A STUDY ON TENSILE STRENGTH OF COMPACTED ANKARA CLAY AND KAOLIN CLAY

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submitted by **VOLKAN DAĞAR** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver
Dean, Graduate School of **Natural and Applied Sciences** __________________

Prof. Dr. İsmail Özgür Yaman
Head of Department, **Civil Engineering** __________________

Prof. Dr. Erdal Çokça
Supervisor, **Civil Engineering Dept., METU** __________________

Examining Committee Members:

Prof. Dr. Sadık Bakır
Civil Engineering Dept., METU __________________

Prof. Dr. Erdal Çokça
Civil Engineering Dept., METU __________________

Prof. Dr. Seyhan Fırat
Civil Engineering Dept., Gazi University __________________

Asst. Prof. Dr. Nejan Huvaj Sarıhan
Civil Engineering Dept., METU __________________

Asst. Prof. Dr. Onur Pekcan
Civil Engineering Dept., METU __________________

Date: 14.08.2017

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ABSTRACT

A STUDY ON THE TENSILE STRENGTH OF COMPACTED ANKARA CLAY AND KAOLIN CLAY

Dağar, Volkan
M.Sc., Department of Civil Engineering
Supervisor: Prof. Dr. Erdal Çokça

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Tensile strength of clay, is a major mechanical parameter and is the main controlling parameter of tensile crack development which is generally encountered in geostructures. The researches to determine the tensile strength of clays are very limited.

There are two kinds of methods which are used to measure the tensile strength of soils and these are named as, indirect and direct methods. In this experimental study, a direct tensile test apparatus was developed for measurement and understanding of the tensile characteristics of compacted clay soil. Also, split tensile test was used as an indirect method to measure the tensile strength of compacted clay soil.

The clayey soil used in this study was collected from the Ankara, Turkey. Beside the tensile strength of Ankara Clay, the unconfined compression test on the same clay samples was also carried out. Tensile strength and unconfined compression test results were compared.

Clays have low tensile strength compared with the compressive strength and to improve the tensile strength properties, the clay soil needs to be stabilized. Stabilization of a clay soil improves its strength and other engineering properties. In this study, the tensile strength of stabilized clays were also tested. Within the scope of this thesis, to monitor the stabilization and improvement of the tensile strength of clay soil, laboratory test were performed on Ankara clay and Kaolin clay with addition of three different kind of materials and various proportions of bentonite. The materials were synthetic fiber, pulverized rubber and metal swarf.

It has been found from the experiments conducted that, the synthetic fiber were the only additive that improved the both split tensile strength and 8-shaped tensile strength. Adding pulverized rubber and metal swarf to the clayey soil did not cause any improvement nor on the tensile strengths neither on the unconfined compressive strengths.

The data between the results of 8-shaped direct tensile tests, indirect split tensile tests and unconfined compression tests were correlated. The ratio of 8-shaped tensile strength to split tensile strength and to unconfined compressive strength was calculated to be 1.9 and 0.4, respectively. Also, the ratio of split tensile strength to unconfined compressive strength was calculated to be 0.2.

Equations with coefficient of determination values of 0.90 and significance F values lower than 0.05, were developed according to the Ankara clay and Kaolin clay mixtures’ tensile strengths and index properties and were proposed to estimate the tensile strength of fine-grained soils from their index properties.

Keywords: Tensile strength of clay, Split tensile strength, 8-Shaped tensile strength, Synthetic fiber, Ankara clay

ÖZ

SIKIŞTIRILMIŞ ANKARA KİLİ VE KAOLİN KİLİ'NİN ÇEKME DAYANIMI ÜZERİNE BİR ÇALIŞMA

Dağar, Volkan
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Erdal Çokça

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Kilin çekme dayanımı, toprak yapılarda genellikle karşılaşılan ve gerilmeler sonucu oluşan çatlakların, gelişimini kontrol eden, önemli bir mekanik parametredir. Killerin düşük çekme dayanımını ölçmek için yapılan araştırmalar oldukça az sayıdadır.

Zeminin çekme dayanımını ölçmek için kullanılan, dolaylı ölçüm ve doğrudan ölçüm yöntemi olarak adlandırılmış, iki tür yöntem vardır. Bu çalışmada, sıkıştırılmış killi zemin numunesinin çekme dayanımına dair özelliklerinin ölçülmesi ve anlaşılması için bir doğrudan ölçüm deneyi ekipmanı geliştirilmiştir. Ayrıca, sıkıştırılmış killi zemin numunesinin çekme dayanımının ölçülmesinde dolaylı ölçüm yöntemi olarak silindir yarma deneyi kullanılmıştır.

Bu çalışmada kullanılan killi zemin numunesi Ankara'dan temin edilmiştir. Aynı kil numuneleri üzerinde serbest basınç deneyleri de yapılmıştır. Çekme dayanımı deneyi ve serbest basınç deneyi sonuçları mukayese edilmiştir.

Killer, basınç dayanımıyla kıyaslandığında, daha düşük çekme dayanımına sahiptirler. Bu nedenle çekme dayanımı özelliklerinin geliştirilmesi için, kilin stabilize edilmesi gerekir. Stabilizasyon, kilin dayanımını ve diğer mekanik özelliklerini geliştirir. Bu çalışmada, stabilize edilmiş killerin çekme dayanımları da araştırılmıştır. Tez kapsamında, Ankara kili ve Kaolin kili numunelerine üç değişik malzeme ve farklı oranlarda bentonit katılmış ve bu katkı maddelerinin numuneler üzerindeki stabilizasyon etkileri gözlemlenmiştir. Kullanılan malzemeler sırasıyla, sentetik fiber, lastik tozu ve metal talaşıdır.

Yapılan deney sonuçlarına göre, sentetik fiber, kilin çekme dayanımı arttırmayı başarabilen tek katkı maddesi olmuştur. Lastik tozu ve metal talaşı katkısı çekme dayanımı üzerinde veya serbest basınç dayanımı üzerinde arttırıcı bir etki göstermemiştir.

8-şeklinde doğrudan çekme dayanımı deneyleri, silindir yarma deneyleri ve serbest basınç deneylerinden elde edilen sonuçlar birbirleri ile ilişkilendirilmiştir. 8-şekilli çekme dayanımının, silindir çekme dayanımına ve serbest basınç dayanımına oranı, sırasıyla, 1.9 ve 0.4 olarak hesaplanmıştır. Ayrıca, silindir çekme dayanımın, serbest basınç dayanımına oranı 0.2 olarak hesaplanmıştır.

Belirleme katsayısı değerleri 0.90 olan ve anlamlılık seviyesi 0.05'den düşük olan denklemler Ankara kili ve Kaolin kili karışımlarının çekme dayanımlarına ve indeks özelliklerine göre geliştirilmiş ve ince taneli zeminlerin çekme dayanımlarını, indeks özelliklerinden hesaplamak için önerilmiştir.

Anahtar Kelimeler: Killerin çekme dayanımı, Silindir yarma deneyi, 8-Şeklinde çekme dayanımı deneyi, Sentetik fiber, Ankara kili

"Unfortunately, soils are made by nature and not by man, and the products of nature are always complex… As soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist. Natural soil is never uniform. Its properties change from point to point while our knowledge of its properties are limited to those few spots at which the samples have been collected. In soil mechanics the accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field."

- Karl von Terzaghi (1883-1963)

This thesis is dedicated to my beloved family.

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SYMBOLS AND ABBREVATIONS

Gs	Specific Gravity
LL	Liquid Limit
PL	Plastic Limit
SL	Shrinkage Limit
PI	Plasticity Index
CC	Clay Content
γ_{dmax}	Maximum Dry Density
w	Water Content
w_{opt}	Optimum Water Content
q_u	Unconfined Compressive Strength
σ_{t_8}	8-Shaped Direct Tensile Strength
$\sigma_{t_{split}}$	Split Tensile Strength
T_{max}	Maximum Tensile Load
P	Compressive Load on Cylinder
D	Diameter of Cylindrical Specimen
L	Length of Cylindrical Specimen
A	Cross Sectional Area
R^2	Coefficient of Determination

CHAPTER 1

INTRODUCTION

The tensile strength of soil have generally been considered to be zero or it is considered to be insignificant compared to the soils' compressive or shear strength. The general idea that the soils' tensile strength is insignificant, originates from the relatively low value of the tensile strength of soil and limited geotechnical laboratory tests to measure it. Even though, the tensile strength of soil is ignored beside its compressive and shear strength, it is, without any doubt, an important parameter when designing a geostructure, because where cracks which are formed by the loss of the tensile strength exist, there is a great possibility of progressive geological problems like landslides in excavation, progressive erosion at river banks etc. So it is important to stabilize the fine-grained soil and improve its tensile strength properties.

Also the tensile strength related problems gains more importance when the geostructures made, involves fine-grained soils, because fine-grained soils are relatively more sensitive to any environmental changes like, temperature changes, rainfall induced moisture content changes or applied compaction energy.

In common geotechnical engineering literature, researchers have classified methods of determining the tensile strength of soils into two categories; direct methods and indirect methods.

In the case of direct methods, a new test setup and addition to the new test set up, new methodologies should be considered.

As it can be referred from the method’s name, in direct methods, applying uniaxial tensile loads is the common way to determine the tensile strength of soil. The tensile load is applied to the ends of soil specimen therefore this kind of tests are most commonly used to obtain tensile strength. Also, the tensile strength can be obtained without any correlation needed.

In the indirect methods, on the other hand, correlations should be developed between different parameters to determine the tensile strength of soil. These developed correlations might be between the suction characteristics, moisture content, index properties, unconfined compressive strength etc. and the tensile strength of soil. Also, in indirect methods, the tensile strength, most commonly is obtained by splitting specimens under compression loads and these applied compression loads are assumed to distribute uniformly on the failure plane. Tamrakar et al. (2005), stated that, in the past, the limitations in the indirect test methods led the researchers to conduct experiments on stiff and highly compacted brittle materials rather than on soft and wet fine-grained clayey soils. Nowadays, these limitations are no longer valid and indirect methods are commonly used for measuring the tensile strength of fine grained soils.

In this experimental study, a direct tensile strength test setup was developed to measure and investigate the tensile strength characteristics of compacted Ankara clay and Kaolin clay soils. This test was called “8-shaped tensile strength test” since a special 8-shaped compaction mold and a piston with a neck section were used. Also as an indirect method, to investigate the correlations between the direct methods, split tensile test (Brazilian Test) was used. Beside the tensile strength tests, unconfined compression tests were also performed on specimens.

Since the aim of this experimental investigation was to study the effects of waste materials on the tensile strength of Ankara clay and Kaolin clay, the soils were tried to stabilize by using synthetic fiber, metal swarf and pulverized rubber, and bentonite was used as an additive.

By using the both developed direct tensile strength method, split tensile test and unconfined compression test, a series of tests were carried out on stabilized soils. This kind of fiber reinforcement or reinforcement with additives is a relatively new method to stabilize and improve soils' mechanical properties and it is a commonly used way by researchers to improve soils' tensile strength characteristics. There are three advantages of using this kind of fiber reinforcement on soils; (1) Fibers either it is synthetic fiber, metal swarf or pulverized rubber etc. can be simply mixed randomly with soils, (2) To distribute the fibers randomly limits the potential planes which weakness might be occur, (3) The addition of fiber and additives only have effect on the physical properties of soil and does not cause any impact on environment.

In the experimental study, which was performed during the thesis period, thirteen different mixture designs were used, this includes the mixtures designs on both Ankara clay and Kaolin clay samples. For every mixture design, the tensile strength test, unconfined compression tests, index property tests, sieve analysis and hydrometer tests were performed. The experiments conducted on samples which were compacted 95% of their dry density and corresponding wet of optimum moisture contents. The results that were obtained from 8-shaped tensile test, split tensile tests and unconfined compression tests are visualized for better understanding of the results found. Correlations between 8-shaped tensile strength-split tensile strength, 8-shaped tensile strength-unconfined compressive strength and split tensile strength-unconfined compressive strength were developed to understand the difference in proposed tensile strength measurement methods.

Empirical equations according to the Ankara clay and Kaolin clay mixtures' tensile strengths and index properties were developed and proposed to estimate the tensile strength of fine-grained soils from their index properties.

This thesis consist of 5 parts. In first chapter, an introduction is made for better understanding of the upcoming parts. Second and third chapter includes a literature review and materials used in the scope of thesis along with the procedures of the tensile tests which were conducted, respectively. Fourth chapter includes the results and discussion of the experimental investigation. The last chapter consists of general conclusions and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1. Tensile Strength of Soils

The tensile strength of soils, generally, is not considered or is ignored by most of the engineers when typical geotechnical engineering problems are examined. Even though, it is commonly ignored or assumed to be zero and insignificant, the tensile strength of soil plays a significantly influential role in the case of examination of, cracking in highway embankments, cores of dam embankments, landfill liners, landslides in excavations, riverbanks etc. A few important examples of tensile cracking are presented in Figure 2.1, Figure 2.2, Figure 2.3 and Figure 2.4. Figure 2.1 demonstrates a tensile crack which was observed at the top of a slope and this crack can be considered as a first sign of a landslide. In Figure 2.2, tensile cracks on a highway are illustrated. These cracks were formed by rainfall induced minor landslide on the highway embankment and further progress of these tensile cracks can cause significant dangers to the drivers who use the highway. Figure 2.3 demonstrates a tensile crack on a retaining wall which is made from reinforced soil. The tensile crack was formed very close to behind of the reinforced zone and caused the development of wall overturning because the water was flowing into this crack. This overturning process on the wall was observable from the shape of the reinforced part of the wall.

Figure 2.1. A crack formed by tension failure which has potential to cause a landslide (Adopted from www.hulldailymail.co.uk)

Figure 2.2. Cracks on a highway surface which are caused by rainfall induced minor landslide on the highway embankment (Adopted from www.codyenterprise.com)

Figure 2.3. A tensile crack behind reinforcement zone of a retaining wall which is made from reinforced soil (Vanicek, 2013)

Also an important attention was given to the tensile crack occurrence probability in the landfill liners and landfill capping systems. It has been stated that, the differential settlement of the deposited waste might cause a great possibility of tensile crack phenomenon. The tensile cracks which occur in the landfill liners and in the capping systems might cause great problems as the rainfall can leak through the tensile cracks on the capping and it might cause an increase in leachate composition. The tensile cracks in the liner, on the other hand, can cause the leachate to leak through to the groundwater and this situation might cause a great environmental pollution. In Figure 2.4, deformation on a landfill capping is illustrated. This deformation, is a result of local differential settlements and affects the functionality of capping system.

These examples mentioned points out the potential effects of the tensile cracking on geostructures. To eliminate the tensile crack induced problems, a great deal of attention should be given to improvement and stabilization of tensile strength characteristics of soils.

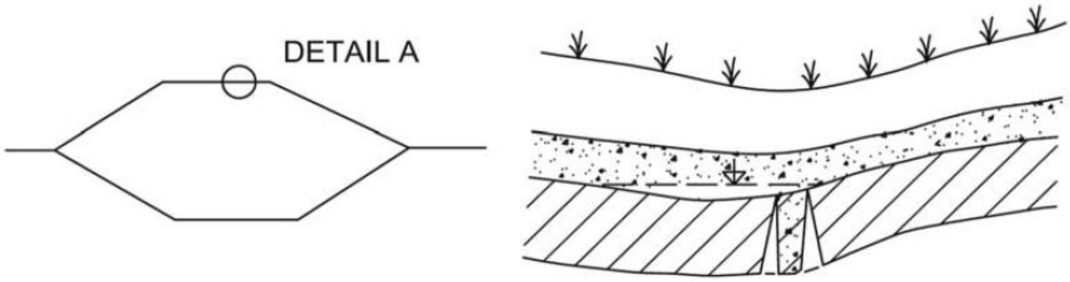


Figure 2.4. Deformation on a landfill capping system which is caused by local differential settlements (Vanicek, 2013)

2.2. Methods Used to Determine the Tensile Strength of Soils

In the existing literature, the tensile strength tests vary in different ways and there are different descriptions for the tensile strength tests that have been conducted. Even though, there is a correlation between the other soil mechanics test, for example compression and shear tests, when the tensile strength tests are considered such correlations cannot be found. The main classification can be made by classifying the principle of loading and the way that loading is applied to the specimen. According to the tensile strength classification there are two main categories for testing the soil for its tensile strength; 1) Direct methods and 2) Indirect methods. In Figure 2.5, a few commonly used tensile strength tests and their loading principles are illustrated. In Figure 2.6, Mohr's circles for the 8-shaped direct tensile test, indirect split tensile test and unconfined compression test which were used in this thesis study, are illustrated.

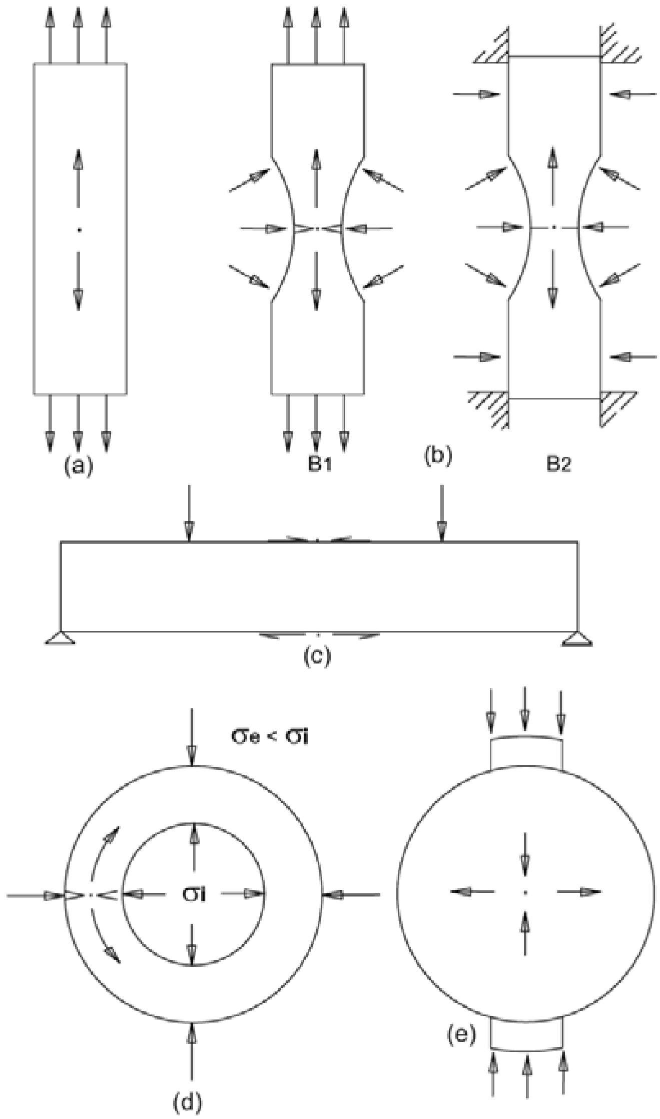


Figure 2.5. Tensile strength tests based on the loading principle. a) Direct tensile test. b) Triaxial tensile test. c) Bending test. d) Tensile testing on hollow cylinder. e) Split tensile test. (Vanicek, 2013)

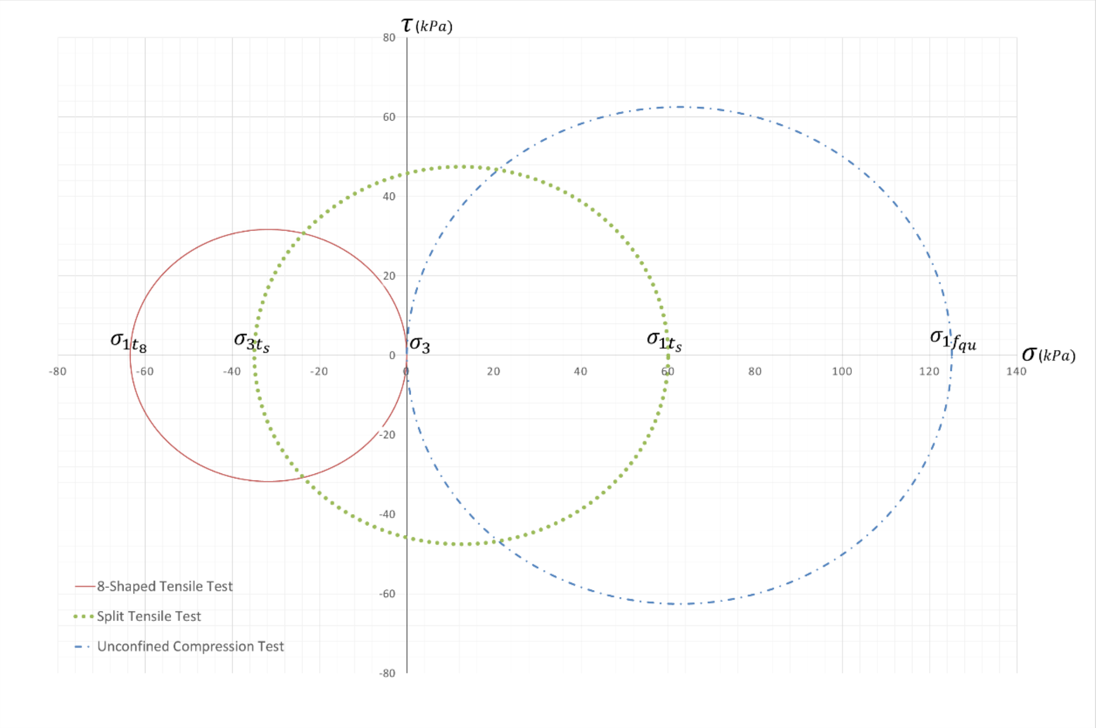


Figure 2.6. Mohr's circles for 8-shaped direct tensile test, indirect split tensile test and unconfined compression test

2.2.1. Direct Methods

Direct methods of tensile strength testing can be considered as uniaxial tensile tests. The load is applied directly to the ends of the soil specimen at the same time or the specimen is attached to a rigid piston and the tensile load is applied to the end of specimen until the tensile failure occurs. Depending on the testing device, the tensile load and the displacement that occurs in the specimen can be controlled. In the case of direct methods, new testing setups should be developed.

