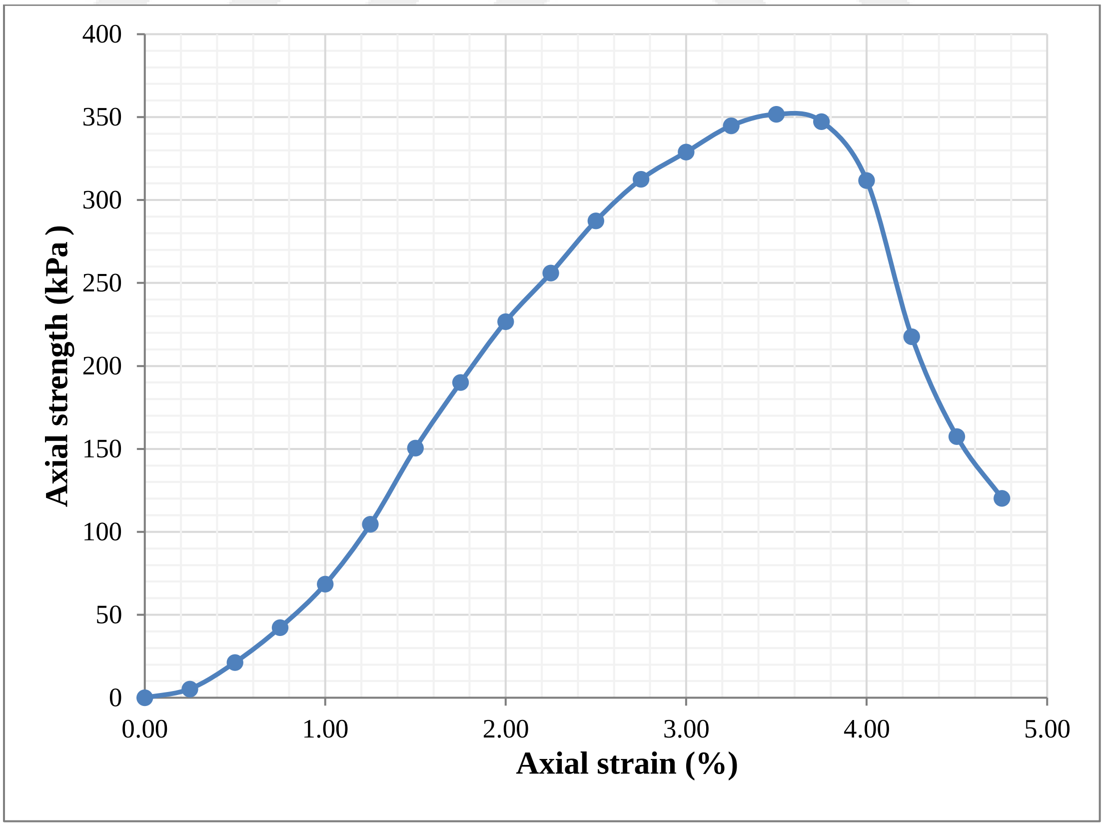

Figure C.46 : Result of the unconfined compression test of Dtm-10 mixed with 4% lime after 7 days curing (Sample 2).

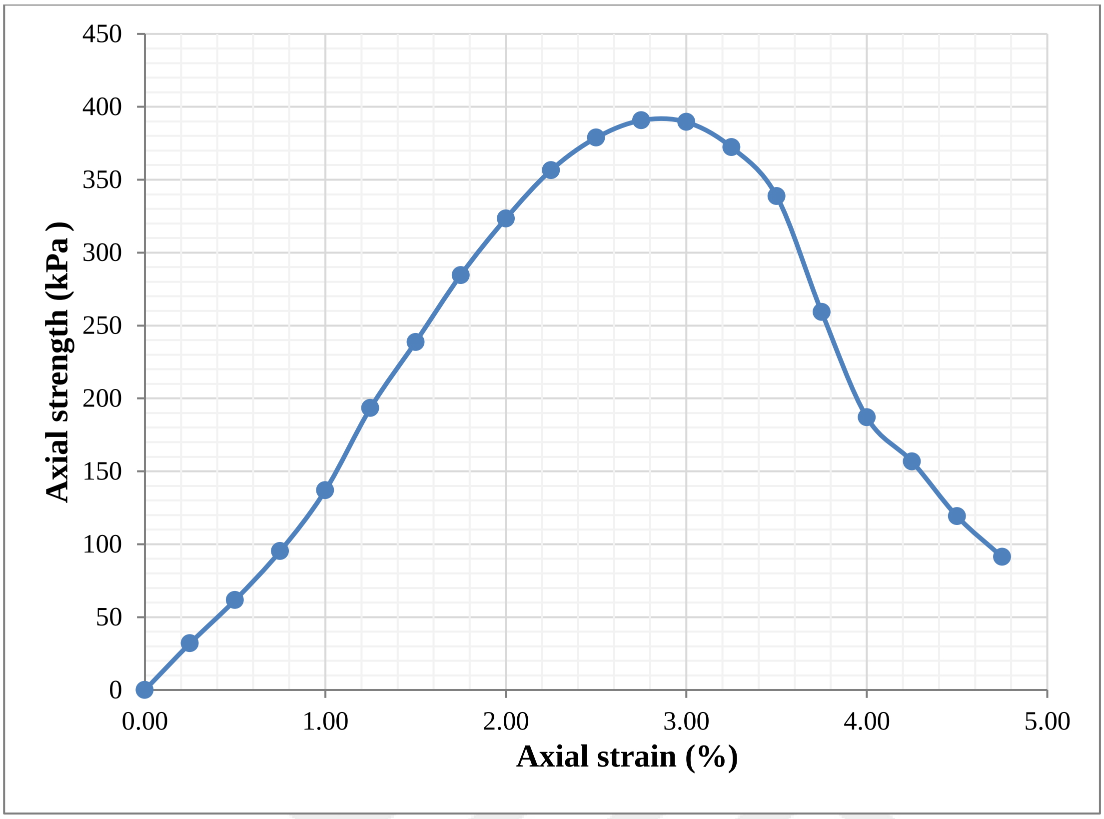

Figure C.47 : Result of the unconfined compression test of Dtm-10 mixed with 4% lime after 28 days curing (Sample 1).

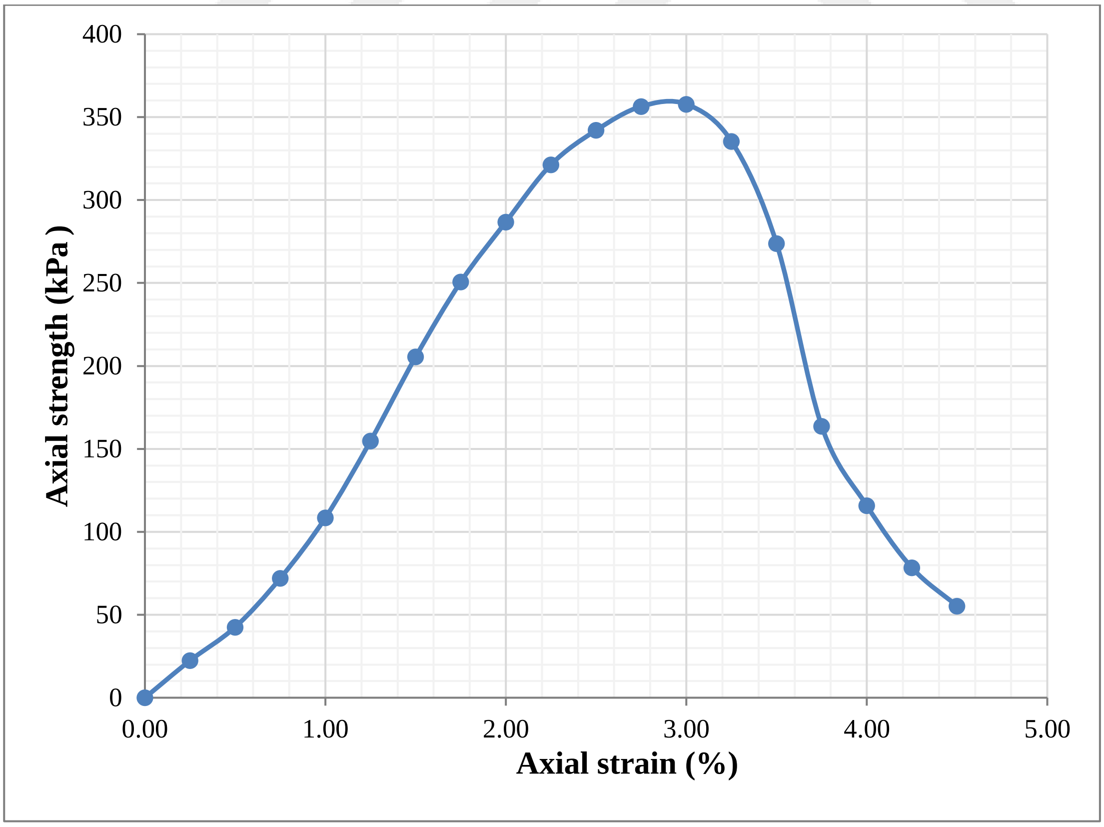

Figure C.48 : Result of the unconfined compression test of Dtm-10 mixed with 4% lime after 28 days curing (Sample 2).

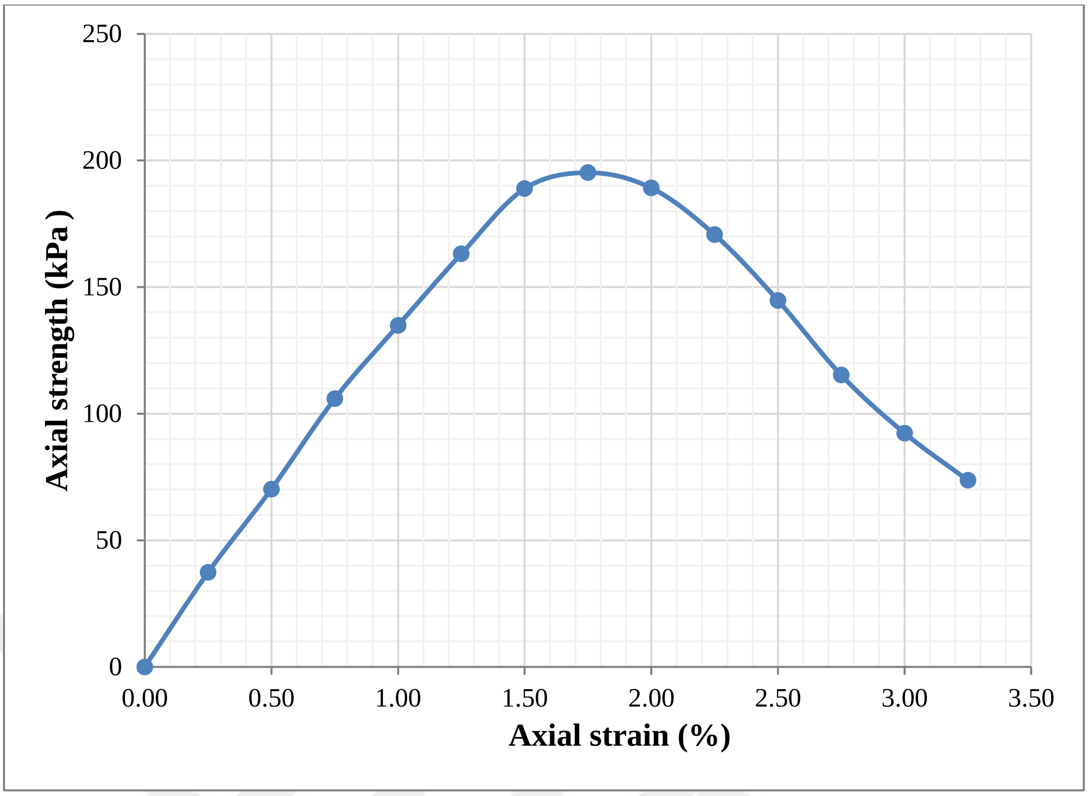

Figure C.49 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 1 day curing (Sample 1).

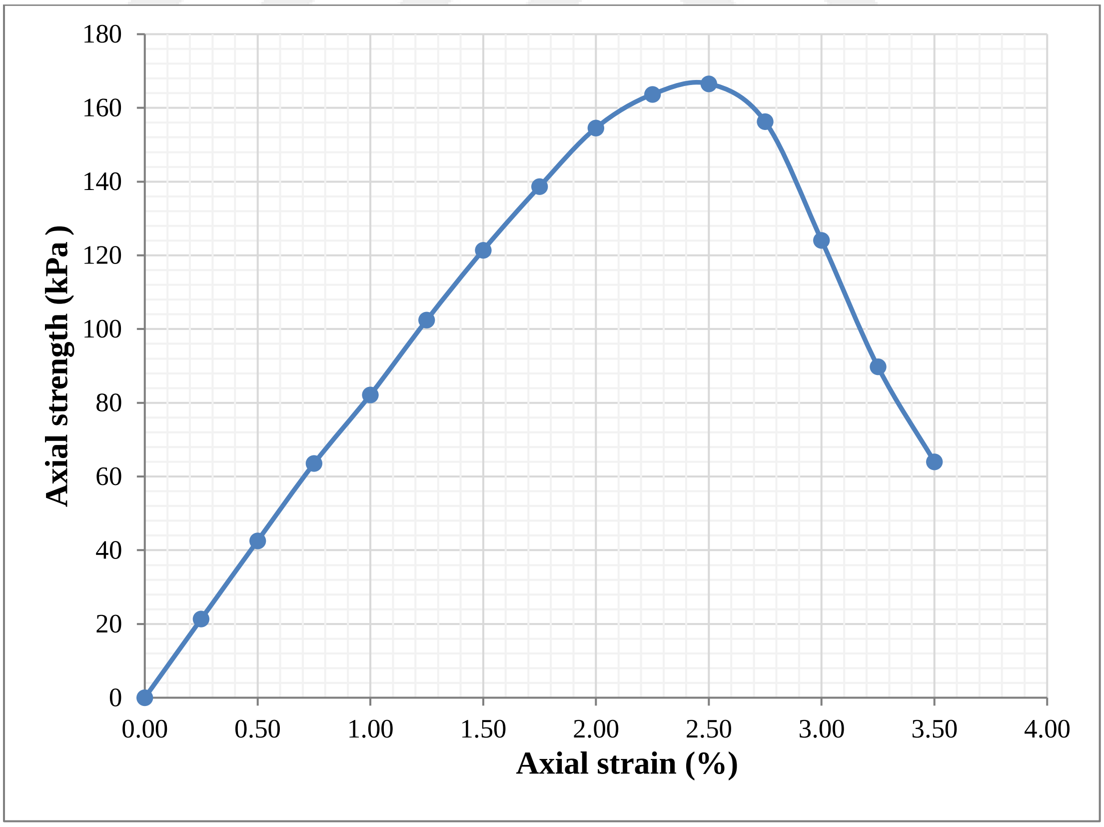

Figure C.50 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 1 day curing (Sample 2).

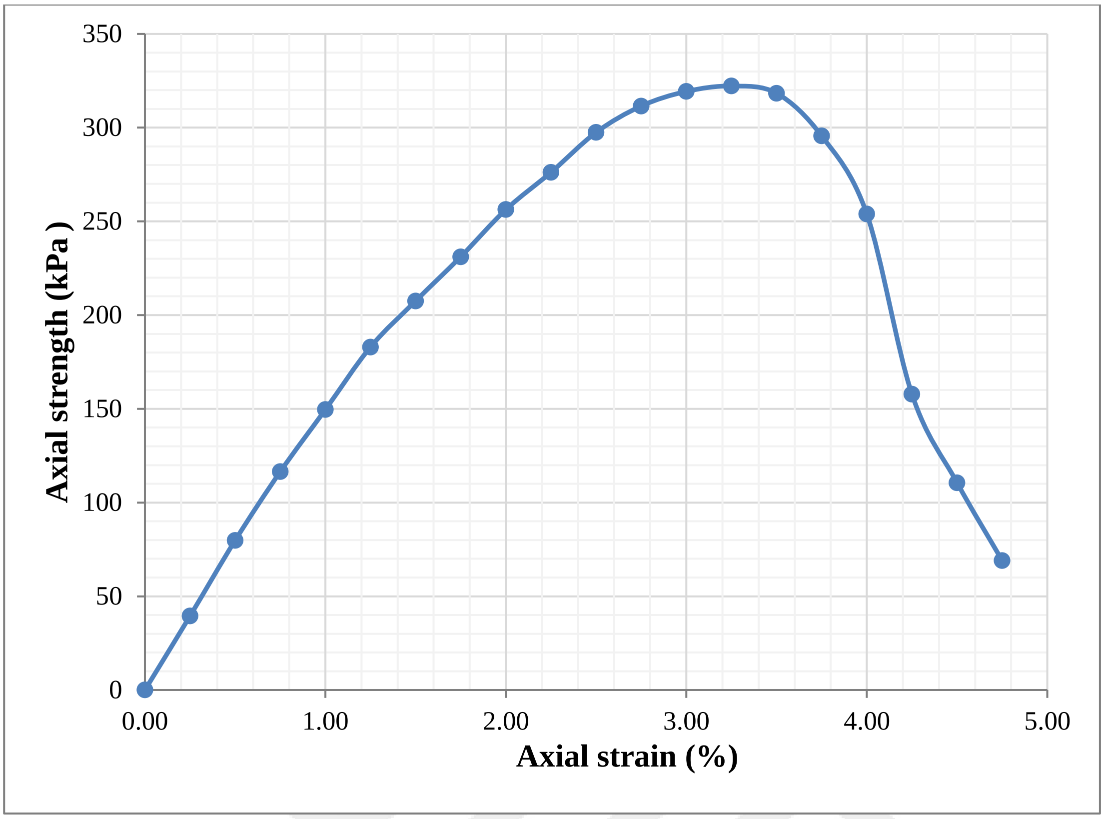

Figure C.51 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 7 days curing (Sample 1).