Zeh and Witt (2007), described a method for measuring the direct tensile strength of clayey soil by preparing a sample in a standard proctor mold with standard compaction requirements. Each sample was compacted at its 97% wet/dry of optimum with a standard hammer by placing the soil in three layers and applying 25 blows to each layer. This compaction process created cylindrical samples of 150*120 mm. Then, the researchers, cut every soil sample into three slices and they prepared hollow cylindrical samples of 90*24 mm with an inner diameter of 8 mm by trimming the each slice individually and drilling hole in them. The prepared hollow-cylindrical samples were cured for two days to obtain homogenous conditions. The researchers stored the prepared samples in waterproof bags and they regularly air-dried or wetted the samples until the water content value which was designated by the researchers was obtained. Then, the researchers weighed the samples and coated them with wax to determine the volume of the samples by dip weighing. Then, the researchers filled the inner hole of each sample with a filter textile and they glued a modified dowel to the both ends of the samples by using epoxy resin. Finally, they drilled two small hooks in the dowels and they applied the tensile force to the samples via these two hooks. The illustration of the testing procedure which is proposed by the researchers are provided in Figure 2.7.

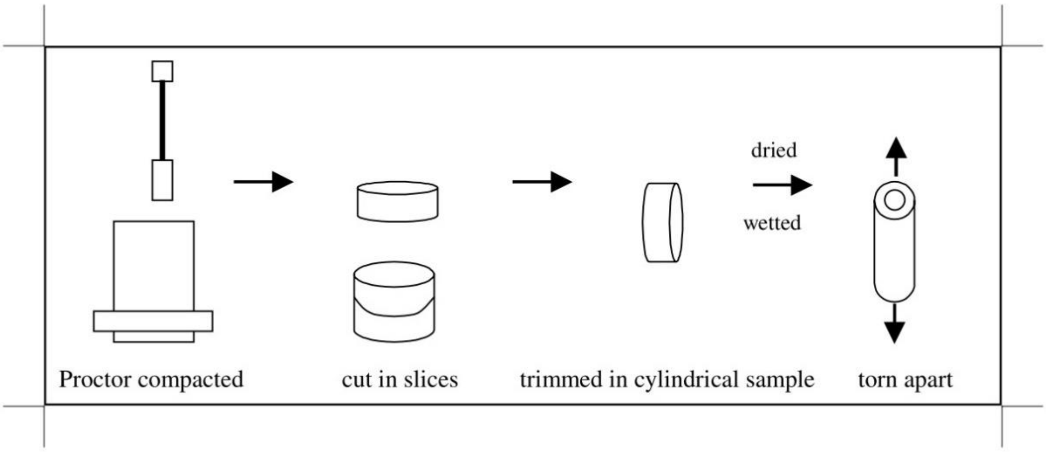


Figure 2.7. Sample preparation and testing procedure for the direct tensile strength test proposed by Zeh and Witt (2007)

Ibarra et al. (2005), have designed a direct tensile strength measurement device which followed the principle of the devices which are used for wood and metal specimens. The researchers prepared cylindrical specimens by using a hydraulic press at a range of bulk densities, compaction pressures and initial moisture contents. The hydraulic press which was used in the research is presented in Figure 2.8. Before compaction process, the researchers sieved and wetted the soil, then the sieved and wetted soil was cured to obtain homogenous water content conditions. After the compaction process, the researchers used a soil lathe to reduce the diameter of compacted sample in the central portion. The soil lathe which was used in the research is presented in Figure 2.9. The aim of reducing the diameter in the central portion was to induce tensile failure in this area. The researchers stated that, this method is not appropriate when soils with high water contents are encountered since the soil lathe limits the range of water content which soil can be self-supporting. Also it is stated by the researchers that, corner stress concentrations were eliminated by choosing cylindrical specimens.

Direct tensile test set up which was developed by Ibarra et al. (2004) is presented in Figure 2.10. The researchers used metal clamps which were fixed to the both ends of the specimen to apply the tensile force. Also they used rubber foam to pad the metal clamps to obtain an even contact between the clamps and the soil. The researchers fixed the lower clamp to the base of the apparatus and they attached the upper clamp to a wire which ran over a pulley rig as it can be seen in Figure 2.10. The loading rate which was used for the test was constant and 0.02 N/s. Friction losses between the wire and the pulley rig were measured by the researchers as 0.02-0.05 N. The friction loss was subtracted from the required tensile force for each soil to fail. When calculating the tensile force at failure, the weight of the failed samples' top portions were subtracted from the loaded weights which were used to induce failure.

It is stated by the researchers that, since the tensile failure occurred at the center of the compacted specimens, the metal clamps did not cause any stress concentration at the ends of the specimens. The proposed direct method for tensile strength testing did not contain any measurement of displacement and that is why tensile strain values could not be calculated by the researchers.

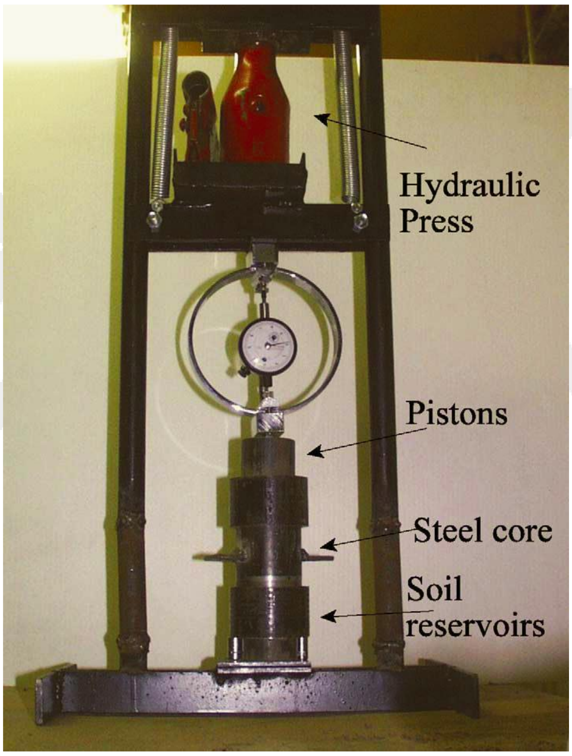


Figure 2.8. The hydraulic press which was used by Ibarra et al. (2004) to prepare soil specimens

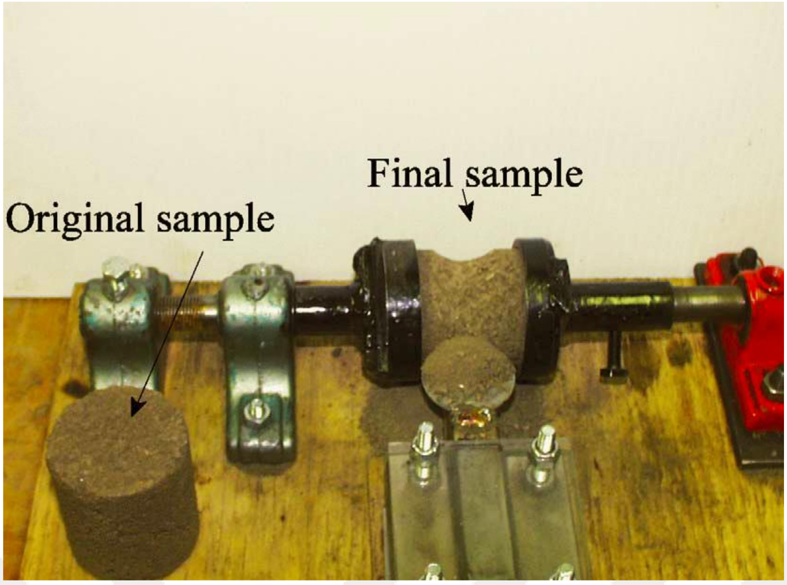


Figure 2.9. The soil lathe which was used by Ibarra et al. (2004) to shape the soil specimens

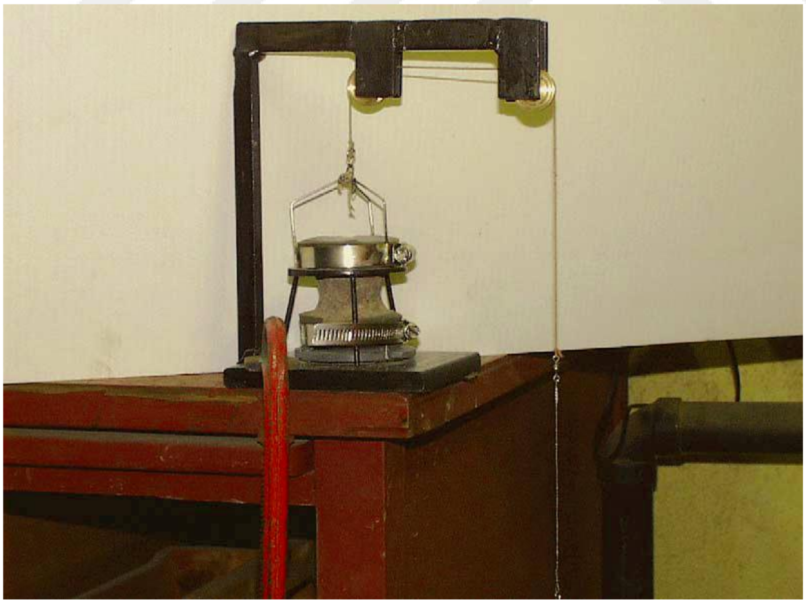


Figure 2.10. Direct tensile strength setup developed for sandy loam soil (Ibarra et al., 2004)

Divya et al. (2014) developed a special direct tensile test setup by preparing a square mold with two separable halves. Four triangular wedges were attached to the inside of the box, which they stated that, these triangular parts made the contact between the soil molds more reliable. Since one half of the mold was rigid, they applied the load to the movable part of the mold and with a loading cell attached to the movable part, the researchers could measure the tensile load that applied to the specimen until it failed. The plan view of the direct tensile set up and a sample after the tensile testing procedure are provided in Figure 2.11 and Figure 2.12, respectively.

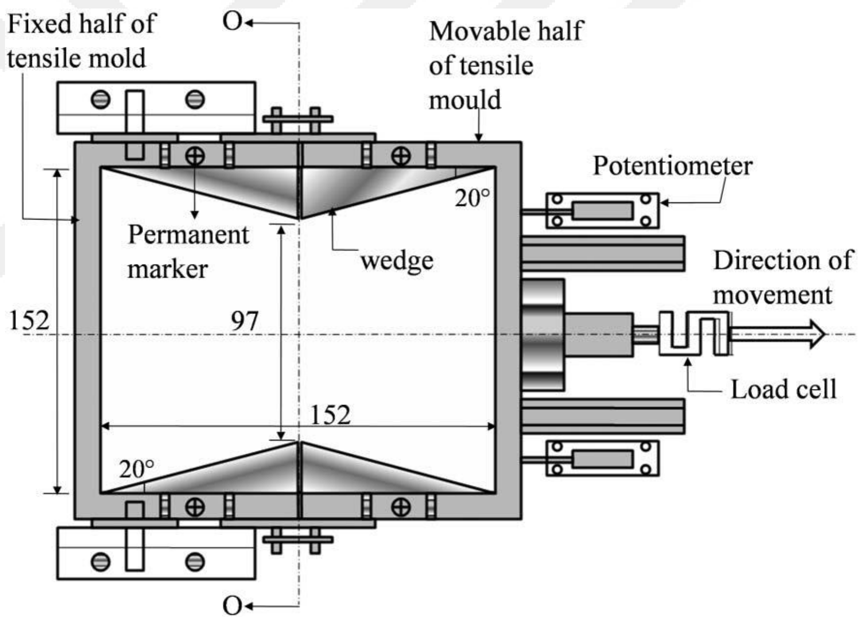


Figure 2.11. The plan view of the direct tensile test which developed by Divya et al. (2014)

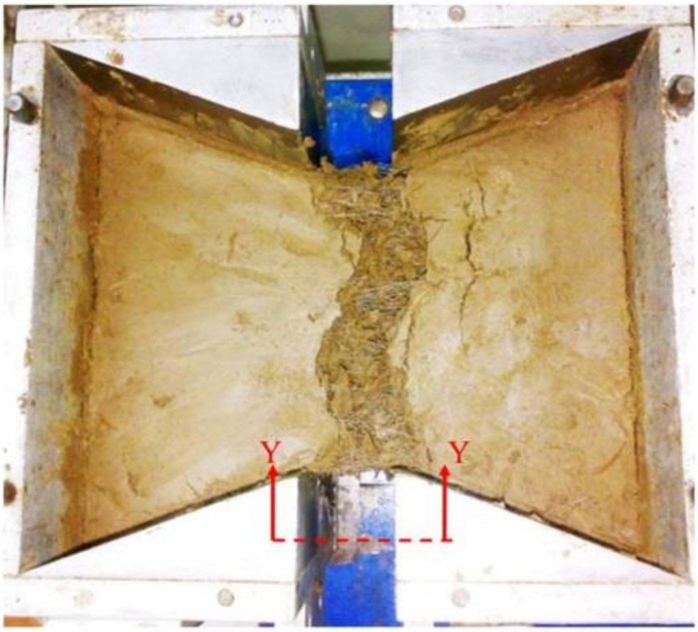


Figure 2.12. The fiber reinforced soil specimen after the direct tensile testing procedure which is proposed by Divya et al. (2014)

Li et al. (2014) employed the direct tensile method and proposed a special mold to apply the testing procedures. The designed mold was 8-shaped with a neck area in the middle of the specimen. Instead of using cylindrical endings, the mold was formed to prepare specimens with square endings. Also the neck area allowed the tensile failure occur at the center of the specimen. After the compaction of the specimen in the mold, the researchers extracted the specimen from the mold for further tensile testing procedure. As can be seen in Figure 2.13, they placed the specimen vertically to the testing equipment which they specially designed and applied the load accordingly until the failure occurred. The loads that applied was carefully recorded by a data logger for further tensile strength calculations.

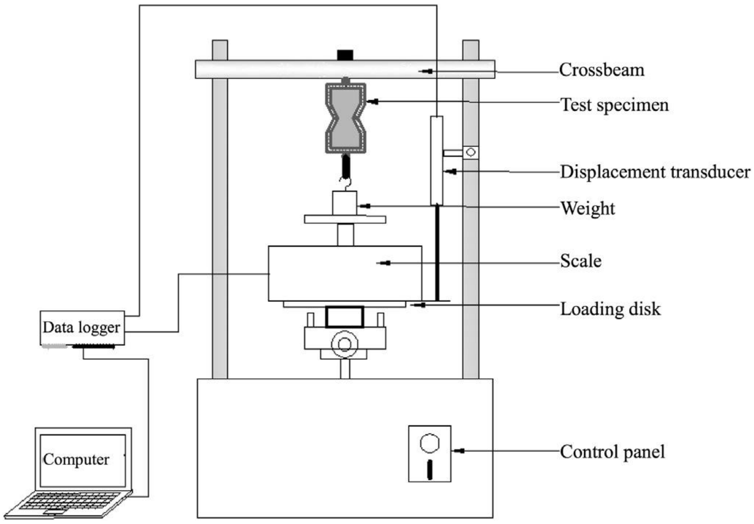


Figure 2.13. The direct tensile test setup developed by Li. et al. (2014)

Perras and Diederichs (2014) stated that, preparing the dog-bone shaped tensile strength specimens which is presented in Figure 2.14.a, are the widely accepted by the researchers because the dog-bone shape decreases the concentration of stress at the both ends of the specimen, the researchers also added that instead of using cylindrical endings, the square endings to this dog-bone shape specimen are sometimes used. But the square shape, results in concentration of stress at the both ends of the specimen and might cause not-acceptable failure on the specimen.

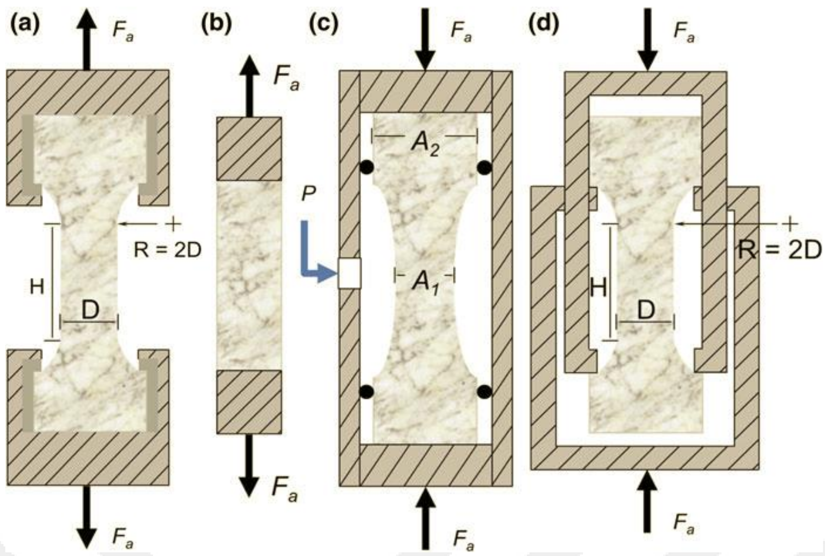


Figure 2.14. Various direct tensile strength setups. a) Split molds for dog bone shaped specimens. b) Caps for cylindrical specimens to be glued to. c) Biaxial extension. d) Compression to tension load converter.
(Perras and Diederichs, 2014)

Tamrakar et al. (2005) also developed a new direct tensile strength test apparatus which includes two parts. This apparatus was 8-shaped but without a neck area in the center. This two halved box consisted of a fixed box and a movable part. Tensile strength device that designed was applying the load horizontally and the movable part of the device could freely move on the platform. Since the friction might cause problems, the researchers placed sliding rollers below and above to the platforms. Movable part of the mold was pulled away until the soil specimen failed. Load cells were used to measure the tensile load applied.