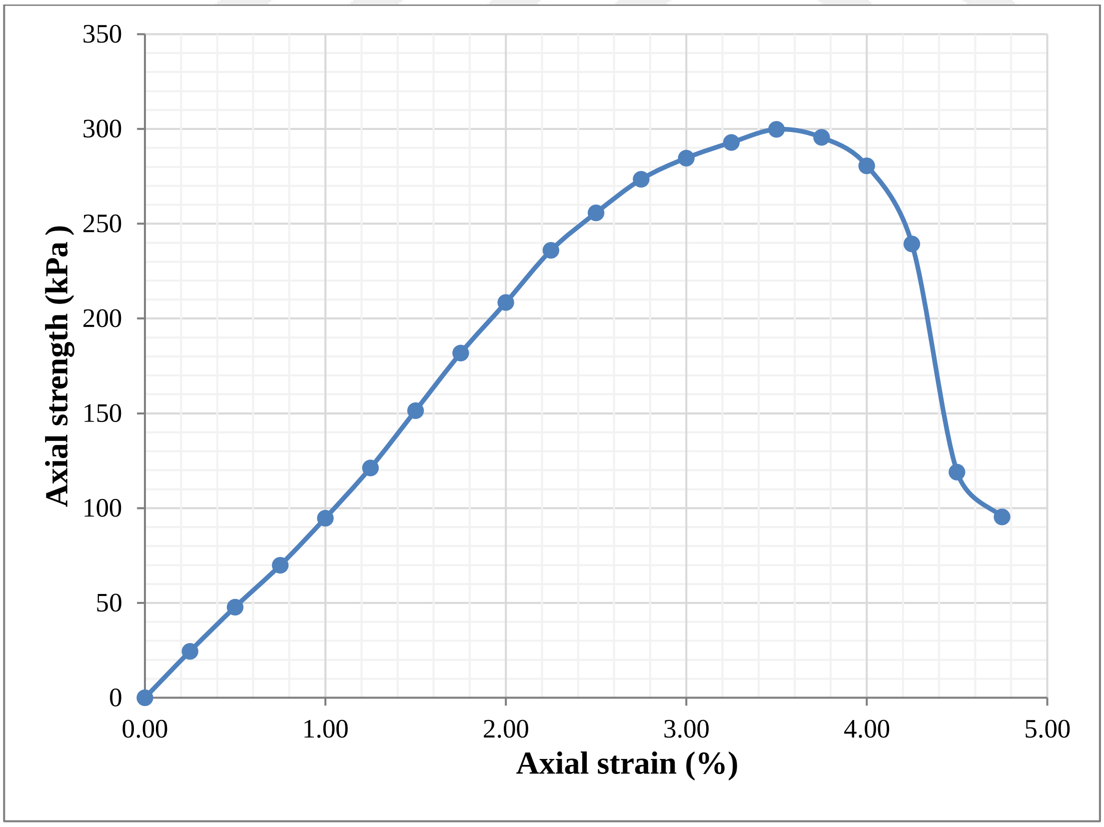

Figure C.52 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 7 days curing (Sample 2).

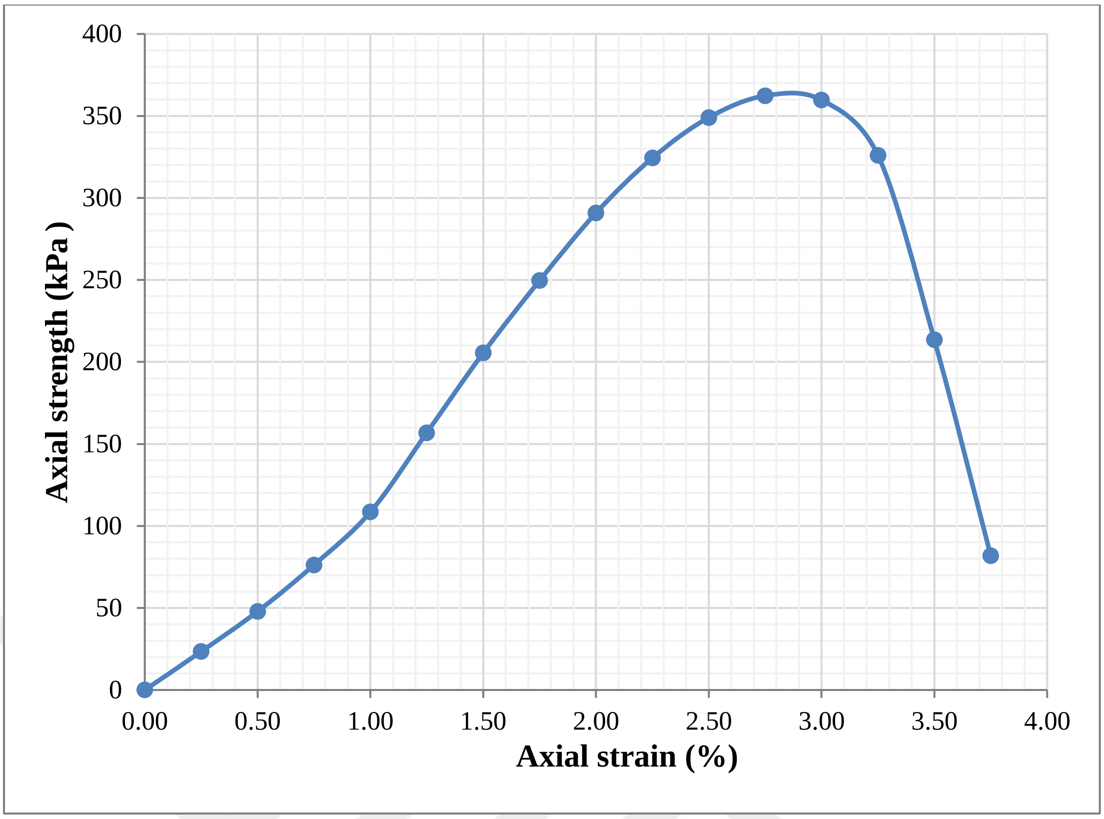

Figure C.53 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 28 days curing (Sample 1).

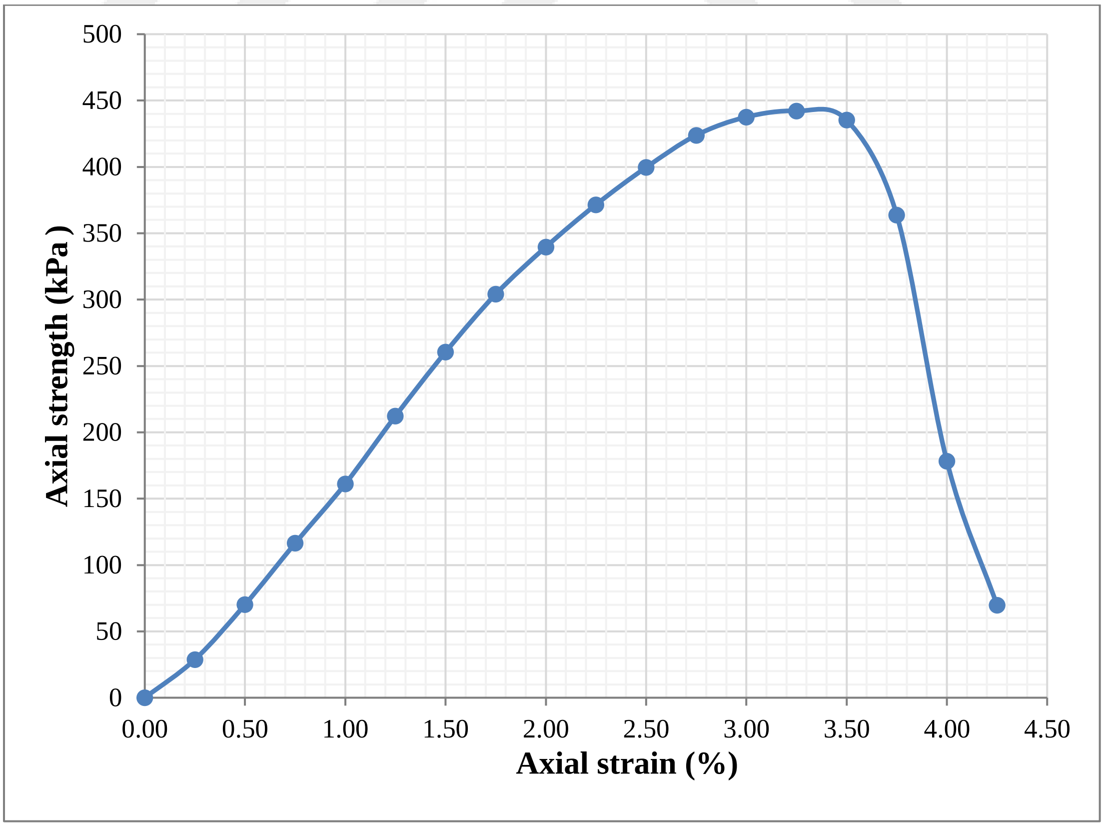

Figure C.54 : Result of the unconfined compression test of Dtm-10 mixed with 6% lime after 28 days curing (Sample 2).