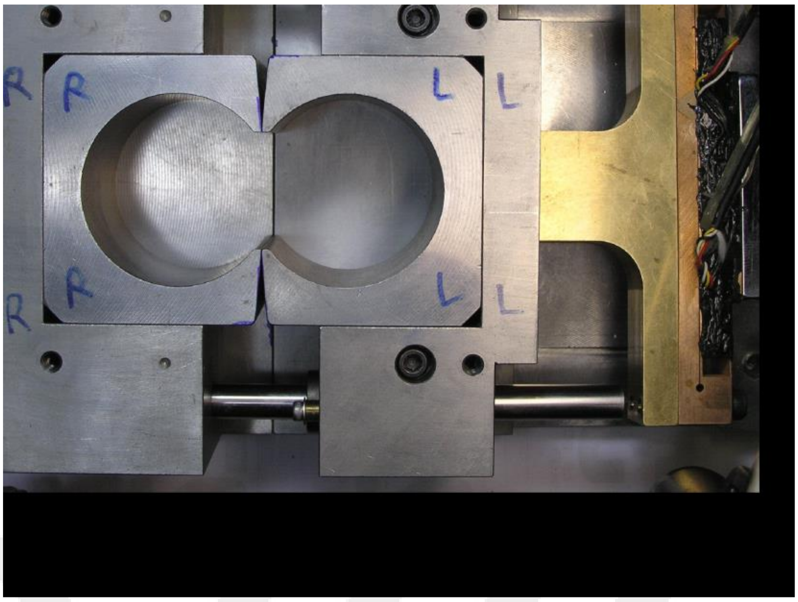


Figure 2.15. The direct tensile strength test apparatus developed by Tamrakar et al. (2005)

2.2.2. Indirect Methods

Indirect methods of soil tensile testing have been most commonly used by researchers rather than developing a direct method to measure the tensile strength of soil. There are more studies and researches which have been conducted to measure the tensile strength of soil by indirect methods than the direct methods.

In indirect methods, the specimens are mostly commonly split under linear and point compressive loads. Since, in these methods, the tensile strength cannot be measured directly, correlations should be developed between different soil parameters to calculate the soils' tensile strength.

There are two most commonly used indirect methods exists in the literature; 1) Split tensile test (Indirect Brazilian test), 2) Unconfined penetration test (Double punch test).

Split tensile test or Brazilian tensile strength test, states that the tensile stress at failure of the specimen, is a function of the diameter of the specimen, the applied load and the length of the cylindrical specimen. In Figure 2.16, an example of split tensile testing and apparatus used for this test is presented.

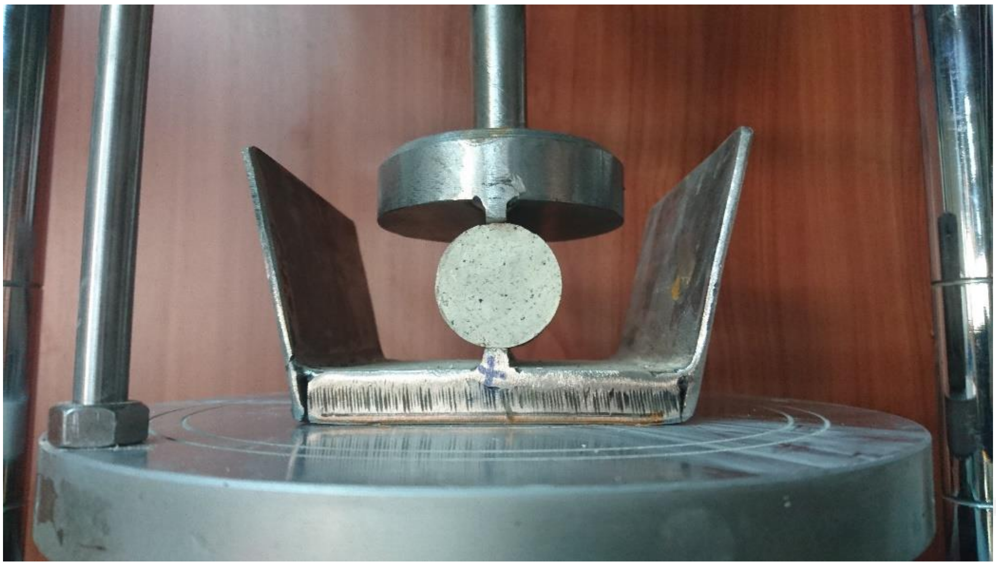
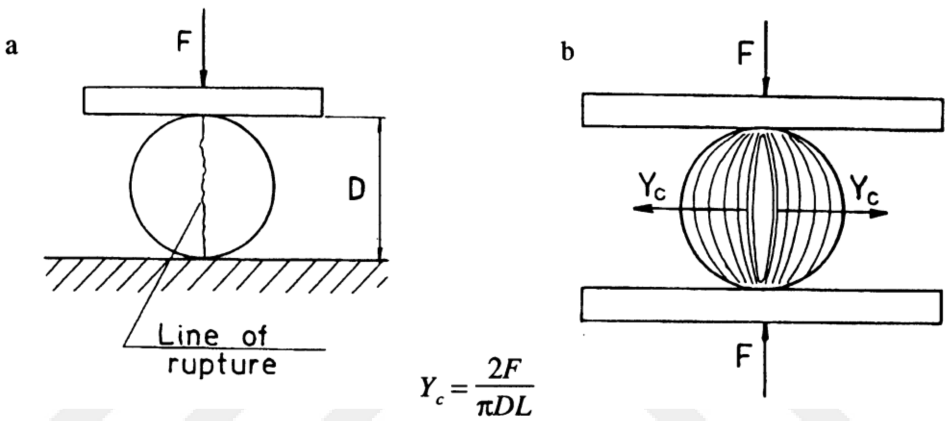


Figure 2.16. An example of split tensile testing and the apparatus used for this test

In Figure 2.17, geometry of split tensile testing, line of rupture, contours of equal tensile stress in split tensile testing and an equation to calculate the split tensile strength are presented. In Figure 2.17, F is the vertical force at failure, Yc is tensile strength, D is sample diameter and L is the length of cylinder.



$$Y_c = \frac{2F}{\pi DL}$$

Figure 2.17. a) Geometry of split tensile testing and line of rupture. b) Contours of equal tensile stress in split tensile testing and equation to calculate the split tensile strength. (Blazejczak et al., 1995)

Double punch test which is developed by Fang and Chen (1970), is a simple test for evaluating the tensile strength of soils. In this test, the cylindrical specimen is tested by applying load to the two steel punches at the top and the bottom of the specimen. The applied load forms two cone-shaped rupture areas beneath the punches and radial tensile cracks on the specimen. The surrounding materials around the cone-shaped rupture areas displaces as the cones moves toward to each other and this situation causes radial tensile cracks. The unconfined penetration test, on the other hand, is similar to the double punch test and is developed by Fang and Fernandez (1981). The researchers modified the double punch test which proposed by Chen and Fang (1970) and proposed the unconfined penetration test. The main difference between the two tests is the double punch testing requires a standard compaction mold to be used whereas California bearing ratio mold is used for unconfined penetration test. The double punch test set up which was proposed by Fang and Chen (1970) is presented in Figure 2.18.

In Figure 2.19, the schematic diagram of double punch test and double punch test equation to calculate the tensile strength of soils is presented. It is stated by Fang and Chen (1970) that, compatible velocity relation which is presented in Figure 2.19, was used to determine the tensile strength of the specimen and it is stated that, it was a matter of calculating the areas of the cone-shaped ruptures’ surfaces of discontinuity.

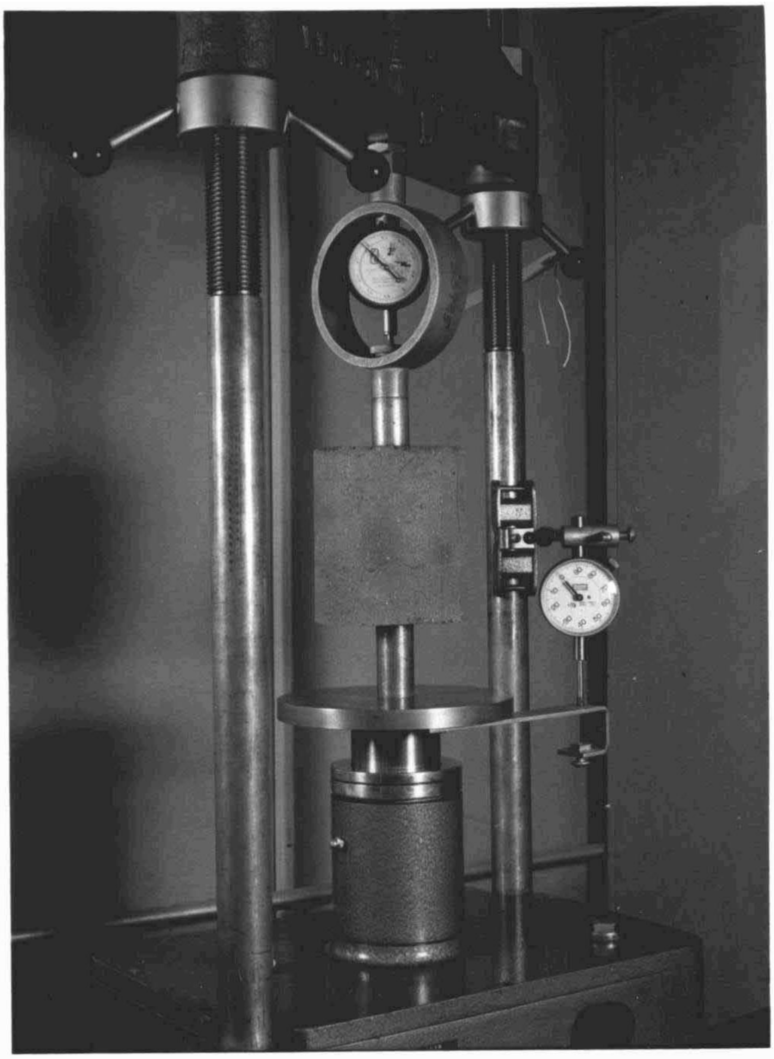
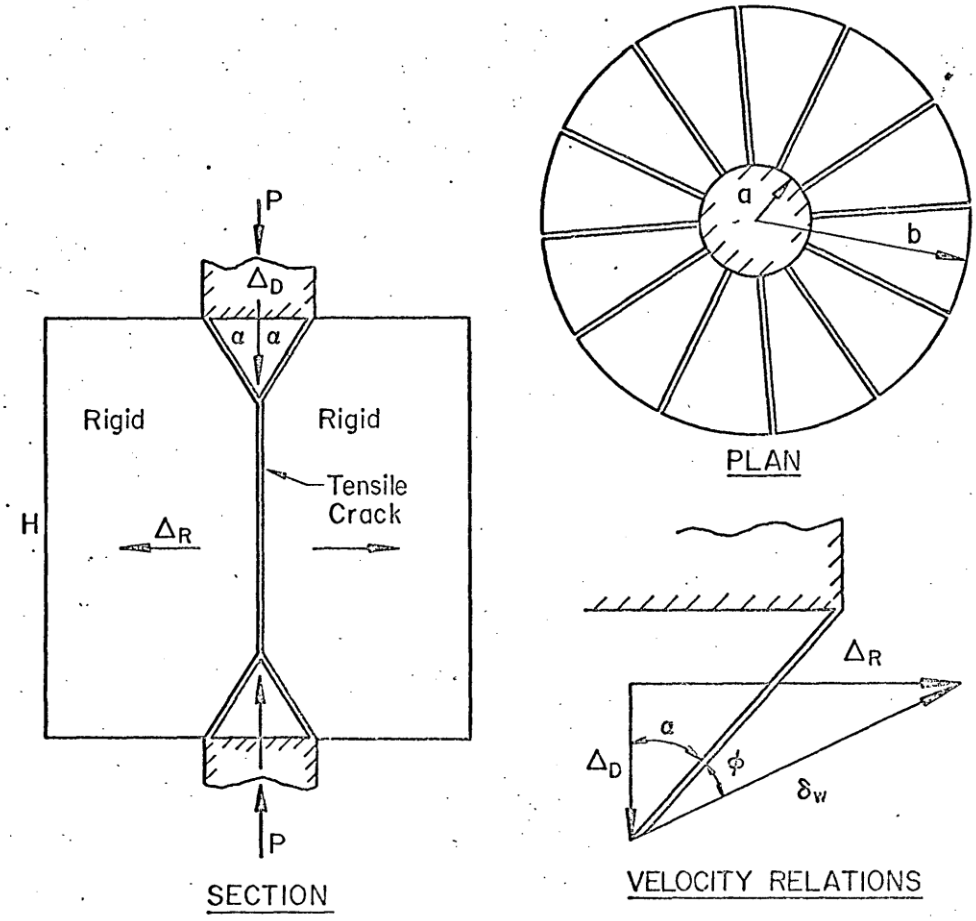


Figure 2.18. Double punch test set up which was proposed by Fang and Chen (1970)



$$\sigma_t = \frac{P}{\pi\ (1.0\ bH - a^2)}$$

Figure 2.19. Schematic diagram of double punch test and double punch test equation to calculate the tensile strength of soils (Fang and Chen, 1970)

2.3. Tensile Strength of Clays, Sands and Rocks

One of the major parameters that causes tensile cracking is the low tensile strength of soil. Since every type of soil either it is clay, silt, sand or rock, shows different tensile strength properties. In this part the tensile strength parameters for different kinds of soil is examined.

2.3.1. Tensile Strength of Fine-Grained Soils

The tensile strength of fine-grained soils, since it can easily be affected by water content changes, temperature, soil fragmentation, suction etc., can be considered more important rather than the tensile strength of sands and rocks. That is why, the researches, on the matter of tensile strength of soil, are generally focused evaluating the tensile characteristics of fine-grained soils. Also, since it is harder to find tensile characteristics of fine grained soils, researchers preferred direct tensile tests to be used on clayey soils rather than using traditional indirect tests.

Tamrakar et al. (2005), in their research, has conducted experiments on fine-grained Kanto loam at different moisture contents by using newly developed direct tensile apparatus and they have found that at 65% water content the tensile strength of Kanto loam is around 13 kPa.

Akin and Likos (2017) stated that, the tensile strength of compacted clay can change according to residual saturation and air entry. They also used the split tensile testing and found that the tensile strength of compacted clay materials with 30% saturation percentage is around 40 kPa.

Li et al. (2014), used a direct method which they developed and they stated that with the increasing value of dry density the tensile strength of fine-grained soil is increases. The maximum tensile strength which is covered in their research was around 60 kPa and this value was found at 1.7 Mg/m^3 dry density.

2.3.2. Tensile Strength of Sands

For sands or more granular soils than clays and silts, the tensile strength displays the materials' capability to withstand the tensile stresses without failure. The intergranular bonding in sands are considered to be weak, so a specially designed apparatus should be used to obtain the tensile strength.

Munkholm et al. (2002), used a direct tensile strength testing apparatus in their research which is conducted on sandy loam specimens. The tensile strength evaluation of the specimens was between 2 and 3.2 kPa.

2.3.3 Tensile Strength of Rocks

In the case of rocks, very little attention has been given to tensile strength characteristics of them except coal. The tensile strength of rocks are also important because in a mining operation the tensile strength of rocks can be exploited. So the tensile strength value of rock is a considerable value.

Hobbs (1963), stated that, there are a few testing methods applied to the rocks to measure the tensile strength, these methods includes split tensile tests, bending tests, the indentation tests etc. Also he stated that, the most suitable method to evaluate the tensile strength of rocks is using diametrical compression on the disks of specimens with central holes in them.

Perras and Diederichs (2014), reviewed the tensile strength concept of rocks and stated that the tensile strength can be found with a new direct tensile testing equipment (dog bone shape and square endings), split tensile testing, sleeve fracturing test, beam bending test etc. With a summary of the tensile strength of rocks that can be found in the literature, it can be observed that the split tensile strength of rocks can be between 5000 and 16000 kPa and the direct tensile strength can be between 2000 and 20000 kPa.

2.4. Factors Affecting the Tensile Strength of Soils

The tensile strength of soils can be influenced by various parameters. Some of these parameters can be listed as follows;

- Suction
- Soil structure
- Clay fraction
- Aggregate strength
- Soil fragmentation
- Pore characteristics
- Curing time
- Water content
- Bulk density
- Liquid Limit

Zeh and Witt (2007) stated that, soil-water interaction plays an important role on engineering properties of clayey soils. They investigated the effects of suction on the tensile strength of clayey soils and found that with increasing suction, the tensile strength tends to increase accordingly. They also stated that the compaction afford made, changes the tensile strength of the specimens as can be seen in Figure 2.20.

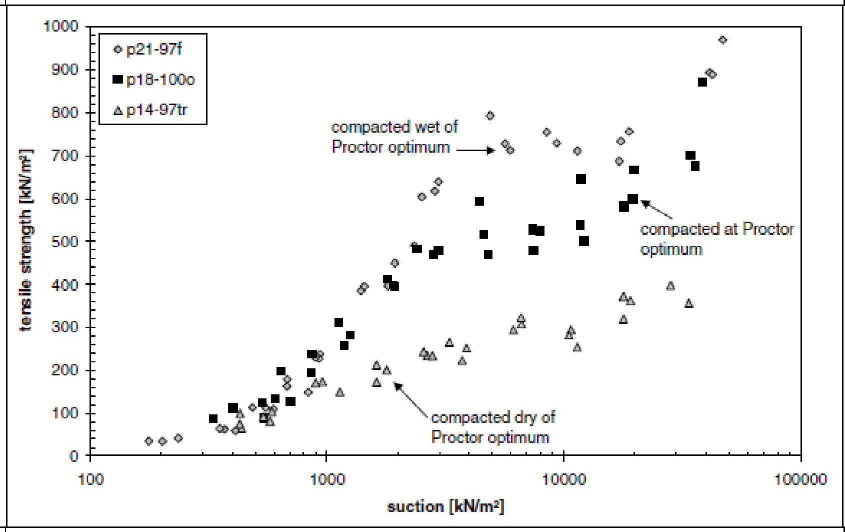


Figure 2.20. Effects of soils structure and suction on the tensile strength of clayey soil (Zeh and Witt, 2007)

Barzegar et al. (1995), in their research, examined the effects of clay fraction on the tensile strength of clayey sand soils and stated that the increase on the percentage of clay content increases the tensile strength of compacted clayey sand soils.

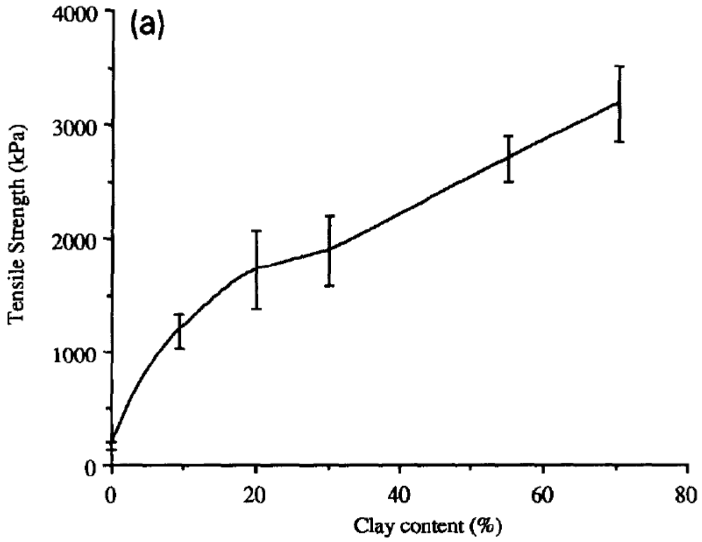


Figure 2.21. The effect of clay content on the tensile strength of clayey soils (Barzegar et al., 1995)

Blazejczak et al. (1995), investigated the effects of bulk density and water content on the tensile strength of silty loamy sands and stated that when bulk density of soil increases so does the tensile strength of soil. As can be seen in Figure 2.22, specimens with three different bulk densities and water contents are prepared and tested and the evaluated tensile strengths are significantly changes depending on the bulk density and changing water content.