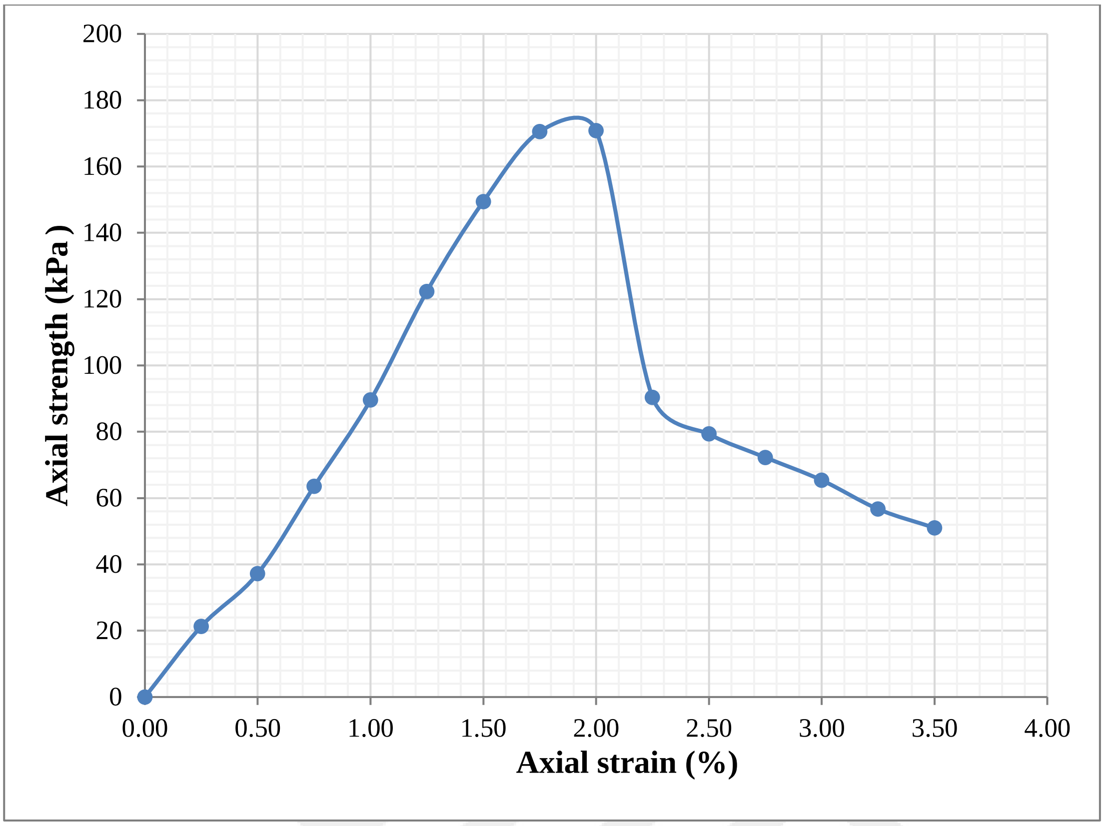

Figure C.55 : Result of the unconfined compression test of Dtm-10 mixed with 5% cement after 1 day curing.

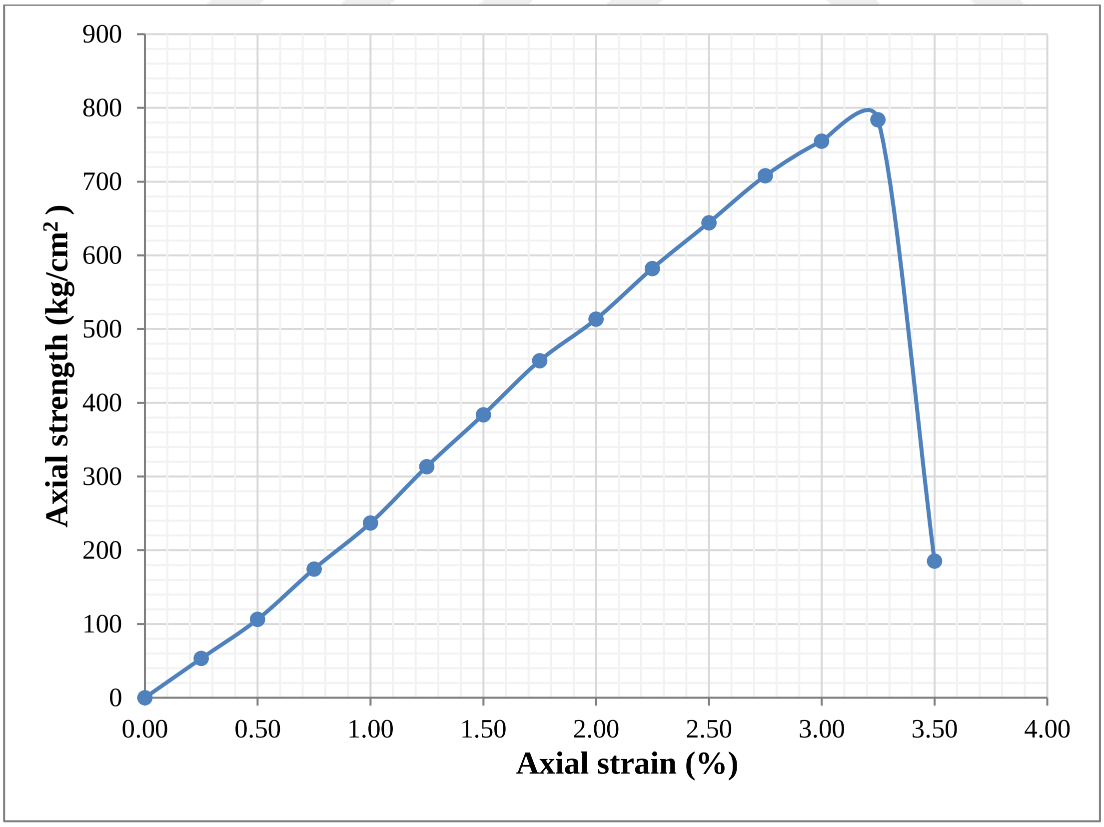

Figure C.56 : Result of the unconfined compression test of Dtm-10 mixed with 5% cement after 7 days curing (Sample 1).