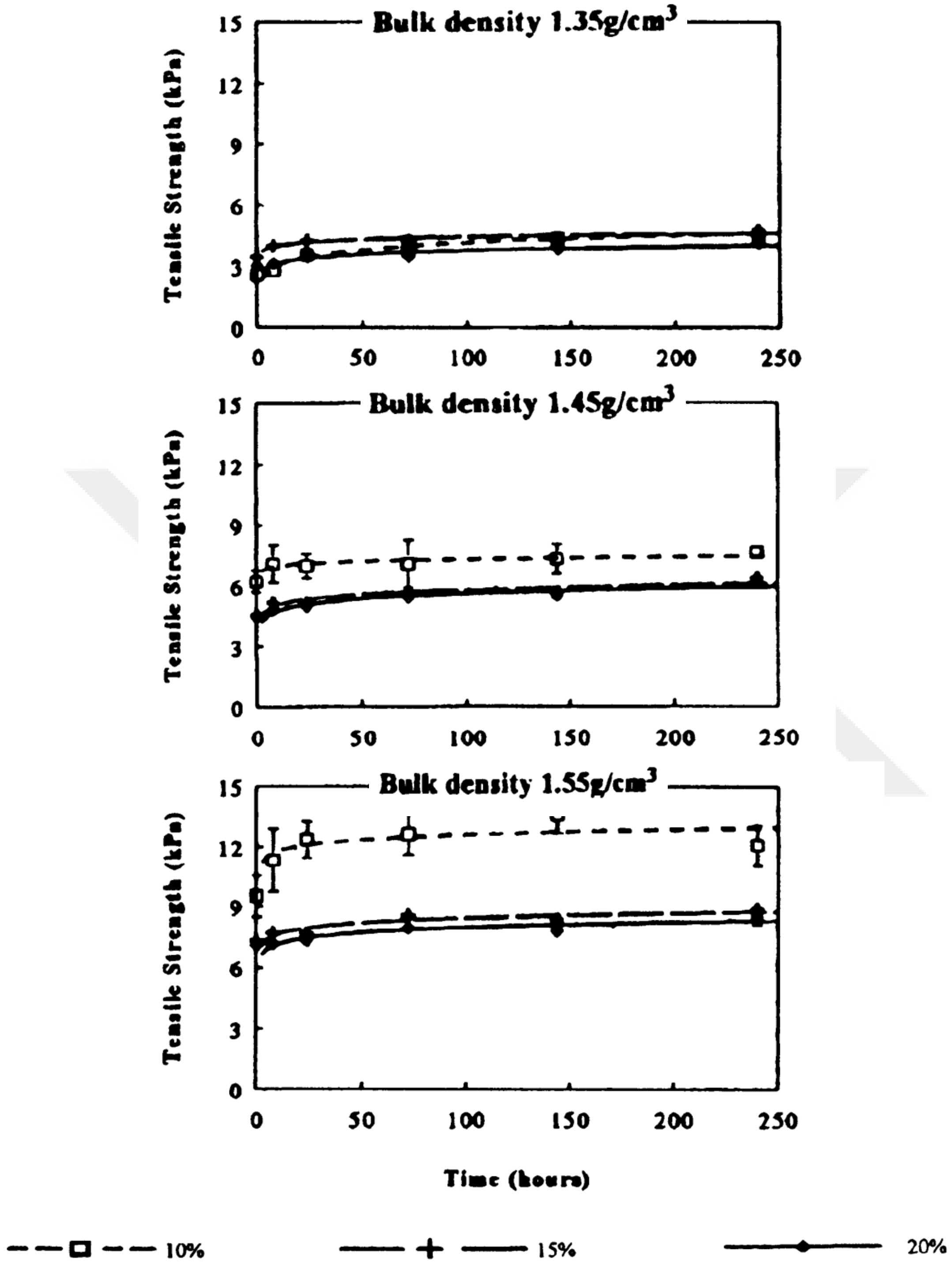


Figure 2.22. Effects of bulk density and water content on the tensile strength of silty loamy sand (Blazejczak et al., 1995)

2.5. Tensile Strength Stabilization and Improvement

As discussed in the previous parts of this thesis, the literature review indicates that the tensile strength of soils is an important mechanical parameter of soil. Since tensile strength related failures may cause significant problems on geostructures, stabilizations and improvements should be made on tensile strength of soils for more durable geostructures.

In the past years, many researchers have tried different methods to stabilize the tensile strength of soils. These stabilizations are made by using coir fibers, polypropylene fibers, and discrete fibers as reinforcements. Also lime, cement, blast furnace granulated slug, surfactants etc. are used by the researchers to improve the tensile strength by developing mixtures with the materials proposed. And it can be seen that, from the literature exists in this matter, the researchers usually succeeded to improve the tensile characteristics of soil. A few examples are mentioned for better understanding of soil stabilization.

Anggraini et al. (2015), stabilized soft marine soil specimens, by lime treatment. They also used elastic coir fiber which have high durability to improve the tensile strength characteristics of soil specimens. The experiments showed that increasing fiber content up to 1%, increases the tensile strength from 20 kPa to 85 kPa on the specimens cured for 90 days. Also they showed that curing has relatively important effects on indirect tensile strength of soils in a positive way.

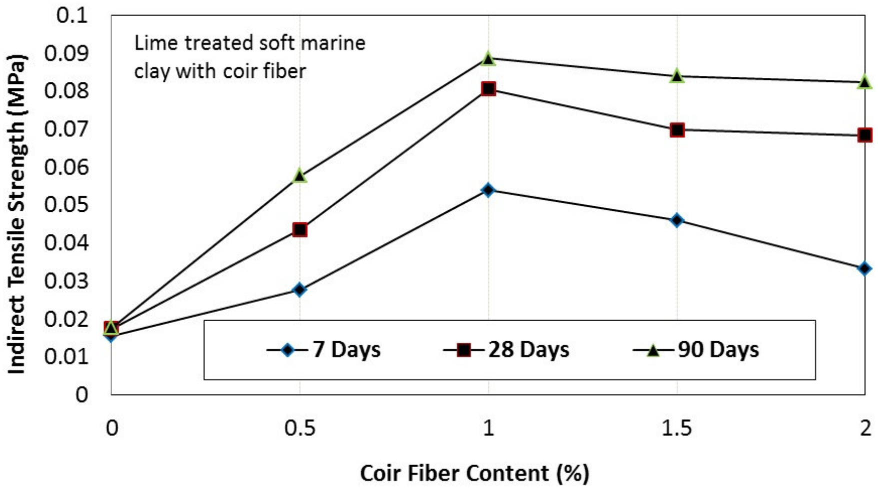


Figure 2.23. Effects of coir fiber content and curing period on lime treated soft marine clays (Anggraini et al., 2014)

Li et al. (2014) also reinforced clayey soil specimens with short discrete polypropylene fiber and stated that, using discrete fiber as reinforcement relatively increases the tensile strength of soil from 47 kPa to 77 kPa, in the case of 0% fiber content and 0.2% fiber content respectively.

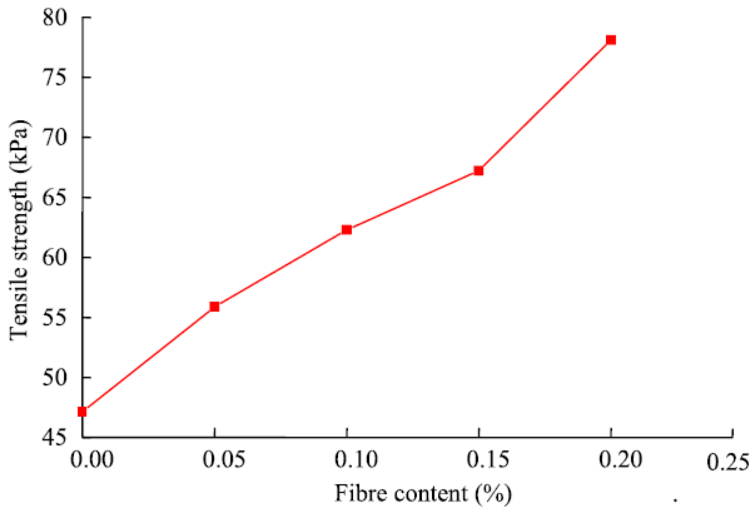


Figure 2.24. Effects of discrete fiber content on the tensile strength of clayey soil (Li et al., 2014)

Lehrsch et al. (2012) investigated the effects of chemical compositions on the tensile strength of soils. To achieve the aim of the research, they used surfactants to stabilize the tensile strength of soil aggregates. In their research, ethylene oxide/propylene oxide block copolymer (COP), IrrigAid Gold (IGG) and an alkyl polyglycoside (APG) were used on different kinds of soils to investigate the improvement effects on tensile strength. As can be seen in Figure 2.25, in the most of the soils which were treated by surfactants, the tensile strength increased.

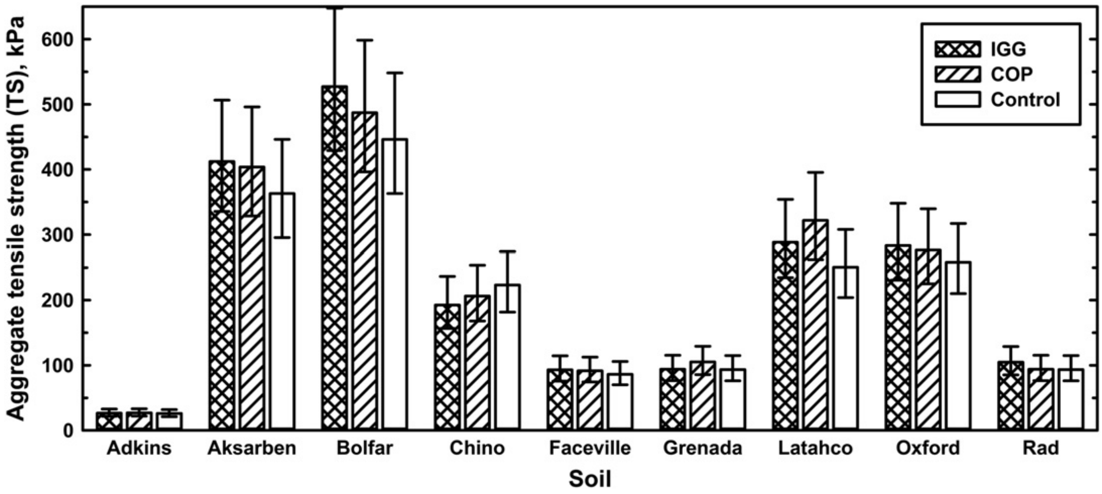


Figure 2.25. The effects of surfactants on the tensile strength of different soils (Lehrsch et al., 2012)

2.6. Ankara Clay; Engineering Characteristics and Geotechnical Variability

Ankara clay can be classified as an expansive soil which is also pre consolidated, highly plastic and most commonly changes from dark brown to reddish brown. The soil can be found in the central, western and southern areas of the Ankara city which is the capital of Turkey.

Ordemir et al. (1965) stated that, Ankara clay's water content and plastic limit varies between 20% and 35%, the liquid limit varies between 55% and 75% and the shrinkage limit of the soil is usually between 15% and 20%. Ankara clay is considered to be highly plastic according to the plasticity index changes between 20% and 40%. The unit weight and specific gravity of Ankara clay changes between 17.5 kN/m^3 - 19.5 kN//m^3 and 2.60 – 2.70 respectively.

Researches that have been conducted on Ankara clay, have commonly been on its swelling potential since it shows considerable swelling characteristics. Also researchers focused on shear strength, suction, mineralogical and sorption characteristics of Ankara clay. Also Ankara clay was investigated for its potential usage as compacted landfill liner and capping. But there is little to no research on the tensile strength of compacted Ankara clay.

Ankara, as capital city of Turkey, has been rapidly expanding and there is significant population growth in the city. This population growth caused constructions of substructure and infrastructure to be more often. And this means that, the city will be needing more geostructures; for example, landfill, embankment etc.

As it is stated in the previous parts of this thesis, the tensile strength parameters are significantly important for geo-structures and since Ankara clay's tensile characteristics are not much known, it will be important to determine the tensile characteristics of the soil and the ways to stabilize and improve it.

2.7. Synthetic Fibers

As it is discussed in the Section 2.5, the synthetic fibers are most commonly used in stabilization of soil specimen. It has been stated that, in most of the researches, synthetic fiber addition to the soil specimen improved the tensile strength in a significant way.

Synthetic fibers are most commonly used in concrete based materials for its crack controlling properties. It has been also used in concrete slab construction. Since the concrete has low tensile strength and shows brittle behavior, usage of synthetic fiber is a good and more economical solution to improve the tensile strength characteristics. This situation led geotechnical engineers to investigate the usage of synthetic fibers also to improve the tensile strength of soils.

The most commonly used synthetic fibers in researches are polypropylene and polyester. Examples of the polypropylene and polyester fibers are presented in Figures 2.26 and 2.27, respectively. The synthetic fibers are elastic, light weighted, have high initial strength and they are highly durable. Also it should be included that the percentage of the synthetic fiber reinforcement used in soil specimens can differ according to the type of soil and other geotechnical engineering aspects of the soil.

Figure 2.26. An example of polypropylene fiber which is used for tensile strength stabilization and improvement (Adopted from www.forta-ferro.com)

Figure 2.27. An example of polyester fiber which is used for tensile strength stabilization and improvement (Adopted from www.polyrope-fence.com)

2.8. Metal Swarf

Metal swarf generally can be classified in to four types; steel swarf, alloy swarf, brass swarf and aluminum swarf and is an important raw material for the recycling industry. The examples of aluminum swarf and steel swarf are presented in Figures 2.28 and 2.29, respectively.

Figure 2.28. An example of aluminum swarf (Adopted from www.weima.com)

Figure 2.29. An example of steel swarf (Adopted from www.weima.com)

There are considerably large amounts of metal waste swarf is produced by metal industry. Financial and environmental difficulties are faced in the stage of disposal of the metal swarf wastes. Since using waste materials can significantly reduce the risk of environmental destruction and reduces waste amount, the use of metal swarf in soil stabilization can be considered as a very beneficial way for disposal of metal swarf.

Stabilization of soils' mechanical properties with metallic fibers is relatively a new method in geotechnical engineering studies. The knowledge on this matter are limited by a low number of researches.

Karabash et al. (2015), in their research investigated the effects of waste aluminum swarf on the unconfined compressive strength of clayey soils. They conducted experiments on clayey soils with various percentages of aluminum swarf to investigate the stabilization effects. They used percentages between 0% and 20% percent by dry weight and the specimens were compacted according to the standards of modified proctor. It has been stated that the unconfined compressive strength increased from 390 kPa to 450 kPa with 10% of aluminum swarf addition to the specimens. And with increasing aluminum swarf content beyond 10% the unconfined compressive strength decreased relatively.

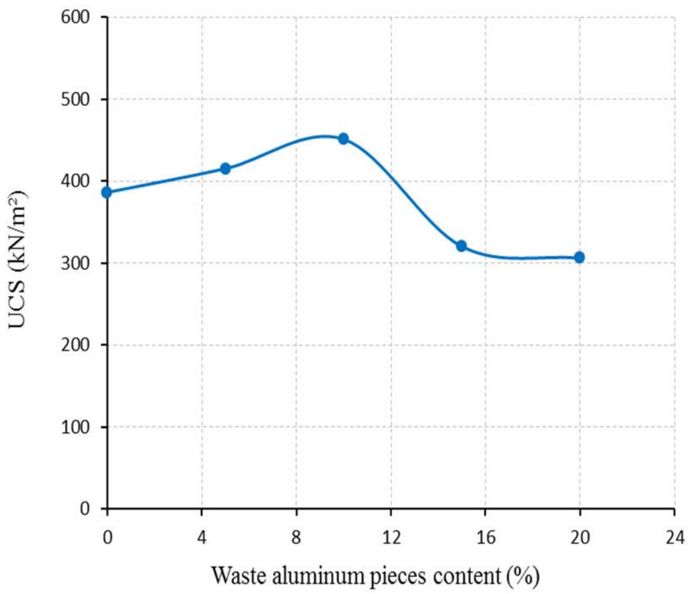


Figure 2.30. Effects of aluminum swarf addition on the unconfined compressive strength of clayey soils (Karabash et al., 2015)

The examples of metal swarf usage to stabilize the soils' mechanical properties have led the consideration of whether the metal swarf can be used to improve other geotechnical engineering parameters of the soils like tensile strength etc. That is why, in this study metal swarf was used to test the stabilization aspects on the tensile strength of Ankara clay and Kaolin clay.

2.9. Rubber

An increasing number of researches have been focusing on developing new approaches to geo-environmental problems. In this regard, engineers have begun to use waste or recyclable materials to improve soils' mechanical properties like synthetic fiber, metal swarf as mentioned at the previous parts. Also rubber and tire wastes are used to improve soil stability. There are three kinds of rubber waste materials which are most commonly used in the literature namely shredded rubber, crumb rubber and pulverized rubber. The examples of shredded rubber waste, crumb rubber waste and pulverized rubber waste are presented in Figures 2.31, 2.32 and 2.33, respectively.

Figure 2.31. An example of shredded rubber waste (Adopted from www.acehardware.com)

Figure 2.32. An example of crumb rubber waste (Adopted from www.continenetal-platform.com)

Figure 2.33. An example of pulverized rubber waste (Adopted from www.continenetal-platform.com)

Like metal swarf deposits, serious environmental pollution might happen because of the tires in stock piles all around the world. Since the rubber tires do not compose in the environment in a short time, the recycling become an important issue for environmental health.

In this section availability and usage of rubber waste in geotechnical engineering will be discussed. Rubber is an elastic material and shows viscous characteristics. The typical rubber consists of ten or more ingredients which help to improve physical properties of rubber and to delay long term deterioration. Also the rubber is vulcanized (heating rubber with sulphur) to improve its tensile strength. Therefore as elasticity and viscosity of rubber can affect the soil in positive way, it also gives soils some elastic properties. That is why, it has been widely appreciated by researchers to be used in geotechnical engineering. Also, since it is a durable material and does not get affected by the environmental changes very easily, an increasing attention is given to the research of using rubber for stabilization of soil.

Issa (2016), conducted experiments by adding waste tires to asphalt mixture. He stated that using bitumen mixes increases the cost of construction therefore alternative materials such rubber might be used instead and it will be more economical and eco-friendly. The researcher also stated that adding rubber to asphalt has the same effect of adding synthetic fibers or other kind of additives to concrete. In this research, it is included that, adding 10% rubber and 5.5% bitumen to asphalt mixture improved the stability by 10%.

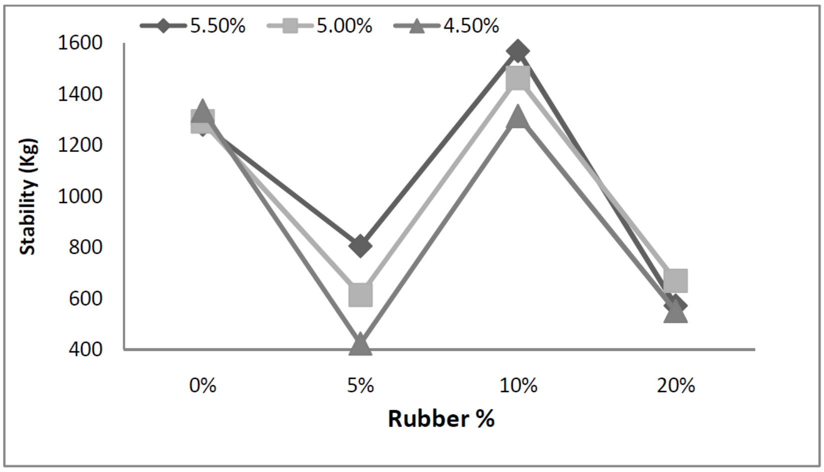


Figure 2.34. Effects of rubber and bitumen addition on the stability of asphalt mixtures (Issa, 2016)

Attom (2005), studied the effects of shredded tires on the shear strength of sands under specific conditions. The researcher conducted direct shear test on three different kinds of sands. He designed mixtures with 10%, 20%, 30% and 40% of shredded tire by dry weight. He also calculated the shear strength without any addition of shredded tire. As can be seen in Figure 2.35, he concluded that the addition of shredded rubber improves the shear strength of sands in a significant way.

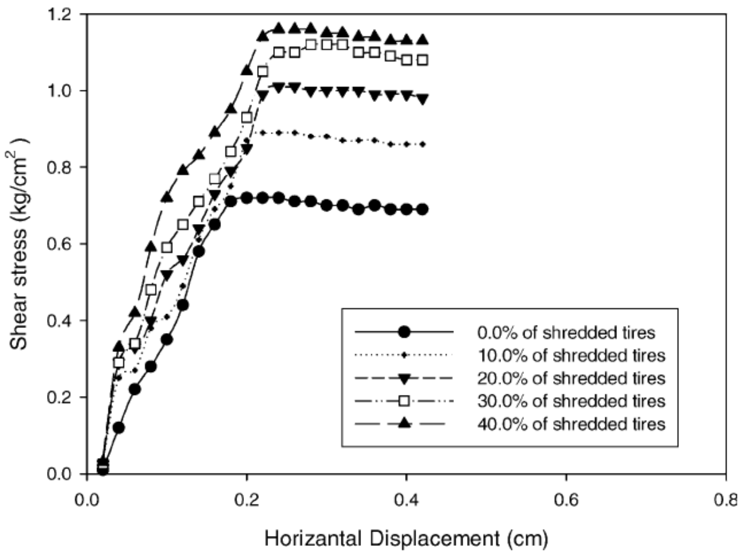


Figure 2.35. The effects of shredded rubber on the shear strength of sands (Attom, 2015)

Reddy et al. (2014), investigated the effects of waste rubber on the soil characteristics. In this matter, the researchers performed unconfined compression tests and California bearing ratio tests on the mixtures which were designed with various percentages of shredded rubber. And the researchers also investigated the curing effects on the specimens tested. As can be seen in the Figures 2.36 and 2.37, with the 5% addition of shredded rubber and 14 days of curing period the unconfined compressive strength and California bearing ratio increased significantly. On the other hand, with the addition of 10% and 15% shredded rubber, the unconfined compressive strength and California bearing ratio decreased.

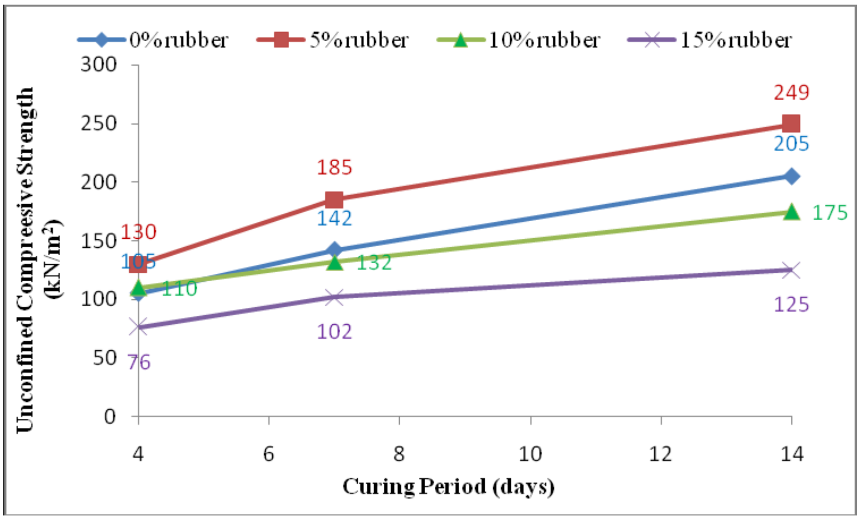


Figure 2.36. Effects of shredded rubber and curing on the unconfined compressive strength of the clayey soil mixed with 4% cement (Reddy et al., 2016)

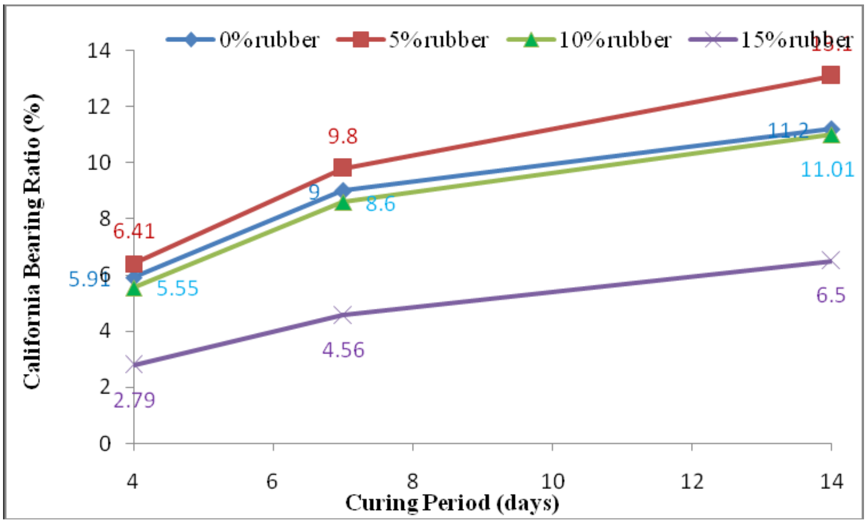


Figure 2.37. Effects of shredded rubber and curing on the California bearing ratio of the clayey soil mixed with 4% cement (Reddy et al., 2016)

Akkaya (2015), in his thesis research performed experiments on foundry sand and green sand by preparing mixtures that contained rubber wastes. The researcher performed split tensile tests on the specimens that contained different amounts of pulverized rubber and shredded rubber. He stated that the mixtures prepared with addition of waste rubber showed an increment in their tensile strength.

As it is stated previously, in many researches mechanical properties of soil improved with addition of rubber waste. That is why, in this study pulverized rubber was used to investigate its stabilization effects on the tensile strength of Ankara clay and Kaolin clay.

2.10. Bentonite

Bentonites are principally considered as montmorillonites. The difference is that; bentonites includes fine quartz particles which can be seen as impurities. Montmorillonite is an alumina silicate mineral which has 2:1 unit layer structure.

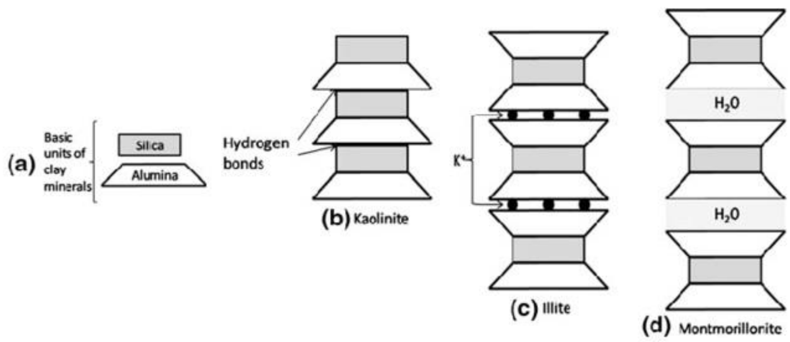


Figure 2.38. Unit layer structures of clay minerals (Adopted from www.kullabs.com)

Bentonites are widely known by their swelling potentials, this kind of bentonites can also be referred as sodium bentonite or sodium montmorillonite. Bentonite, in the past years, gained a significant value in waste disposal projects because individual clay particles of bentonites are plate like shaped and when exposed to the water or leachate the particles show great swelling potential. This makes bentonite a suitable material for soil permeability improvement. When bentonite is mixed to soil, the pore spaces in soil gets occupied by the bentonite particles therefore the hydraulic conductivity decreases significantly. In this matter, many researchers have investigated the effects of bentonite on the various soil mechanics parameters. It has been stated that, since the addition of bentonite decreases pore space it may also increase the strength properties of the soil specimen.

As discussed previously, the bentonite was also used in this experimental research to investigate its effects on the tensile strength and unconfined compressive strength of Ankara clay and Kaolin clay.

2.11. Kaolin Clay

Kaolin clay, is considered as a significant clay type for geotechnical engineering purposes. Kaolin clay is formed as a result of extreme weathering process and it is a 1:1 layer material. The chemical composition of kaolinite formed by a silica-tetrahedral sheet, an alumina octahedral sheet which a plane of oxygen atoms are stored and hydrogen bonds exists between the layers of the mineral. As a result of this structure, Kaolin clay particles are hard to be broken down and the layers cannot be easily separated. Therefore, Kaolin clay is widely used in the researches for its highly durable form.

Kaolin clay is commonly used in stability improvement tests by the researchers. Maher and Ho (1994), investigated the stabilization effects of polypropylene and glass fiber addition to Kaolin clay by conducting unconfined compression tests, split tensile tests, flexural toughness, hydraulic conductivity and moisture density tests. As can be seen in Figure 2.39 and Figure 2.40, it is stated that, the fiber addition to Kaolin clay increased the unconfined compressive strength and split tensile strength of soil.

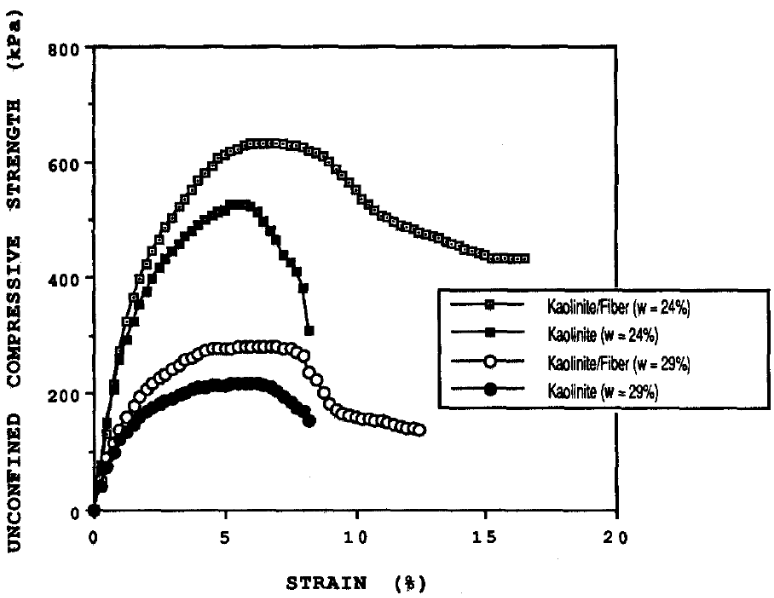


Figure 2.39. The effects of polypropylene fiber on the unconfined compressive strength of Kaolin clay (Maher and Ho, 1994)

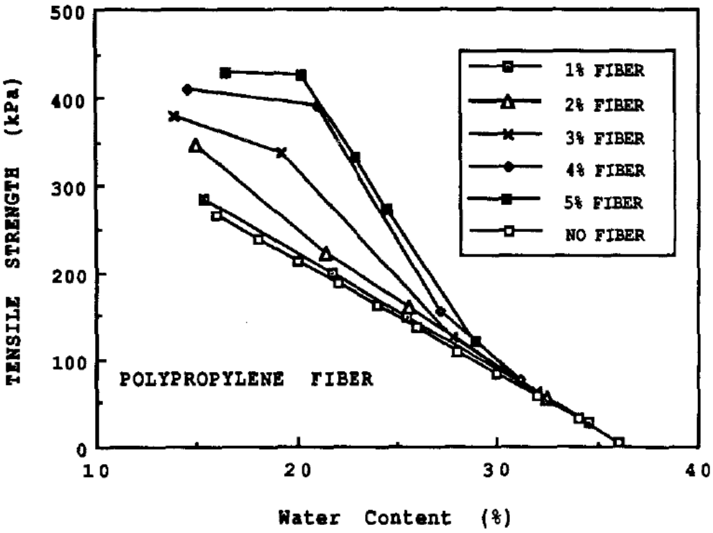


Figure 2.40. The effects of polypropylene fiber on the tensile strength of Kaolin clay (Maher and Ho, 1994)

In this study, the stabilization effects of synthetic fiber, metal swarf and pulverized rubber on the tensile strength and unconfined compressive strength of Kaolin clay were investigated for better understanding of tensile strength improvement.

CHAPTER 3

EXPERIMENTAL STUDY

3.1. Materials Used

In the past years, as it can be seen in the literature review, many researchers have investigated the effects of synthetic fibers, rubber wastes and metal swarf on the mechanical properties of various soils when they are mixed with the soils with various percentages. Also researchers performed experiments with chemical materials and different kind of natural clays and minerals like bentonite etc. to stabilize and improve the mechanical properties of soils.

In this study, the tensile characteristics and unconfined compressive strength of Ankara clay was investigated by designing mixtures with addition of synthetic fiber, pulverized rubber, metal swarf and bentonite. Even though there are various studies on the mechanical properties of Ankara clay, there are little to no research on the tensile strength of this soil. The effects of proposed materials on the Kaolin clay's tensile strength and unconfined compressive strength were also investigated in this experimental study to understand how the tensile strength and unconfined compressive strength behavior change with the addition of proposed materials on different soil types. A flowchart of this study is provided in Figure 3.1.

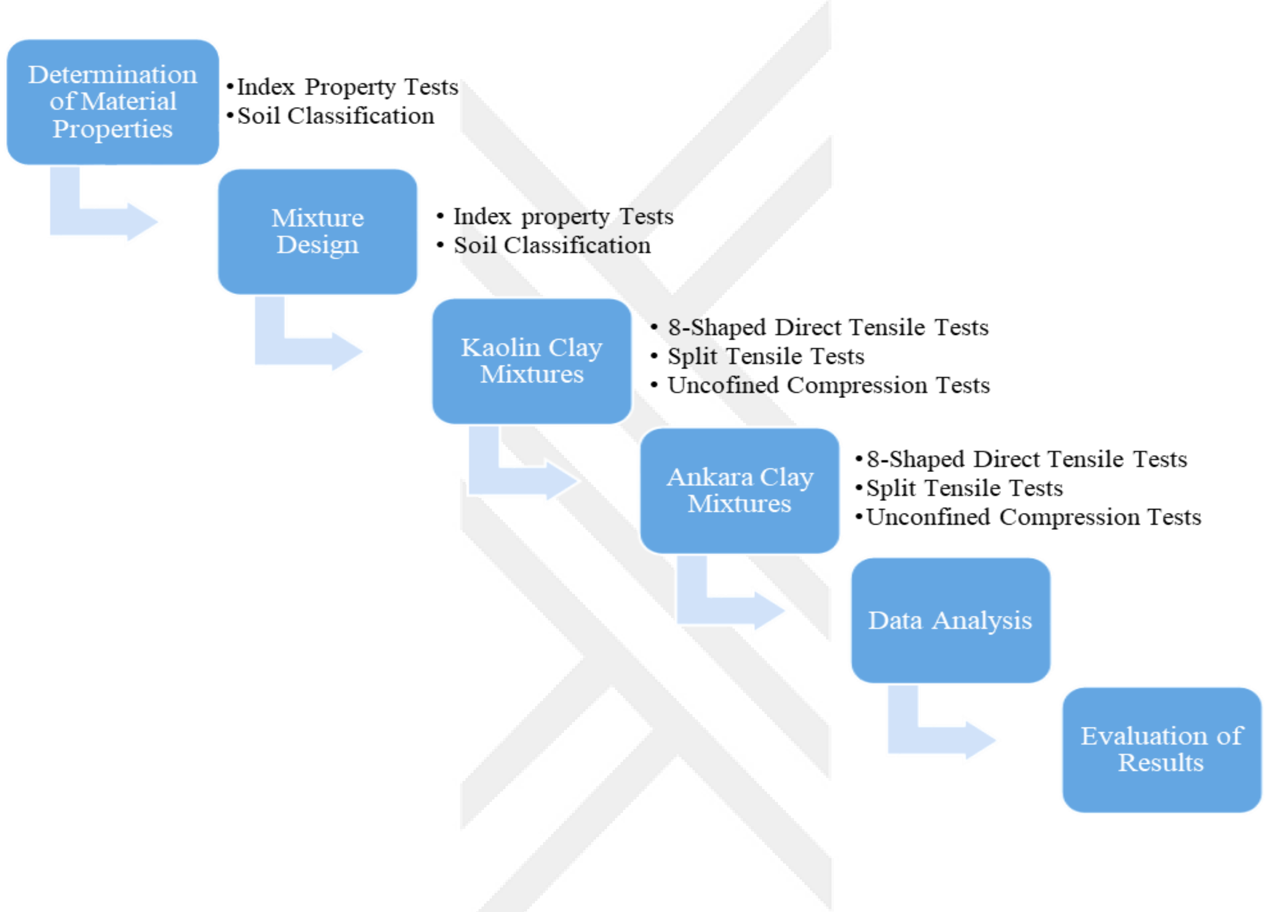


Figure 3.1. Flowchart of the experimental study

3.1.1. Ankara Clay

Ankara clay which was used in this study was collected from Cankaya province of Ankara, Turkey. The soil was collected from an excavation area for ongoing building construction. The depth which soil was taken was around 10 meters.

The collected Ankara clay samples were oven dried at 105 °C for 24 hours and then sieved from No.4 sieve for further studies. Ankara clay which was used in this study was reddish-brown. The final form of the Ankara clay which was used in this study is presented in Figure 3.2.

Figure 3.2. Ankara clay sample which was used in this study

The index properties and grain size distribution curve of Ankara clay samples are presented in the Table 3.1 and Figure 3.3, respectively.

Evaluation of grain size distribution curve pointed out that 73.8% of the collected samples were fine-grained. Also the soil was classified as “CH” according to the Unified Soil Classification System (USCS) by evaluating the index properties and grain size distribution curve of Ankara clay.

The particle size analysis were performed by sieve analysis and hydrometer tests according to the ASTM D-6913 and ASTM D-422 standards, respectively. Standard pycnometer method was used according to the ASTM D-854 standard to obtain the specific gravity value of the soil. The liquid limit and plastic limit values was obtain according to the ASTM D-4328-10e1 standard by using Casagrande liquid limit apparatus, hand rolling method and fall-cone test.

Table 3.1. Index properties of Ankara Clay

Index Properties of Ankara Clay	
USCS Soil Classification	CH
Specific Gravity	2,711
Maximum Dry Density (Mg/m3)	1,52
Optimum Water Content (%)	24
Fines (%)	73,8
Sand (%)	26,2
Gravel (%)	-
LL (%)	55,9
PL (%)	26,92
SL (%)	20,19

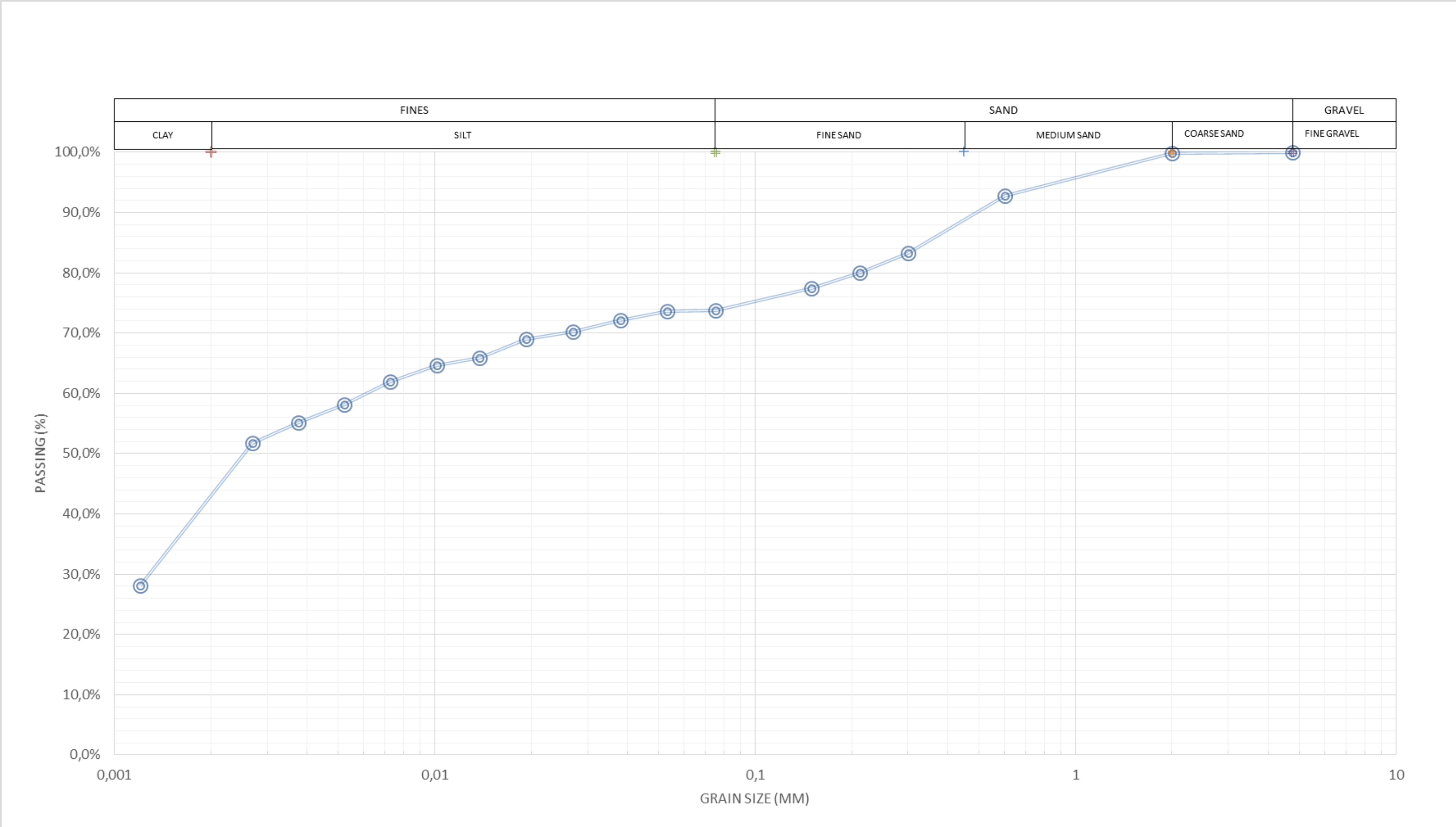


Figure 3.3. Grain size distribution of Ankara clay

3.1.2. Kaolin Clay

Kaolin clay which was used in this study was provided from Kale Mining Inc. which is located in Canakkale, Turkey. Kaolin clay samples were carefully stored in suitable nylon bags to be used in experimental studies. Kaolin clay used was oven dried at 105°C for 24 hours, then samples were sieved from No.40 sieve for experiments conducted in this study.