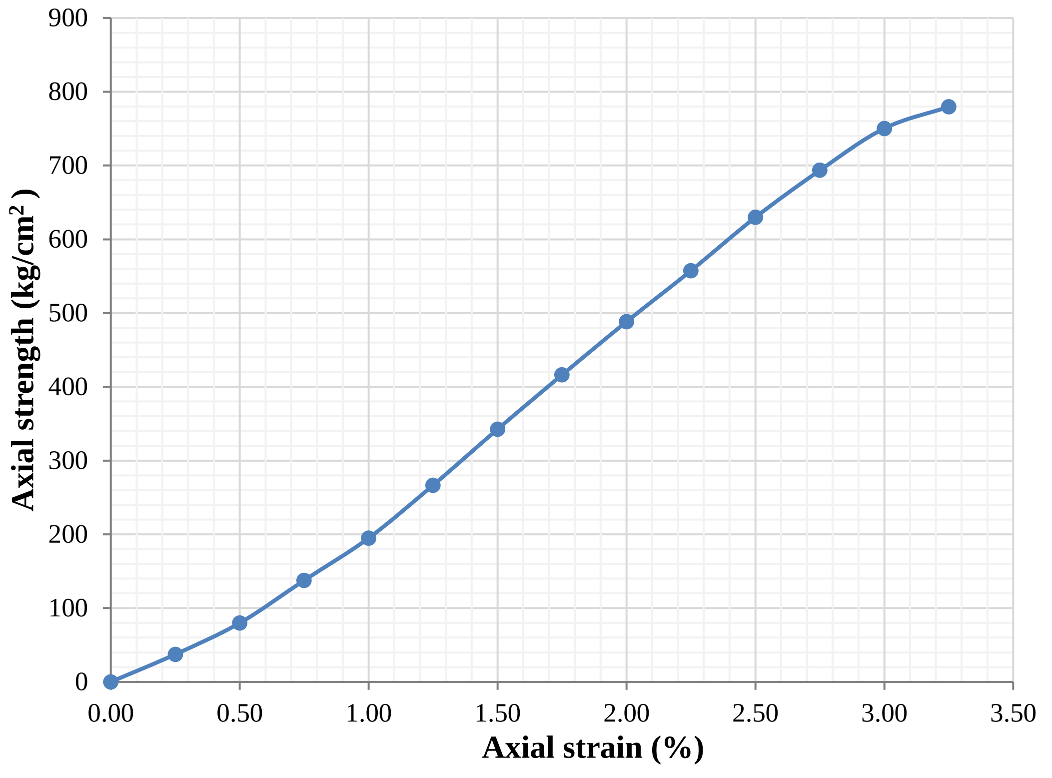

Figure C.57 : Result of the unconfined compression test of Dtm-10 mixed with 5% cement after 7 days curing (Sample 2).

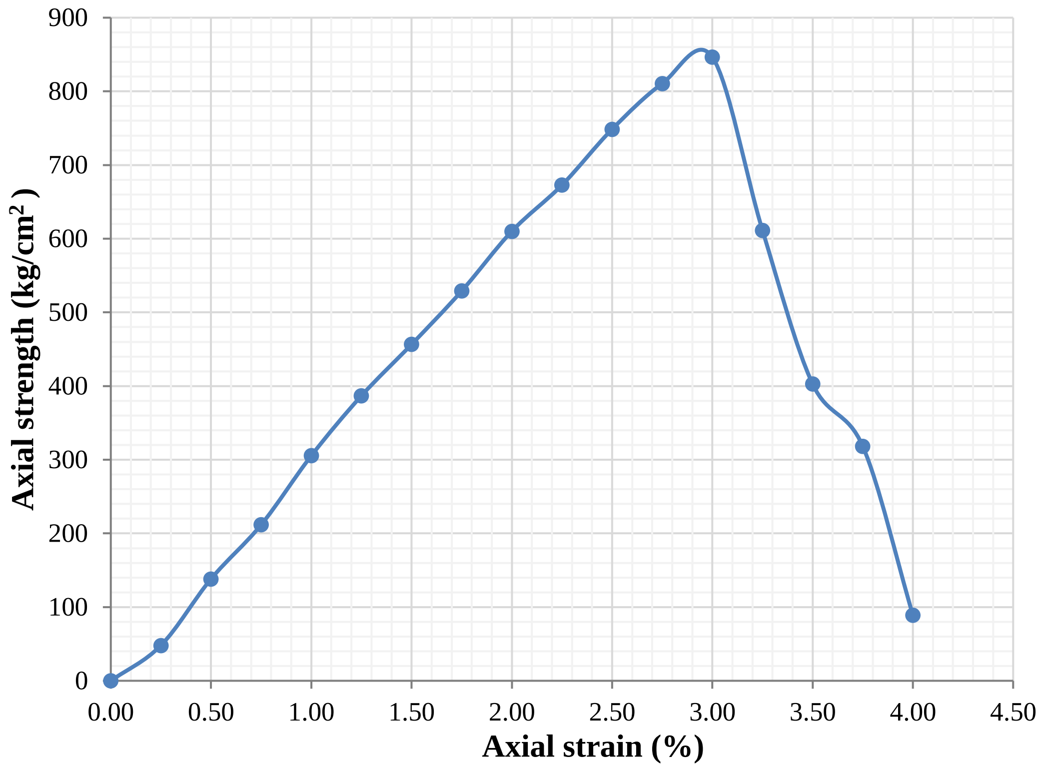

Figure C.58 : Result of the unconfined compression test of Dtm-10 mixed with 5% cement after 28 days curing (Sample 1).

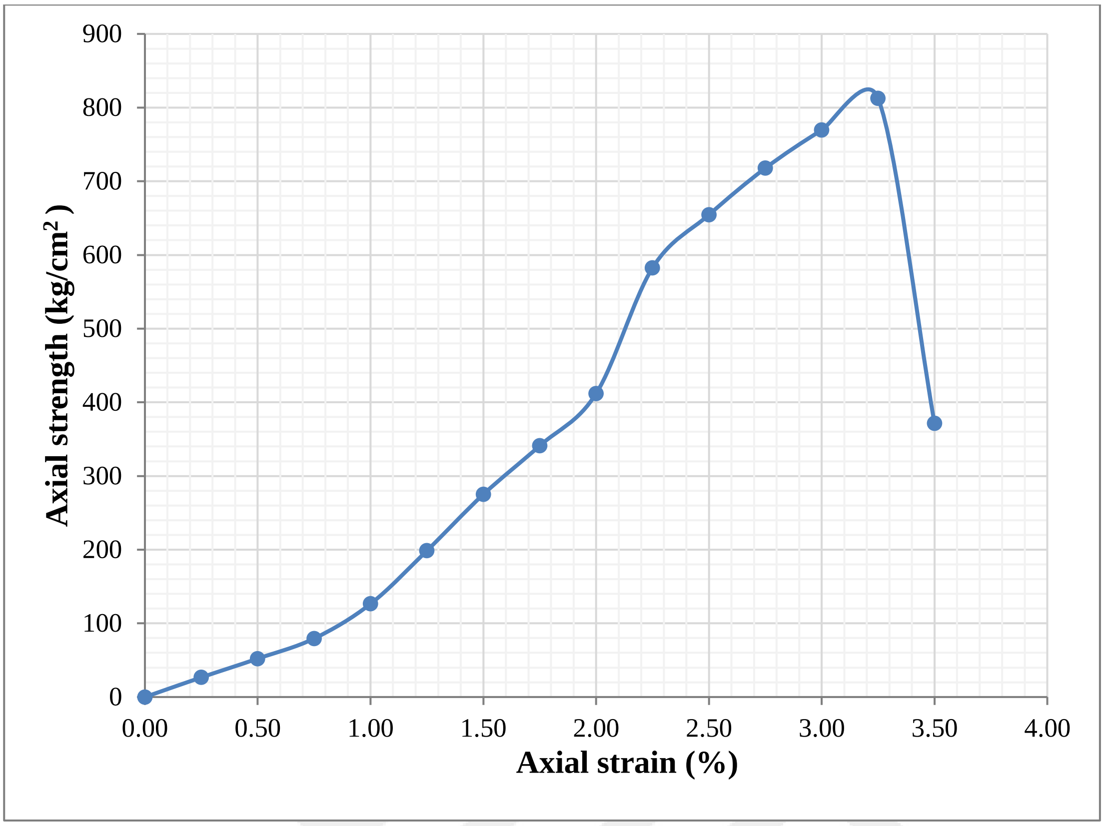

Figure C.59 : Result of the unconfined compression test of Dtm-10 mixed with 5% cement after 28 days curing (Sample 2).