Kaolin clay which was used in this study and grain sized distribution curve of the Kaolin clay samples are presented in Figure 3.4 and Figure 3.5, respectively. Evaluation of grain size distribution curve of Kaolin clay pointed out that 99.6% of the samples are fine-grained. The particle size analysis were performed by sieve analysis and hydrometer tests according to the ASTM D-6913 and ASTM D-422 standards, respectively.

Figure 3.4. Kaolin clay sample which was used in this study

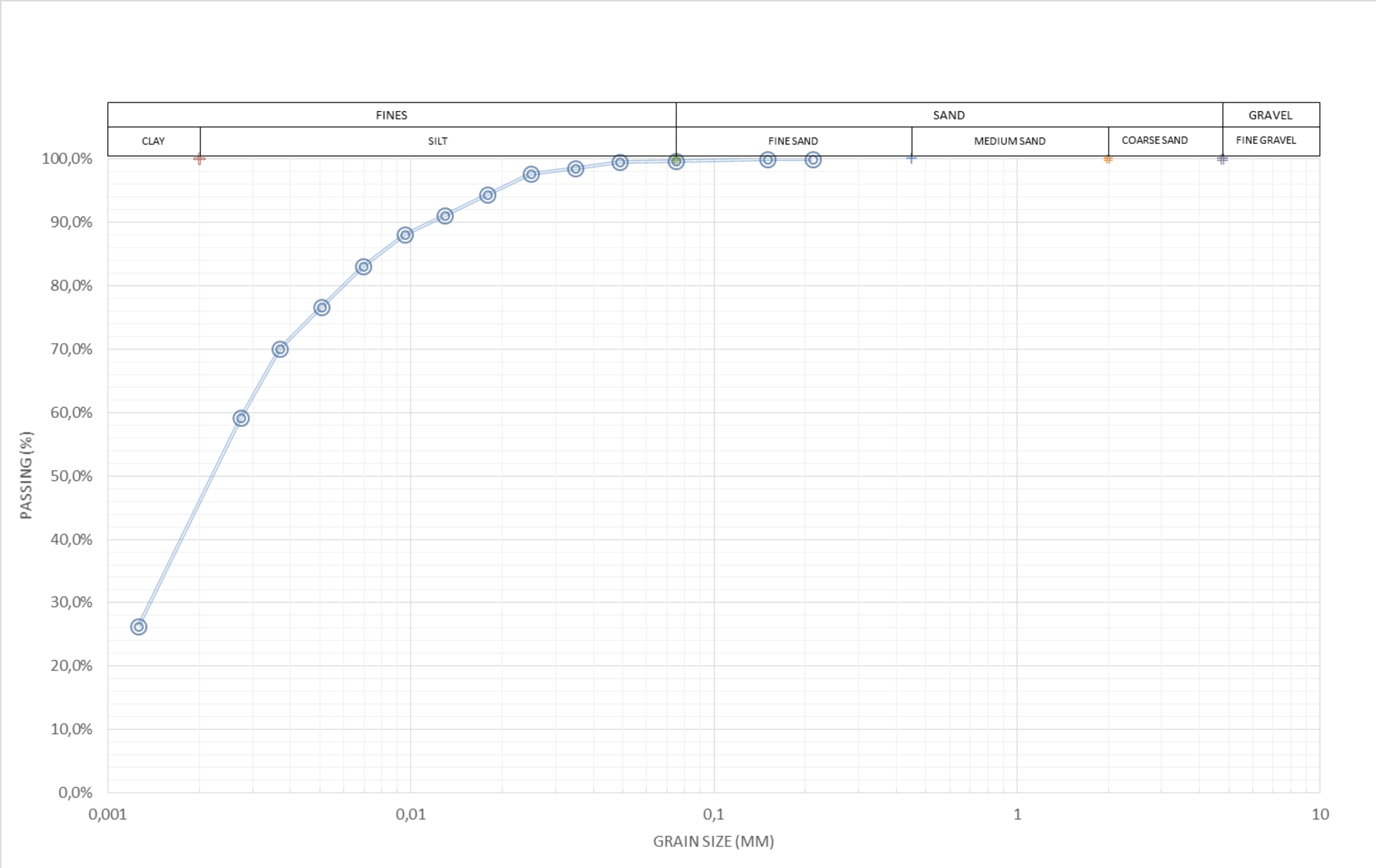


Figure 3.5. Grain size distribution of Kaolin clay

3.1.3. Bentonite

Bentonite which was used for the experimental study was provided from Karakaya Bentonite Factory which is located in Ankara, Turkey. The specific gravity and percent weight passing No.200 sieve and the chemical composition of the bentonite which was used in this study is presented in Table 3.2. Bentonite sample which was used in this study is presented in Figure 3.6.

Table 3.2. The specific gravity, percent weight passing No.200 sieve and chemical composition of the bentonite which was used in this study (Chemical composition is adopted from www.karakaya.com)

Index Properties of Bentonite		
Specific Gravity	2,38	
Percent Weight Passing No.200 Sieve	99,20%	
Chemical Composition	Oxides	Percentage
	Silicon Dioxide	61,28
	Aluminium Oxide	17,79
	Iron (III) Oxide	3,01
	Calcium Oxide	4,54
	Sodium Oxide	2,7
	Magnesium Oxide	2,1
	Potassium Oxide	1,24
	Loss of Ignition	7,34

Figure 3.6. Bentonite sample which was used in this study

3.1.4. Synthetic Fiber

Structural synthetic fiber which was used in this study was provided from Forta Construction Co. which is located in Istanbul, Turkey. Synthetic fibers which was used in this study were 100% virgin copolymer/polypropylene. As it can be seen in Figure 3.7, the synthetic fiber used was consisting of a twisted bundle and the length of the synthetic fibers were 38 mm. The physical properties of synthetic fibers are tabulated in Table 3.3.

The synthetic fibers which was used in this study are designed to improve mechanical properties of concrete based structural elements as it will reduce the concrete shrinkage and increase the concrete toughness and tension crack resistance.

Since it was not suitable to use synthetic fibers with their full length (38 mm), the synthetic fibers were cut equally in three pieces to use in the mixture designs. Also the twisted bundles were pulled and separated from each other to obtain better mixing workability with the soil.

In this experimental study, synthetic fiber was used for stabilization of the Ankara clay and Kaolin clay mixtures to improve the tensile strength and unconfined compressive strength of the soils.

Figure 3.7. Synthetic fiber which was used in this study

Table 3.3. Physical properties of Synthetic Fiber (Adopted from www.forta-ferro.com)

Physical Propoerties of Synthetic Fiber	
Materials	Virgin Copolymer/Polypropylene
Form	Monofilament/Fibrillated Fiber System
Specific Gravity	0,91
Tensile Strength	570-660 Mpa
Length	38 mm
Color	Gray
Acid/Alkali Resistance	Excellent
Absorption	Nil

In Figure 3.8, the synthetic fiber after the preparation process for the mixture designs is presented.

Figure 3.8. Final form of the synthetic fiber which was used in this study

3.1.5. Metal Swarf

METU Department of Metallurgical and Material Engineering Machine Shop provided the waste metal swarf samples which were used in this study. The metal swarf waste was a mixture of waste aluminum, steel and brass swarf. These metal swarf samples were the resultant materials of the computer numerical control machine's (CNC) mechanical process. The specific gravity of metal swarf which was used was around 2.90 and metal swarf was sieved from No.10 sieve before it was used in the mixtures. In Figure 3.9, waste metal swarf which was used in this study is presented.

Figure 3.9. Waste metal swarf which was used in this study

3.1.6. Rubber

Mainly pulverized rubber was used in this experimental study and Akyuz Innovation and Recycling Technologies provided the waste rubber materials. Even though the aim was to use both pulverized rubber and shredded rubber in this study, the shortage on shredded rubber led pulverized rubber to be used in the experiments. One mixture with shredded rubber was designed and the stabilization effect on the direct tensile strength could be investigated on that mixture.

Grain size distribution and index properties of pulverized rubber are presented in Figure 3.10 and Table 3.4, respectively.

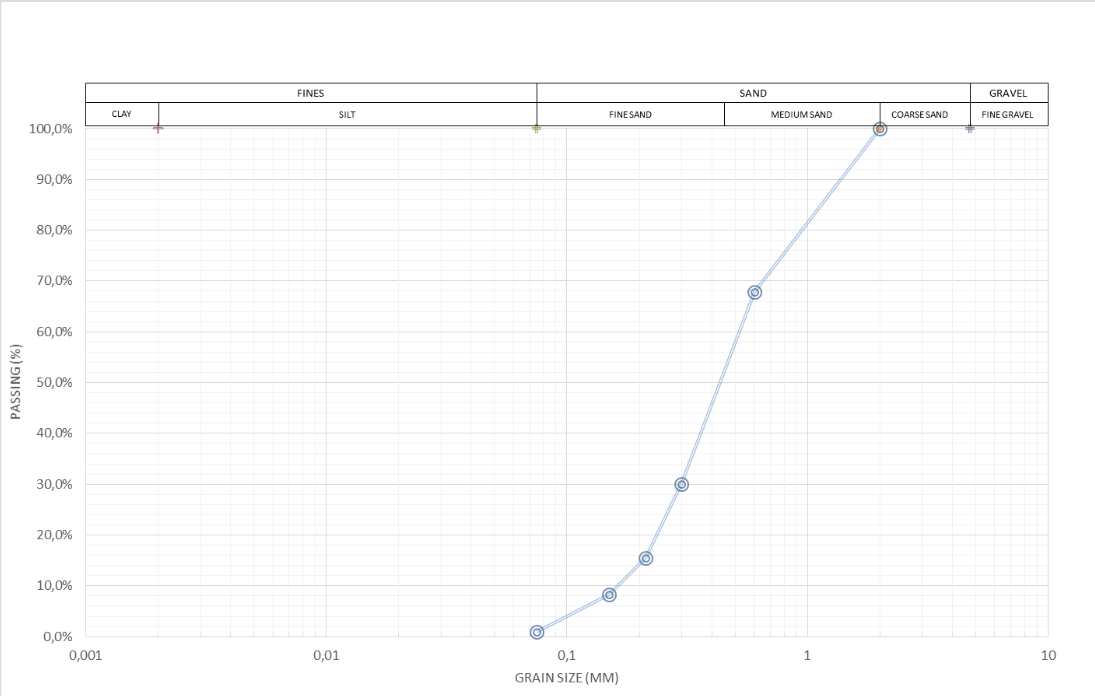


Figure 3.10. Grain size distribution of pulverized rubber

Table 3.4. Index properties of pulverized rubber

Index Properties of Pulverized Rubber	
Specific Gravity	0,65
Fines (%)	1
Sand (%)	99
Gravel (%)	-

The pulverized rubber and shredded rubber which were used in this study are illustrated in Figure 3.11 and Figure 3.12, respectively.

Figure 3.11. Pulverized rubber which was used in the experiments

Figure 3.12. Shredded rubber which was used in the direct tensile strength test

3.2. Mixture Designs

The mixtures were designed according to the dry weight percentages of total mixture. After the determination of compaction characteristics of all mixtures, all mixtures were designed according to their 95% of max dry density and corresponding wet of optimum water contents.

In order to investigate the effects of materials which were used in this study, on the tensile strength and unconfined compressive strength of the mixtures, various percentages of synthetic fiber, pulverized rubber, metal swarf and bentonite were used as it can be seen in Table 3.5. Every mixture design was named to avoid unnecessary complexity.

Table 3.5. Mixture designs and mixtures' code names

Mixture Design	Mixture Code
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04
Ankara Clay 100% + Water Content 27,2%	AC-01
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09
Ankara Clay 95% + Shredded Rubber 2,5% + Bentonite 2,5% + Water Content 28%	AC-10

3.3. Index Properties of Mixtures

For every mixture, sieve analysis, hydrometer tests, consistency limit tests and specific gravity tests were performed. The procedures and the results are presented in following subsections.

3.3.1. Grain Size Distribution

All mixtures were subjected to sieve analysis and hydrometer tests for the parts of mixtures which are retaining on No.200 sieve and passing No.200 sieve, respectively. Grain size distribution curves for Ankara clay and Kaolin clay mixtures are provided in Figure 3.13 and Figure 3.14, respectively. Also the combined gradation curve for all mixtures is provided in Figure 3.15. Clay contents of the mixture designs are provided in Table 3.6. All mixtures' clay contents were determined to be in the range of 40 to 49%. Soil classifications were made according to USCS and AASHTO soil classification system and tabulated in Table 3.7. The grain size distribution for all mixture designs are provided separately in Appendix B. Mixtures were determined to be either high plasticity clay (CH) or high plasticity silt (MH) according to the USCS.

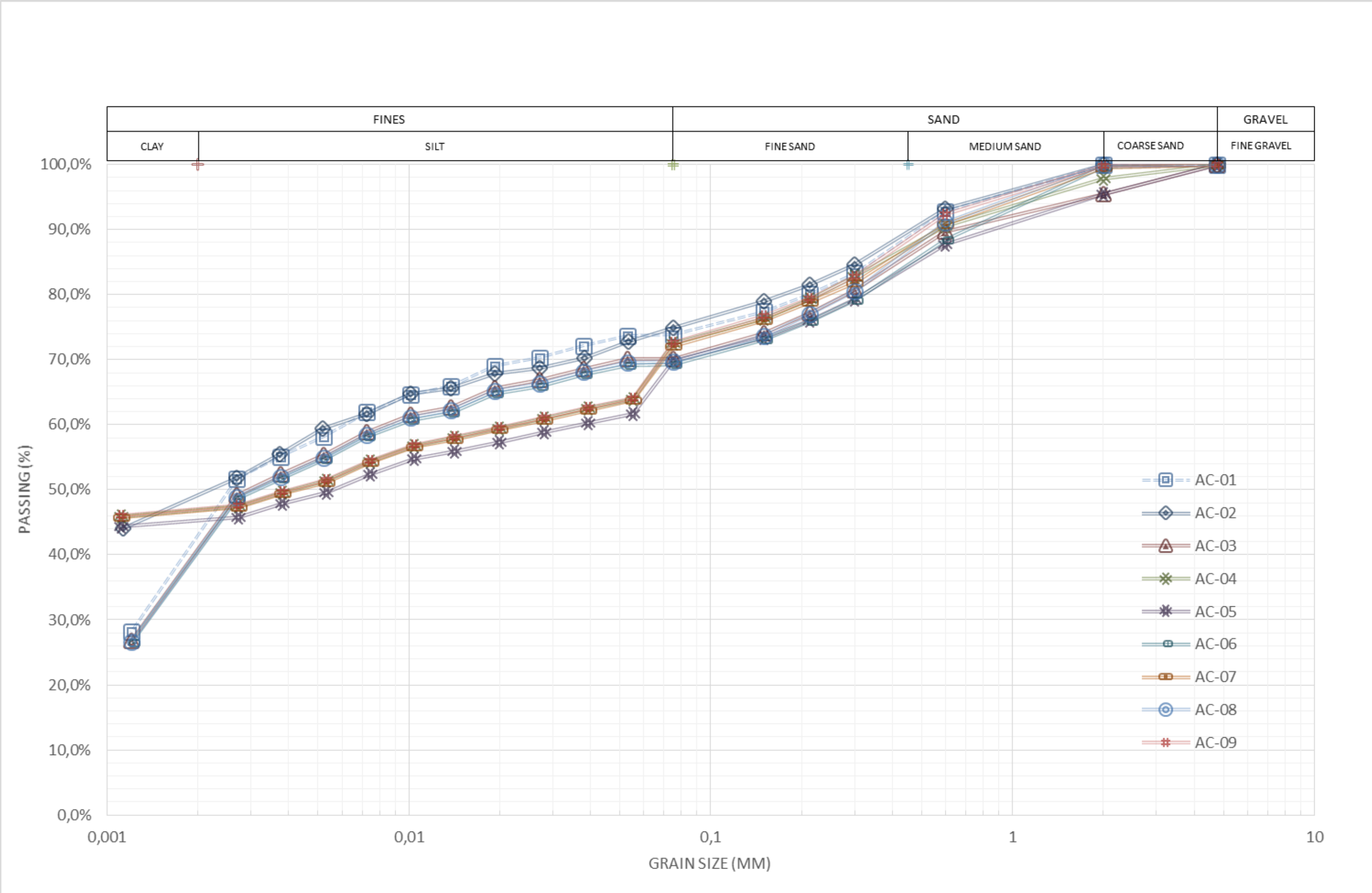


Figure 3.13. Grain size distribution of Ankara clay mixture designs

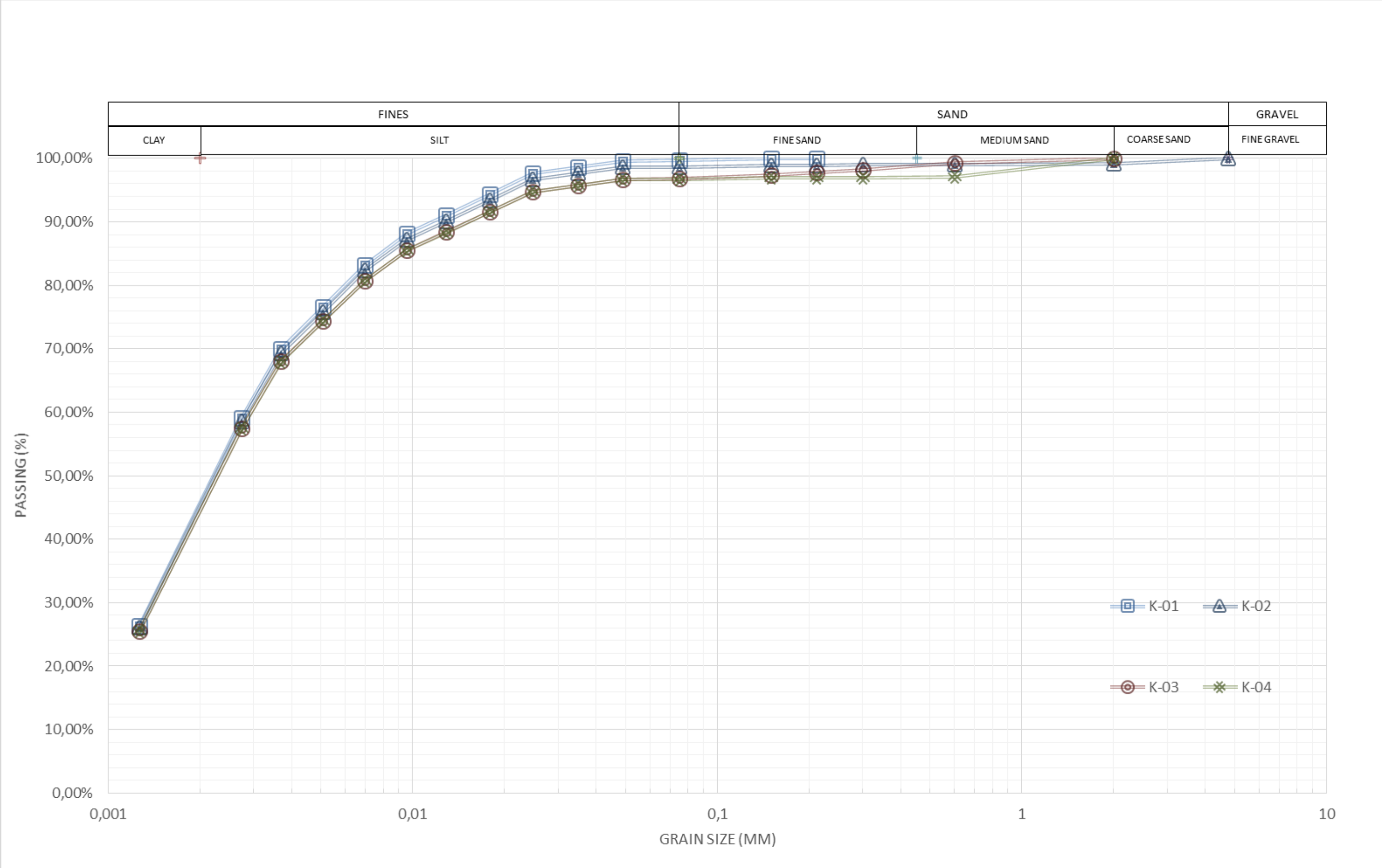


Figure 3.14. Grain size distribution of Kaolin clay mixture designs

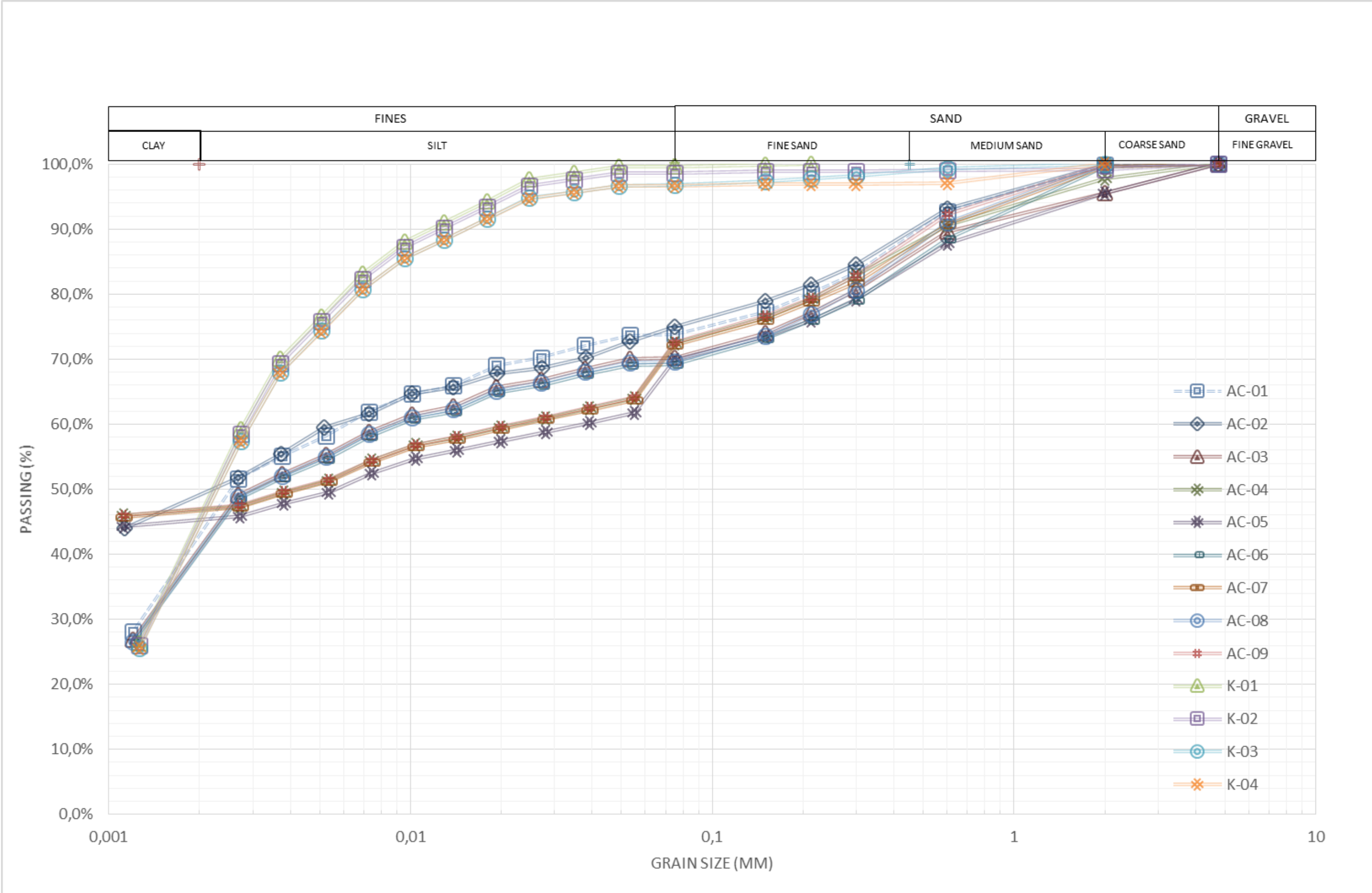


Figure 3.15. Combined grain size distribution of all mixture designs

Table 3.6. Clay contents of the mixture designs

Mixture Design	Mixture Code	Clay Content (%)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	46
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	46
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	44
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	44
Ankara Clay 100% + Water Content 27,2%	AC-01	43
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	49
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	41
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	47
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	45
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	40
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	47
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	40
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	47

Table 3.7. Soil classification of mixtures according to USCS and AASHTO Soil Classification

Mixture Design	Mixture Code	Soil Classification (USCS)	Soil Classification (AASHTO)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	MH	A-7-5
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	MH	A-7-5
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	MH	A-7-5
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	MH	A-7-5
Ankara Clay 100% + Water Content 27,2%	AC-01	CH	A-7-5
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	CH	A-7-5
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	MH	A-7-6
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	MH	A-7-6
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	MH	A-7-6
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	CH	A-7-5
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	CH	A-7-5
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	CH	A-7-5
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	CH	A-7-5

3.3.2. Specific Gravity

All of the mixtures except the ones with pulverized rubber were subjected to specific gravity tests according to ASTM D-854 standard pycnometer method.

The specific gravity of the mixtures with pulverized rubber content was not obtainable by standard pycnometer method because of the relatively low density of the rubbers. Rubber particles were floating on the water and applying air-extraction process caused rubber particles to spill out from the bottle with some of the soil. In order to determine the specific gravity of the mixtures with pulverized rubber, kerosene was used instead of water because of its low density relative to water. With kerosene method, the pulverized rubber particles were able to sink and specific gravity calculations were able to be made.

Every mixture was cured for at least one day to obtain uniformity on water content before specific gravity testing. The specific gravity values of AC-01 and K-01 mixtures were determined to be 2.711 and 2.592, respectively. For both Ankara clay and Kaolin clay mixtures, addition of synthetic fiber and pulverized rubber significantly decreased the specific gravity values of the related mixtures. On the other hand, addition of metal swarf increased the specific gravity values of both related Ankara clay mixtures and Kaolin clay mixtures. It can be inferred from the determined specific gravity values that, the addition of materials with relatively high specific gravity values to the soil mixture increases the specific gravity of the mixture design whereas addition of materials with relatively low specific gravity values decreases the specific gravity of the mixture design. All of the specific gravity values for mixture designs are tabulated in Table 3.8.

Table 3.8. Specific gravity of mixtures in this study

Mixture Design	Specific Gravity (Gs)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	2,592
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	2,486
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	2,564
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	2,647
Ankara Clay 100% + Water Content 27,2%	2,711
Ankara Clay 95% + Bentonite 5% + Water Content 28%	2,714
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	2,363
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	2,482
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	2,419
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	2,823
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	2,726
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	2,475
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	2,487

3.3.3. Consistency Limits

All of the mixtures' liquid limits, plastic limits, plasticity indexes and shrinkage limits were determined and the values are presented in Table 3.9 and Figure 3.16.

Liquid limit and plastic limit tests for the mixtures AC-01, AC-02 and K-01 were performed with Casagrande method and rolling thread method according to ASTM D-4381. For the other mixtures consist of synthetic fiber, metal swarf and pulverized rubber, it was not suitable to use same methods to determine consistency limits. In order to overcome this problem fall cone test was used to determine the mixtures' liquid limits and plastic limits.

The fall cone method was more suitable way for determination of the consistency limits of mixtures because using traditional Casagrande methods would not be able to give acceptable results. The waste materials in the mixtures were sticking to each other and were not letting grooving tool to pass through the soil layer, also for rolling thread test the waste materials were not staying in the rolled parts and this situation made the rolling thread method unreliable.

The fall cone method was conducted according to the BS 1377 (1975). Since the fall cone test is widely used for determination of liquid limit of soils, many researchers have been also investigating determination of plastic limit from fall cone method.

Wood and Wroth (1975) stated that cone penetrometer test can be used to determine both LL and PL values of fine-grained soils. The researchers suggested to use two different cones with different weight on the same soil samples to perform cone penetrometer test and to plot data as water content vs log cone penetration. As a result they suggested following equation that PI can be calculated from.

$$PI = \frac{2\Delta}{\log(W_1/W_2)}$$

where PI is plasticity index of soil, W_1, W_2 are the weights of the two cones which are used, and Δ is defined as vertical separation on the linear graphs of water content versus the logarithmic values of fall cone penetration depth for two cones.

Muntohar and Hashim (2015), conducted fall cone tests on the clayey soil samples according to the BS 1377 standard and also the researchers performed traditional rolling thread test for determination of PL on the same samples. The researchers stated that, using rolling thread method to determine the PL of soils has major disadvantages because the method mostly rely upon the operator as the pressure applied to the soil thread may vary according to the operators on the rate of rolling and they stated that by using cone penetrometer test, these disadvantages can be eliminated. According to the results that they calculated and the method of determination of plastic limits by fall cone test using two different cones which is suggested by Wood and Wroth (1978), the researchers stated that, the plastic limit can be determined in range of 2-4 mm at cone penetration depth.

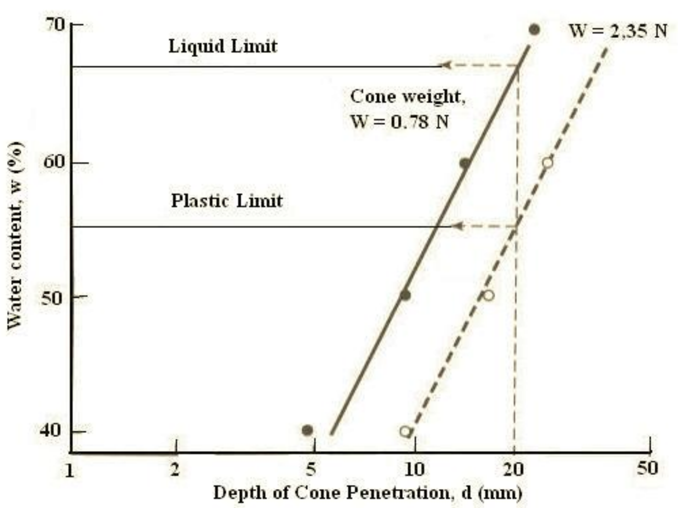


Figure 3.16. Determination of PL using fall cone test with two different cones (Wood and Wroth, 1978)

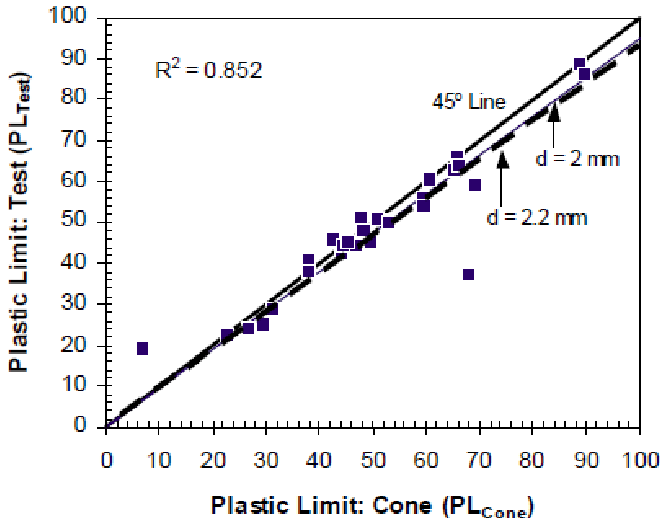


Figure 3.17. Correlation between PL calculated from rolling thread and fall cone test (Muntohar and Hashim, 2015)

As suggested by the researchers the fall cone test was used to determine both LL and PL of all mixtures. The LL and PL values of mixtures K-01, AC-01 and AC-02 were determined from both Casagrande methods and fall cone test. As it can be seen in Table 3.9, the results were quite close to each other and this demonstrated the reliability of using fall cone test to determine the PL and LL of fine-grained soils.

LL and PL value of AC-01 mixture determined to be 55.9% and 26.92%, respectively whereas LL and PL value of K-01 mixture determined to be 54.77% and 32.69%, respectively. It can be inferred from the determined LL and PL values that, the addition of synthetic fiber significantly increased the LL and PL values of the related Ankara clay and Kaolin clay mixtures.

On the other hand, addition of pulverized rubber and metal swarf decreased the LL and PL values of the related Ankara clay and Kaolin clay mixtures. Also it can be stated that, the addition of bentonite to the Ankara clay mixtures increased the LL values and decreased the PL values of the related mixtures.

Shrinkage limits of the mixtures were determined according to the ASTM D427-04 by the mercury method. The results are also tabulated in Table 3.8. SL value of the AC-01 mixture determined to be 20.19% whereas SL value of the K-01 mixture determined to be 32.69%. Shrinkage limit values increased for both Ankara clay and Kaolin clay mixtures with addition of synthetic fiber, pulverized rubber and metal swarf. Addition of bentonite, on the other hand, decreased the shrinkage limits of the Ankara clay mixtures.

All mixtures without bentonite addition were cured in curing chamber for at least one day, the mixtures with bentonite addition were cured at least two days due to the swelling reactions which might happen between water and bentonite.

Table 3.9. Consistency limits of mixtures in this study

Mixture Design	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (PI)	Shrinkage Limit (%)	Liquid Limit (%) (Casagrande Method)	Plastic Limit (%) (Rolling Thread Test)
K-01	54,77	42,94	11,83	32,69	53,2	46,3
K-02	56,61	40,82	15,79	31,09	-	-
K-03	53	39,78	13,22	37,25	-	-
K-04	53,5	44,02	9,48	36,30	-	-
AC-01	55,9	26,92	28,98	20,19	55	27,2
AC-02	60	23,55	36,45	19,10	58,3	25,4
AC-03	76,81	44,06	32,75	40,45	-	-
AC-04	69,85	35,12	34,73	23,37	-	-
AC-05	74,33	39,34	34,99	29,03	-	-
AC-06	53,5	27,40	26,10	24,20	-	-
AC-07	58	21,20	36,80	17,60	-	-
AC-08	51	25,33	25,67	23,53	-	-
AC-09	57	19,41	37,59	14,51	-	-

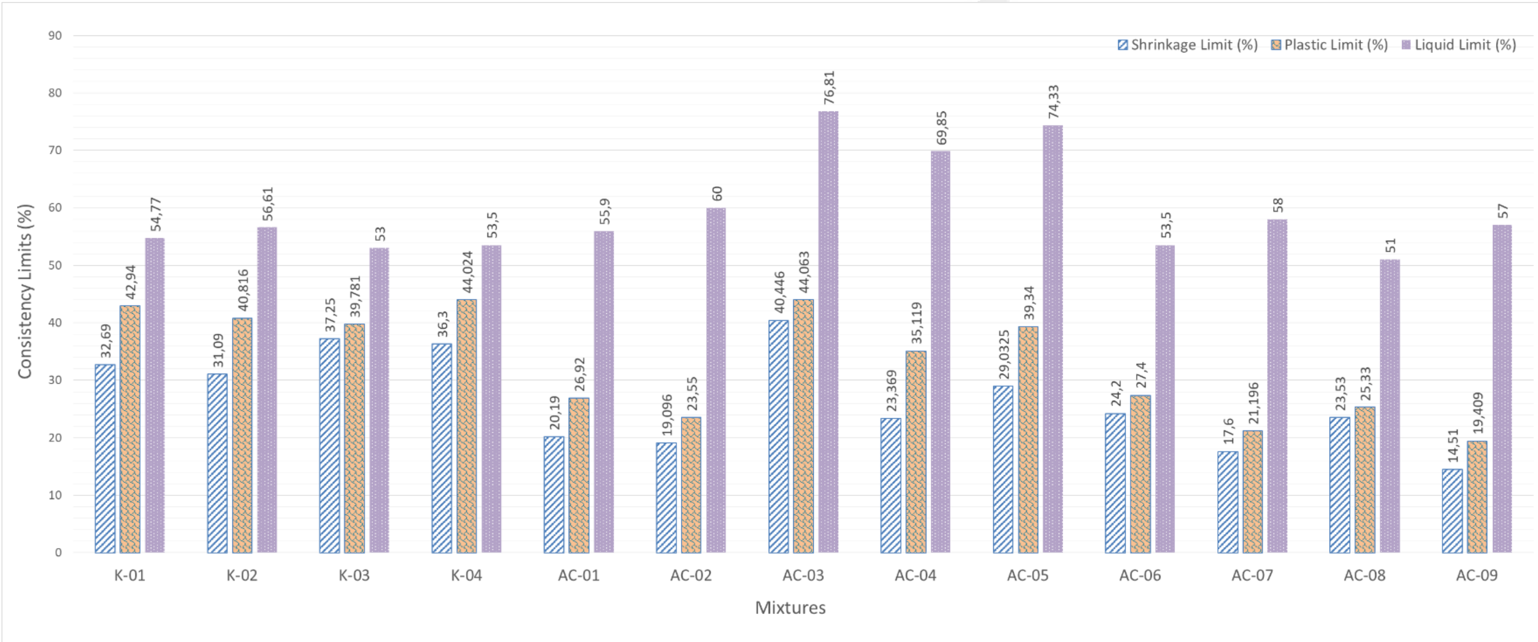


Figure 3.18. Consistency limits of mixtures in this study

3.3.4. Activity of the Mixture Designs

Activity classes of the all mixture designs were determined according to the LL values, PL values and clay contents of the related mixtures. Activities and the activity classes of the mixtures are tabulated in Table 3.10. In terms of activity, the specimens were determined to be inactive and normal clay.

Table 3.10. Activities and activity classes of the mixtures

Mixture Code	Activity (Ac)	Activity Class
K-01	0,26	Inactive Clay
K-02	0,34	Inactive Clay
K-03	0,30	Inactive Clay
K-04	0,22	Inactive Clay
AC-01	0,67	Inactive Clay
AC-02	0,75	Normal Clay
AC-03	0,80	Normal Clay
AC-04	0,75	Normal Clay
AC-05	0,78	Normal Clay
AC-06	0,65	Inactive Clay
AC-07	0,78	Normal Clay
AC-08	0,64	Inactive Clay
AC-09	0,80	Normal Clay

3.4. Compaction Characteristics of the Mixtures

Compaction characteristics of all mixture designs were determined according to ASTM D-698 by standard proctor test. Mixtures were compacted in 3 layers and every layer was compacted by applying 25 strokes with 2.5 kg rammer which falls freely from 30 cm. height.