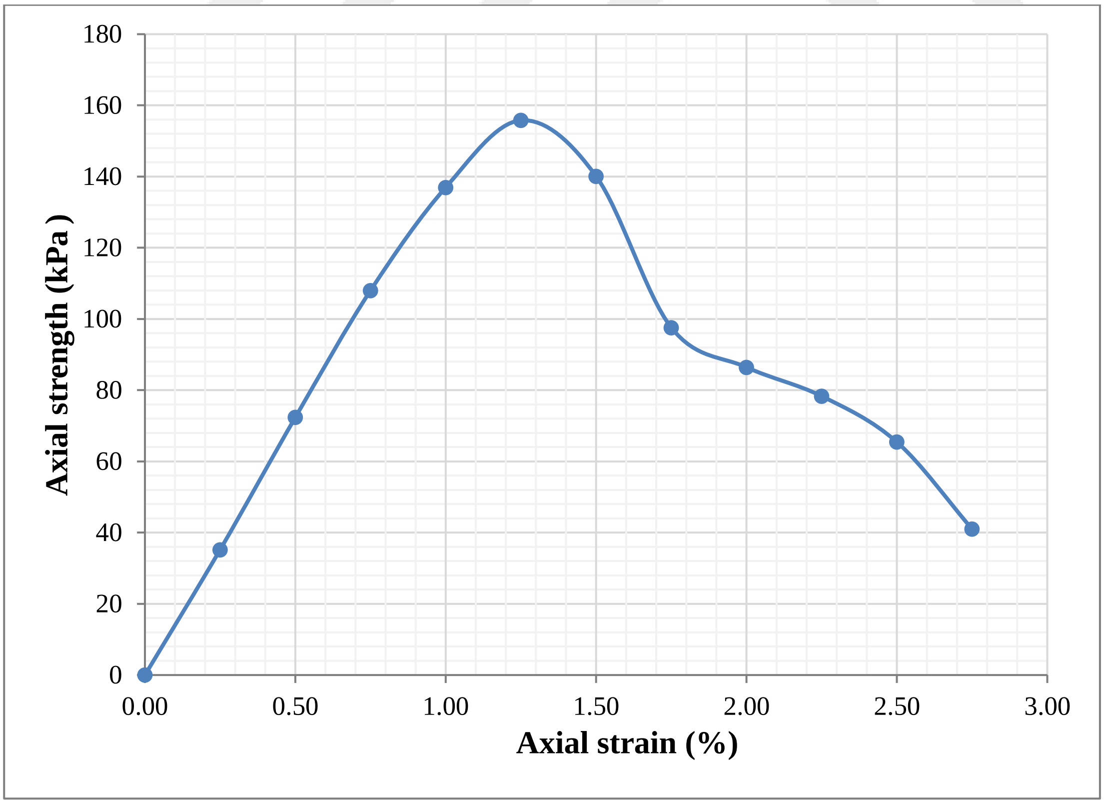

Figure C.60 : Result of the unconfined compression test of Dtm-10 mixed with 10% cement after 1 day curing.

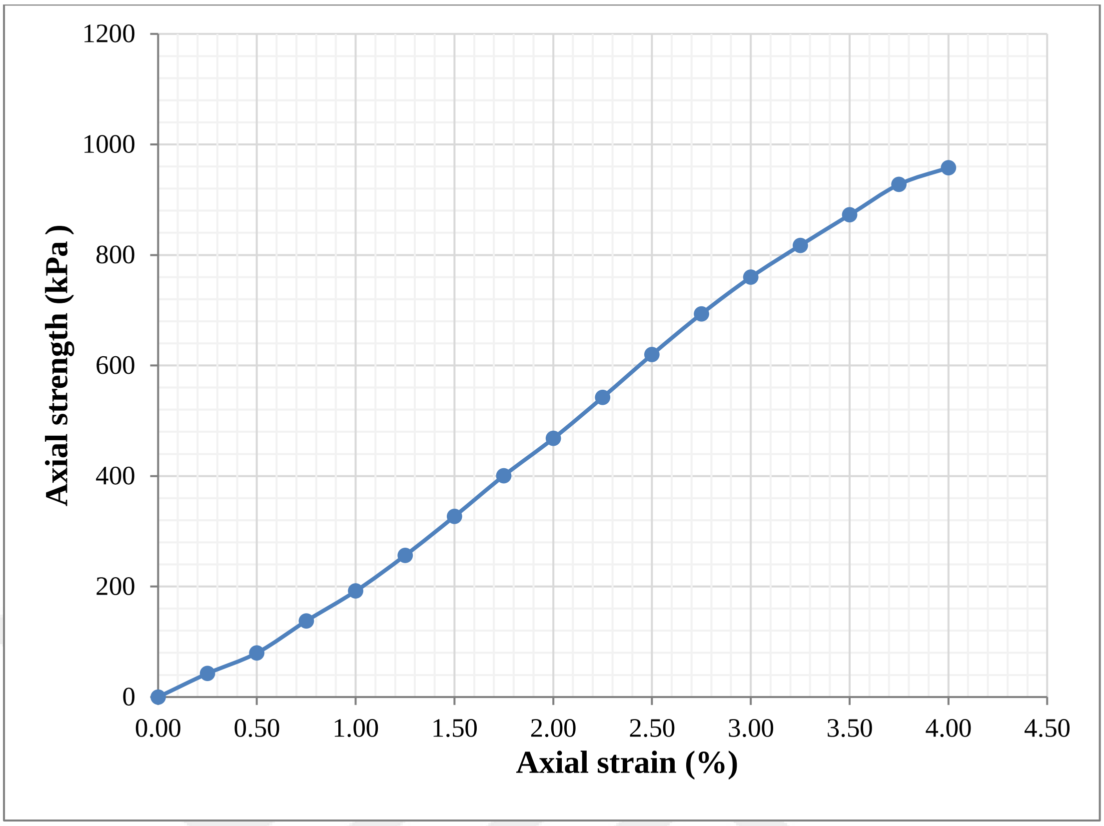

Figure C.61 : Result of the unconfined compression test of Dtm-10 mixed with 10% cement after 7 days curing (Sample 1).

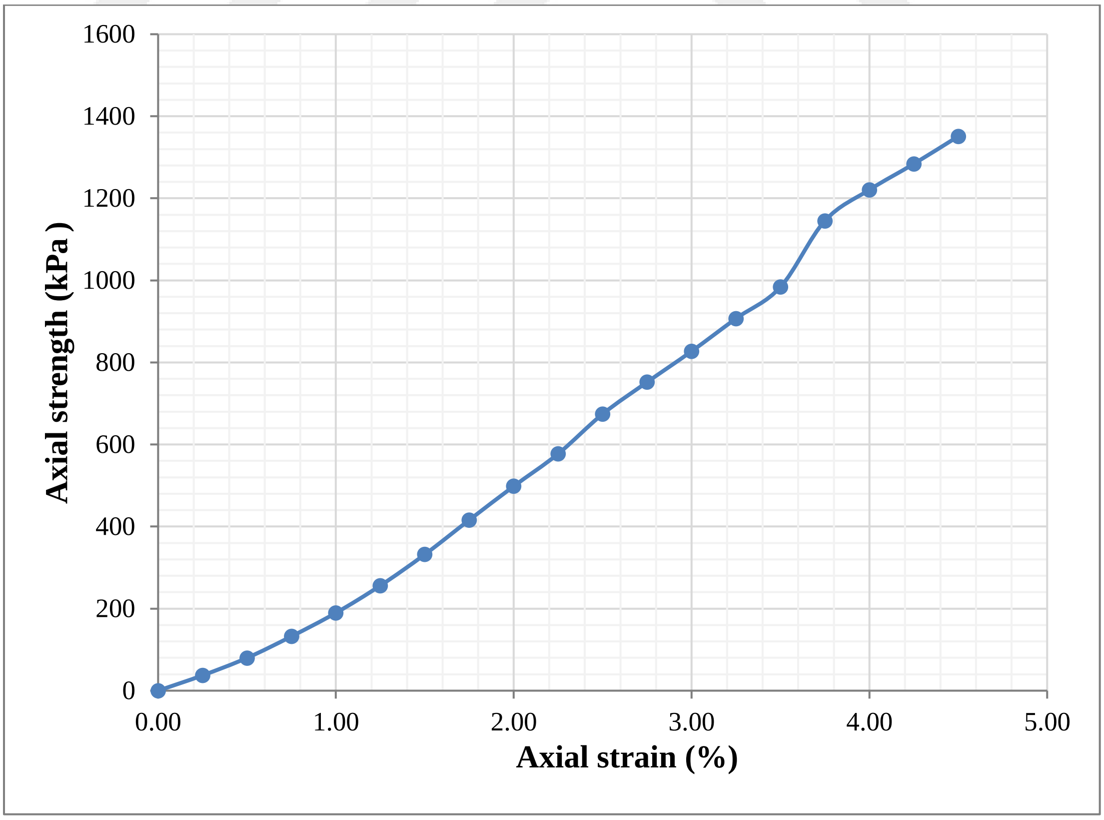

Figure C.62 : Result of the unconfined compression test of Dtm-10 mixed with 10% cement after 7 days curing (Sample 2).

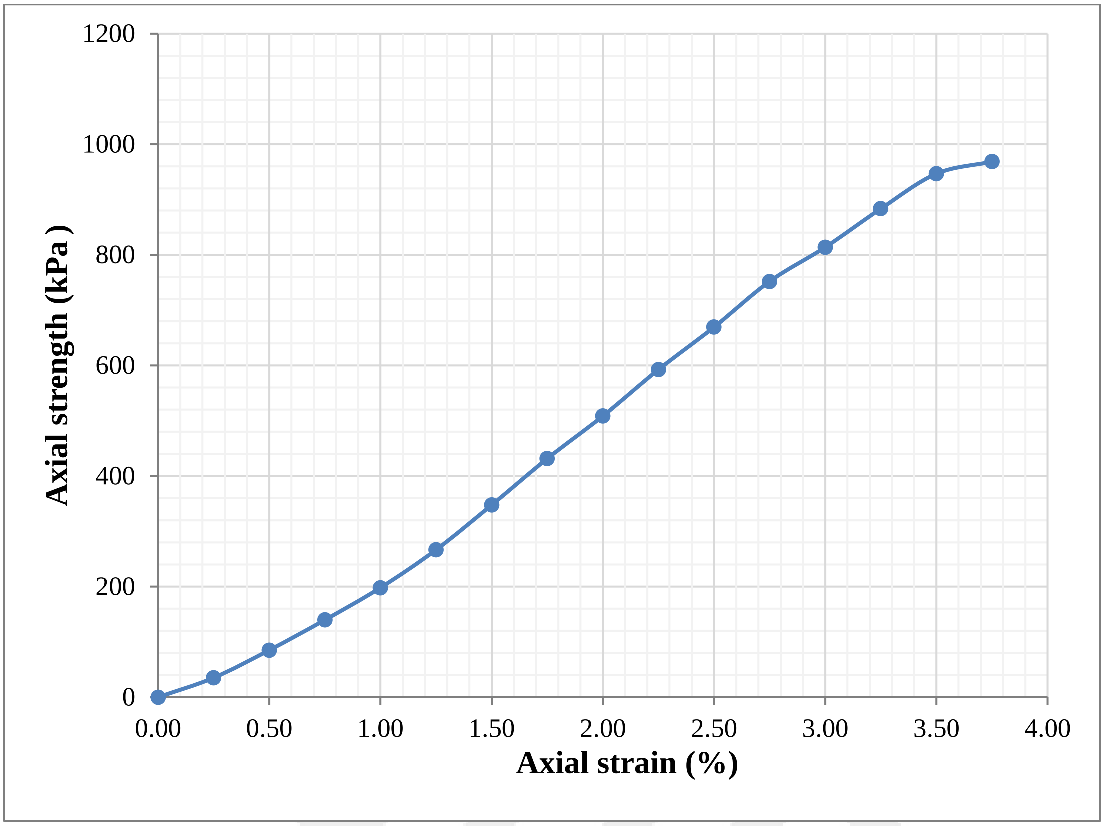

Figure C.63 : Result of the unconfined compression test of Dtm-10 mixed with 10% cement after 28 days curing (Sample 1).

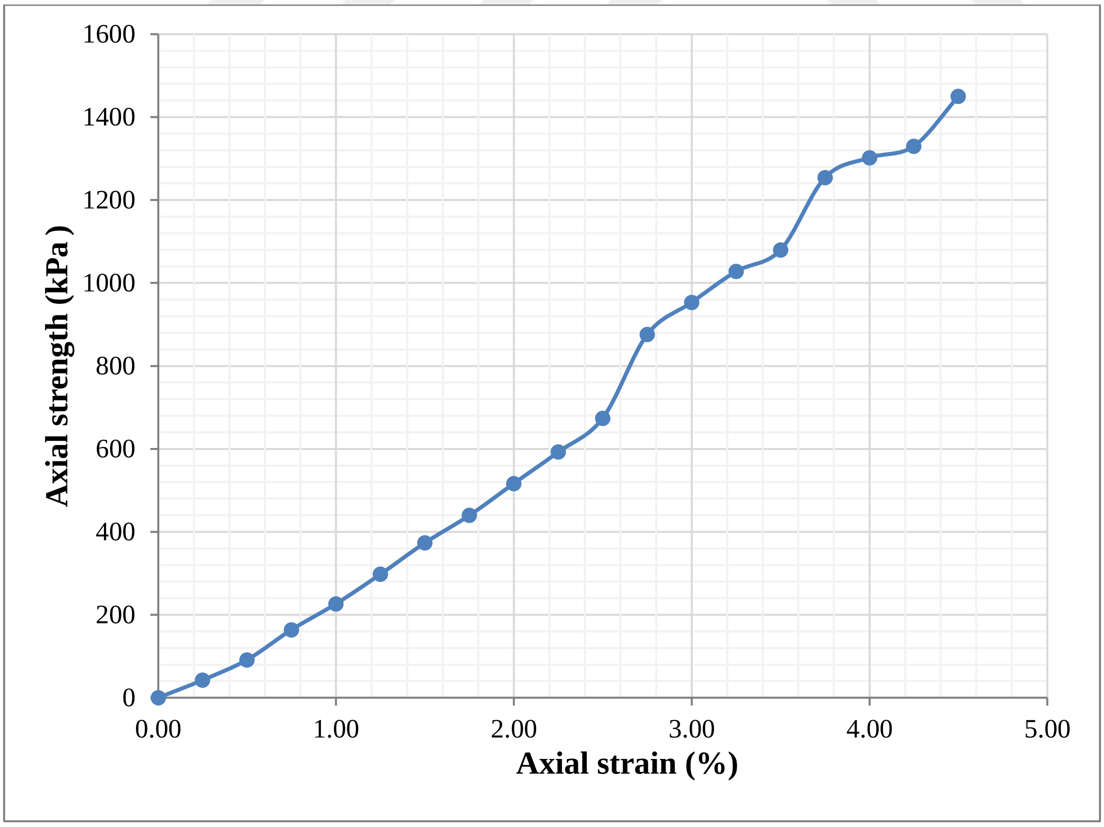

Figure C.64 : Result of the unconfined compression test of Dtm-10 mixed with 10% cement after 28 days curing (Sample 2).

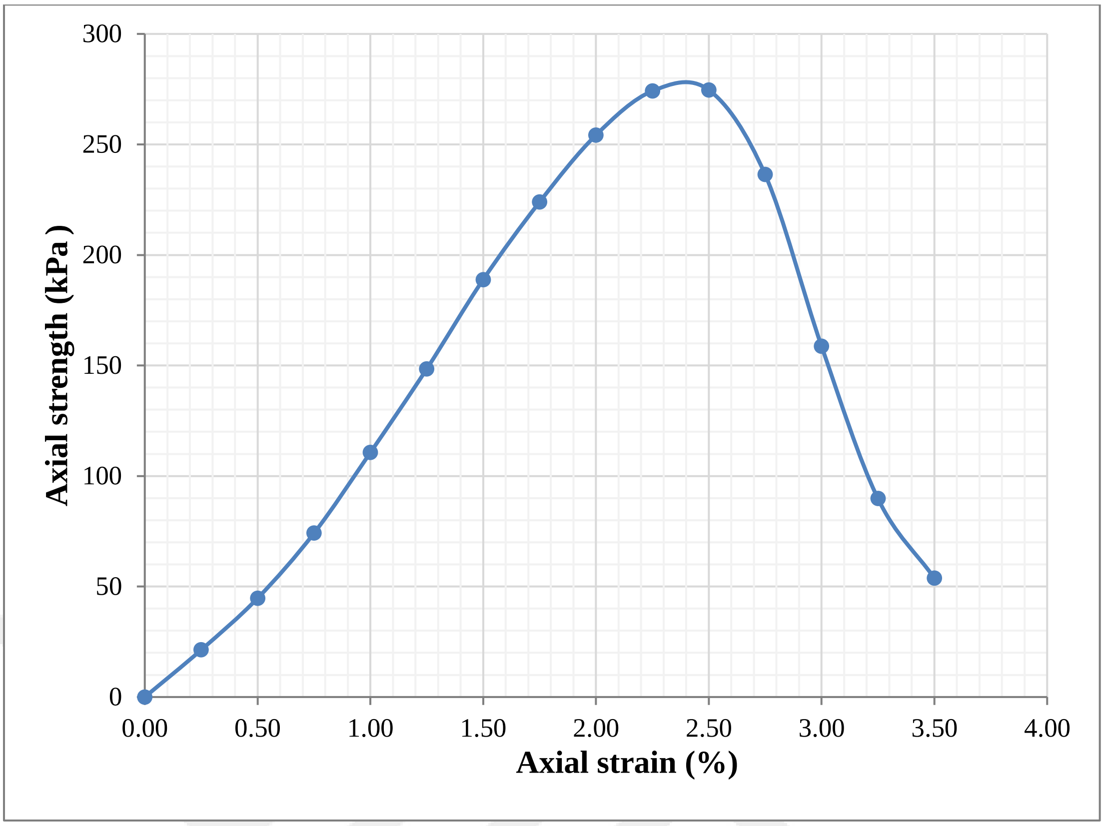

Figure C.65 : Result of the unconfined compression test of Dtm-10 mixed with 15% cement after 1 day curing (Sample 1).

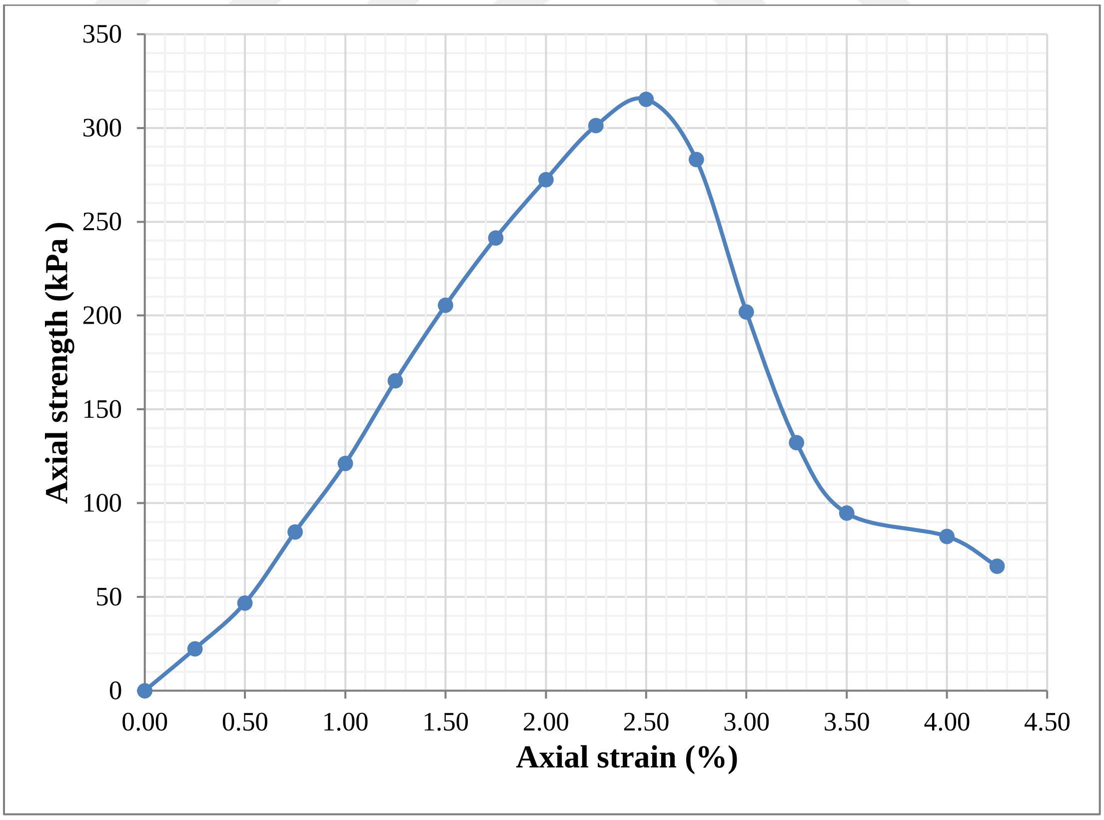

Figure C.66 : Result of the unconfined compression test of Dtm-10 mixed with 15% cement after 1 day curing (Sample 2).

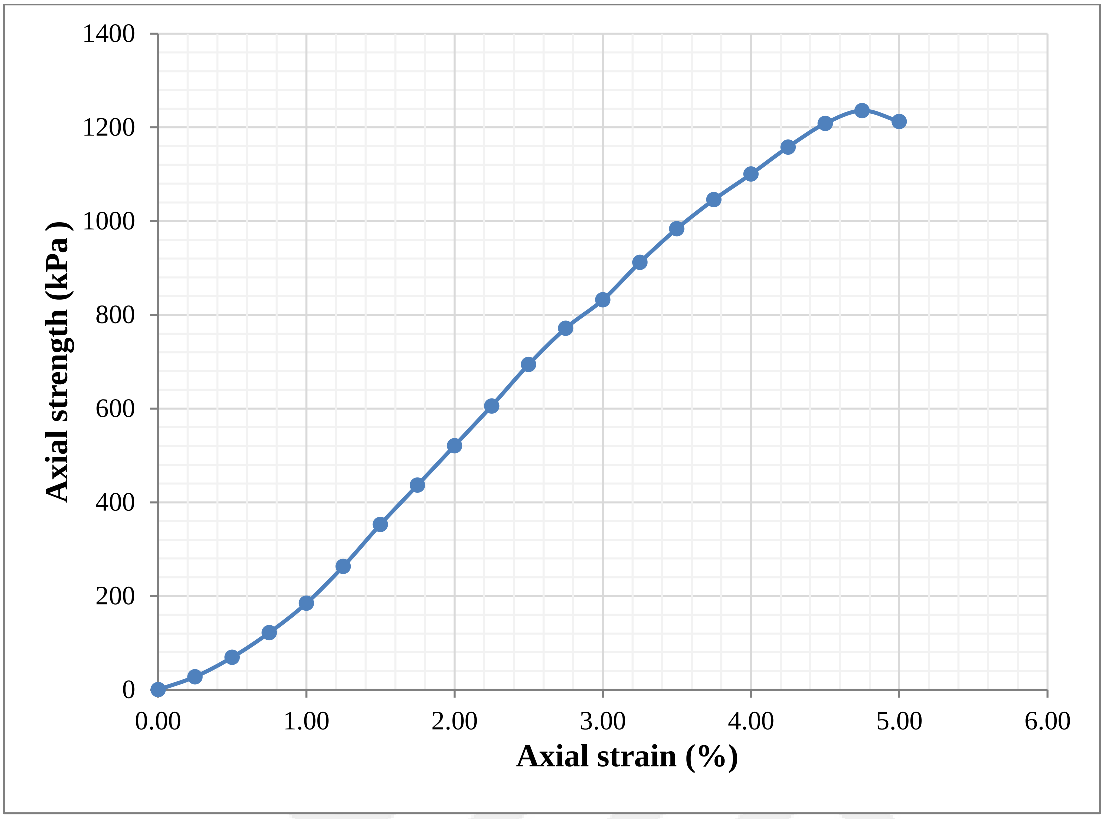

Figure C.67 : Result of the unconfined compression test of Dtm-10 mixed with 15% cement after 7 days curing (Sample 1).

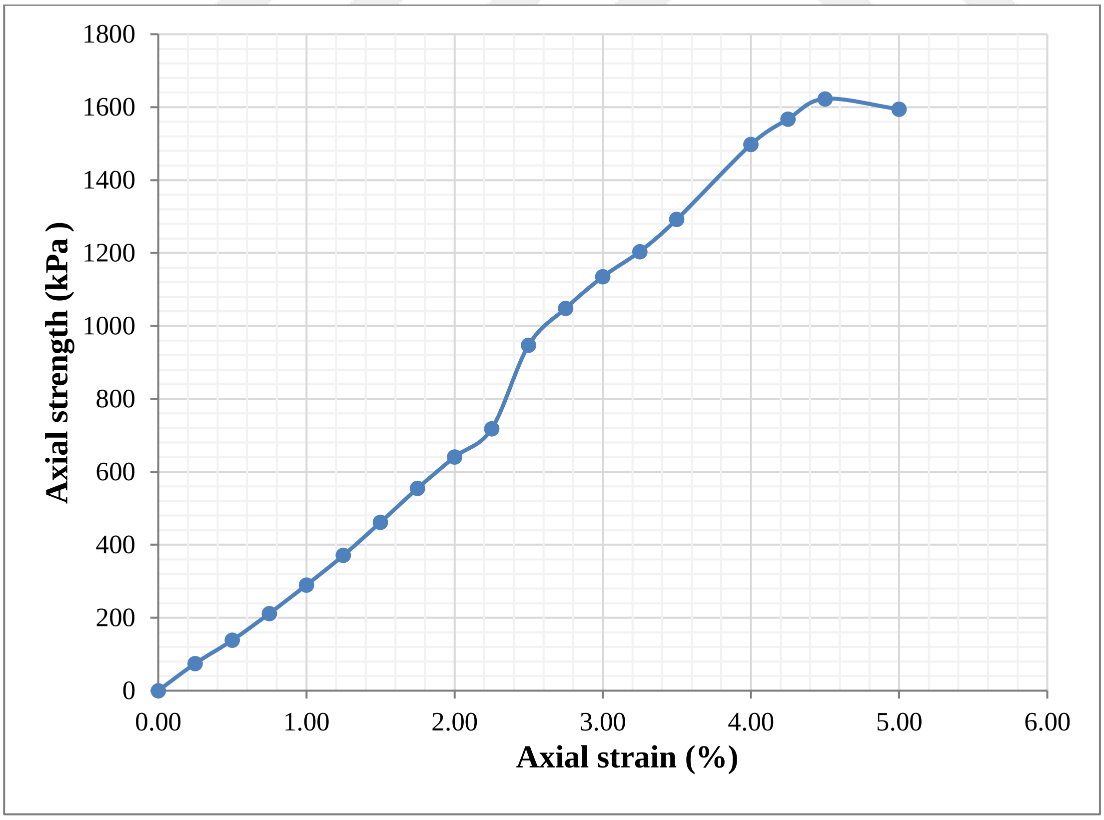

Figure C.68 : Result of the unconfined compression test of Dtm-10 mixed with 15% cement after 28 days curing (Sample 1)

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