Maximum dry densities and optimum moisture contents of mixtures are tabulated in Table 3.11. Combined compaction curves of Ankara clay and Kaolin clay mixtures are presented in Figure 3.19 and Figure 3.20, respectively. Also the compaction curves for each mixture design are provided in Appendix A. Maximum dry density and optimum moisture content of AC-01 mixture were determined to be 1.52 Mg/cm^3 and 24%, respectively whereas maximum dry density and optimum moisture content of K-01 mixture were determined to be 1.46 Mg/cm^3 and 26%, respectively. It can be inferred from the determined maximum dry densities and optimum moisture contents that, synthetic fiber and pulverized rubber addition to Ankara clay decreased the maximum dry densities of the related mixtures whereas the optimum moisture contents remained approximately at same value for all material additions. For Kaolin clay mixtures, addition of pulverized rubber and metal swarf increased the maximum dry densities of the related mixtures whereas addition of synthetic fiber did not significantly affect the maximum dry density of the related mixture. For all Ankara clay mixtures and Kaolin clay mixtures, optimum water contents did not show any significant difference between each other. The difference of optimum moisture contents remained between 1-2%.

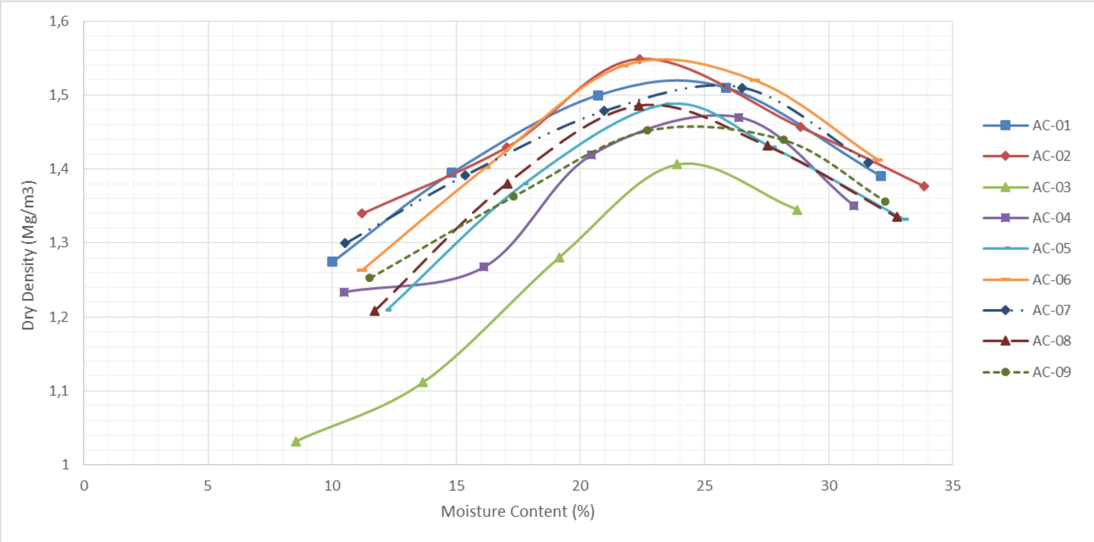


Figure 3.19. Combined compaction curves of Ankara clay mixtures

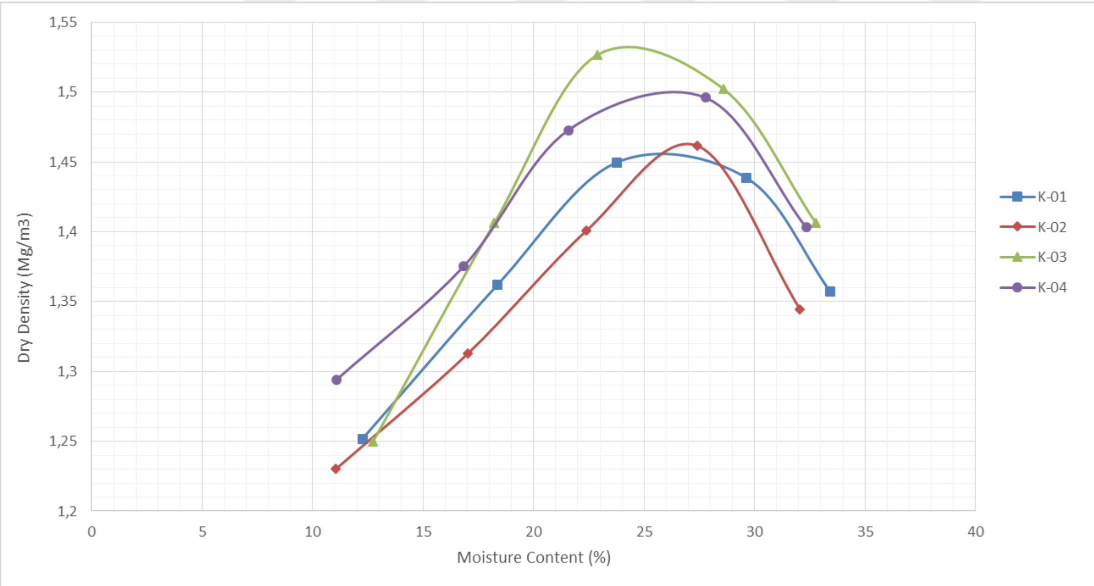


Figure 3.20. Combined compaction curves of Kaolin clay mixtures

Table 3.11. Maximum dry densities and optimum moisture contents of the mixtures

Mixture Design	Maximum Dry Density (Mg/cm3)	Optimum Moisture Content (%)
K-01	1,46	26
K-02	1,465	27
K-03	1,53	24,5
K-04	1,5	26,5
AC-01	1,52	24
AC-02	1,55	22,5
AC-03	1,41	24
AC-04	1,46	25,5
AC-05	1,425	24
AC-06	1,55	24,5
AC-07	1,515	25,5
AC-08	1,49	22,2
AC-09	1,46	24,5

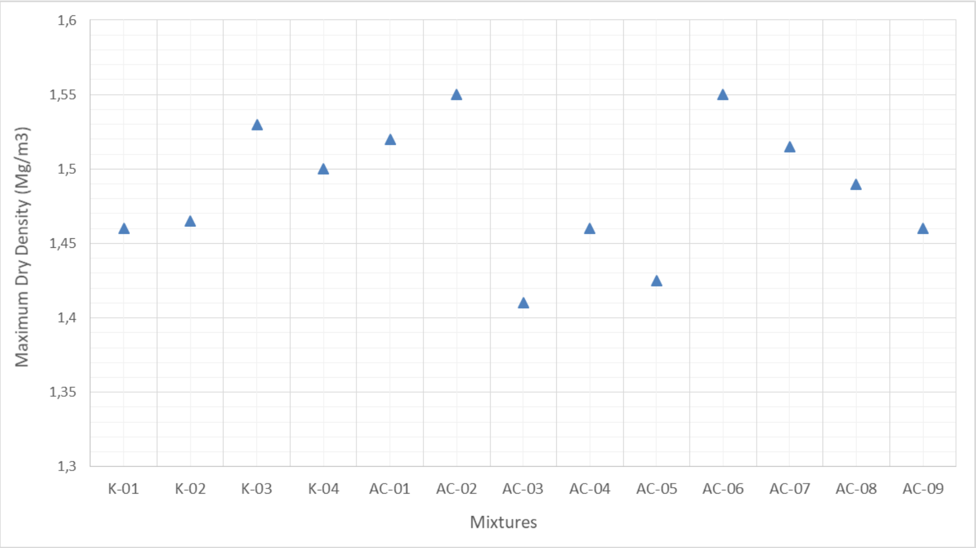


Figure 3.21. Maximum dry densities of the mixture designs

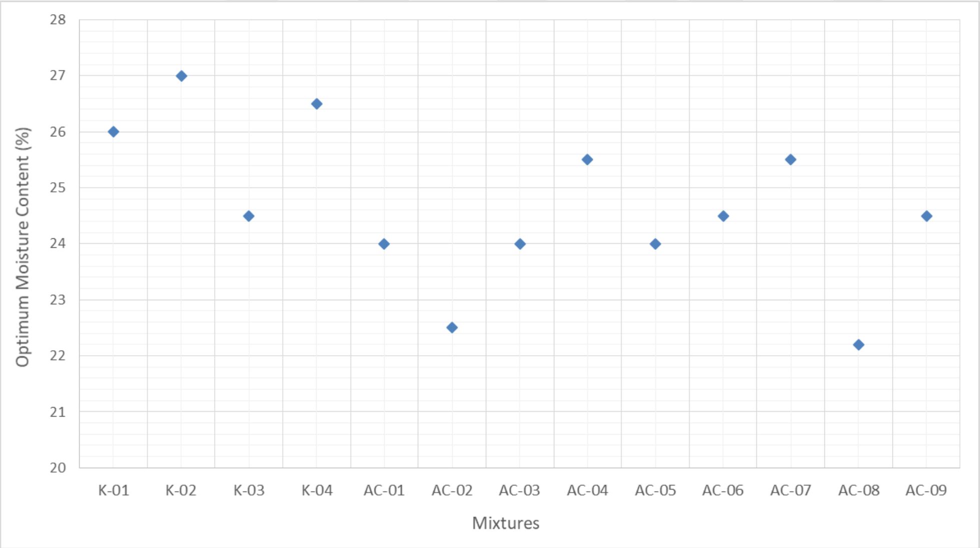


Figure 3.22. Optimum moisture contents of the mixture designs

3.5. Experimental Procedures

3.5.1. 8-Shaped Direct Tensile Strength Test

Brace (1964) stated that, specimens which has the height to diameter ratio between 2-3 of the central test region are named as dog-bone shape or 8-shaped and considered to be the best shape for direct tensile testing. It is also stated by Brace (1964) that, the stress concentration happens on the neck area of the specimen when the uniaxial tensile force is applied to the 8-shaped specimen and hence, corner stress concentrations are eliminated by performing direct tensile strength tests on dog-bone shape or 8-shaped specimens.

In this study, a special 8-shaped mold was used to prepare and compact the specimens for direct tensile testing as can be seen in Figures 3.23, 3.24 and 3.25. The mold provided to form a necked specimen which can be considered as a dog-bone shape. This neck area allowed failure to occur at the center of the specimens. The compaction was made by using Harvard miniature compaction tamper by calibrating the spring pressure to 9.07 kg. Before compaction the inner surfaces of the mold were greased by vaseline to extract the compacted soil from mold without any damage caused to the specimen. During compaction, the soil was put in three layers and every layer was dynamically compacted by 25 strokes with Harvard miniature compactor tamper. After the compaction, the specimens were carefully extracted from the mold by separating two halves of the mold from each other. An example of compacted soil specimen before and after extracting from the mold are presented in Figure 3.26 and Figure 3.27, respectively. The dimensions of the compacted soil specimen is illustrated in Figure 3.28. Direct tensile tests were conducted on the compacted 8-shaped specimens by newly developed set up as shown in Figure 3.29. The direct tensile set up consisted of two grips suitable for 8-shaped specimens to place the specimens and a bucket attached to the lower grip to apply the load. The grips which were used for this set up are presented in Figure 3.30.

To conduct the experiments, compacted specimen was firstly placed in the rigid grip then the lower grip with the bucket was attached carefully placed on the specimen. After placing both grips and bucket, sand was poured into the bucket. The sand was poured very gently and close to the bottom of the bucket to avoid any impact related damage to be caused to the specimens. The sand was poured into the bucket until the failure occurred. After the failure, the lower part of the specimen which split from the upper part was extracted from inside of the lower grip, then the bucket, lower grip and the sand poured were weighted to calculate the maximum tensile strength of the specimens. Also it should be stated that, since this described direct tensile method did not propose any displacement measurement, tensile strain qualifications could not be calculated. An example of tension failure of the 8-shaped specimen after direct tensile testing is provided in Figure 3.31.

The tensile strength of specimens was obtained by dividing the weight of the lower grip and sand-filled bucket by the cross-sectional area of the neck.

$$\sigma_{t_8} = \frac{T_{max}}{A}$$

where σ_{t_8} is 8-shaped tensile strength of soil, T_{max} is maximum tensile load and A is the cross-sectional area of the neck.

The direct tensile test specimens were compacted at 95% of their maximum dry density and corresponding wet of optimum moisture content by dynamic compaction because as it can be seen in Figure 2.20, Zeh and Witt (2007) stated that the tensile strength of the specimens compacted at their wet of optimum gives higher tensile strength value. Also the workability increased by preparing specimens at their wet of optimum.

Mixtures were cured for one day to allow water content distributes uniformly. Also the mixtures with bentonite content were cured for two days in order to allow bentonite fully interact with the water content.

The direct method proposed in this study was performed according to the ASTM (2008a) D2936-08 standard and all the direct tensile tests were repeated three times in order to assure the reliability of the study.

Figure 3.23. Compaction mold which was used in this study to prepare 8-shaped specimens

Figure 3.24. Compaction mold which was used in this study to prepare 8-shaped specimens

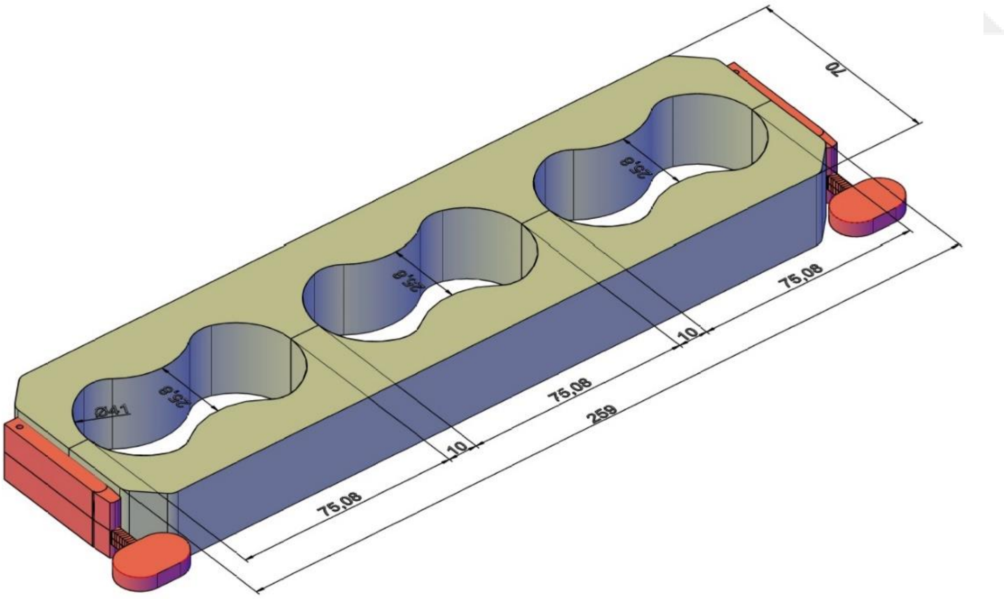


Figure 3.25. Dimensions of the compaction mold in millimeters

Figure 3.26. Specimen after compaction process in the mold

Figure 3.27. Compacted and extracted soil specimens for direct tensile testing

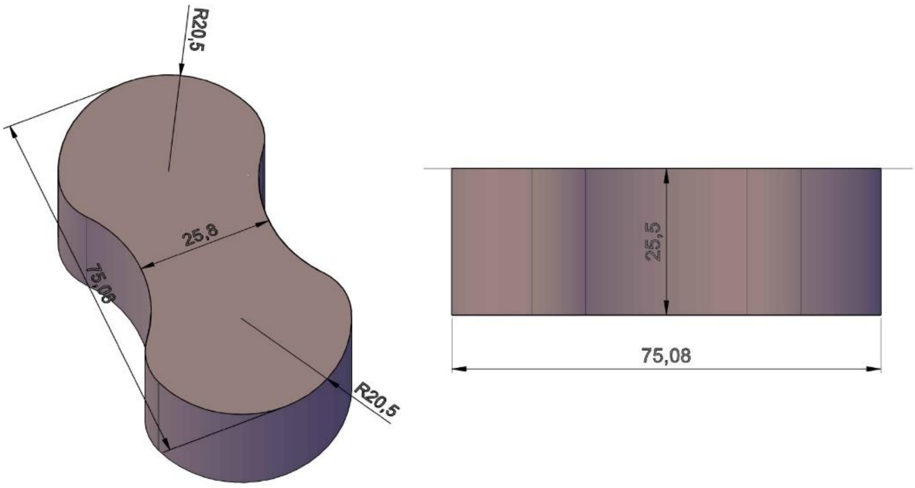


Figure 3.28. Dimensions of the compacted 8-shaped specimen (in millimeters)

Figure 3.29. Direct tensile testing set up which was developed and used in this study

Figure 3.30. Grips which were used to place 8-shaped soil specimen for direct tensile testing

Figure 3.31. Tension failure of the 8-shaped specimens after direct tensile testing

3.5.2. Split Tensile Test

Split tensile test or Brazilian tensile strength test was used in this study as an indirect method of tensile testing. A cylindrical specimens were prepared by Harvard miniature compaction apparatus to apply the same compaction energy which applied to the 8-shaped tensile test specimens. Before compaction the inner surface of the mold was greased with vaseline for specimens to be easily extracted. During compaction, the soil was put in 3 layers and every layer was compacted by 25 strokes with Harvard miniature compaction tamper. After the compaction, specimen was extracted by specimen ejector. Compacted specimens for split tensile testing are presented in Figure 3.32.

The split tensile mold consisted of two platens for cylindrical specimen and this mold was suitable for ASTM C-496. An illustration of the mold with its dimensions, is presented in Figure 3.33. Before placing the specimen in between the split tensile mold plates, the plates were calibrated by aligning two platens with the help of unconfined compression test machine as seen in Figure 3.35. The specimen, then, was placed horizontally on the platens on the split tensile test molds by centering the specimen as it can be seen in Figure 3.36.

Finally the load was applied by an unconfined compression test machine until the radial tension cracks and failure occurred. An example of split tensile test specimen after the testing procedure is presented in Figure 3.37. The strain rate used on unconfined compression test machine was 0.5 mm/min and a sensitive proving ring is used for reliable results.

The split tensile strength values of the specimens were calculated from the following equation:

$$\sigma_{t_{split}} = \frac{2P}{\pi * D * L}$$

where P is maximum compressive load on specimen, D is cylindrical diameter of specimen and L is the length of the specimen. To obtain maximum compressive load on specimen, unconfined compressive strength calculation procedures were used.

The split tensile test specimens were compacted at 95% of their maximum dry density and corresponding wet of optimum moisture content by dynamic compaction. Also all tests were repeated three times in order to assure the reliability of the study.

Figure 3.32. Cylindrical specimens prepared for both split tensile testing and unconfined compression testing

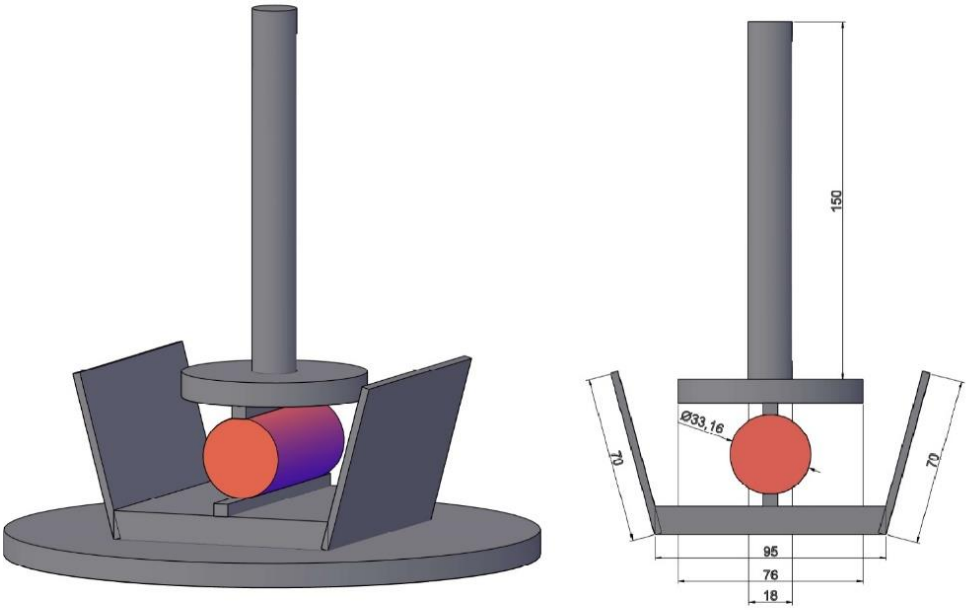


Figure 3.33. Illustration of split tensile testing mold and the dimensions of the mold (in millimeters)

Figure 3.34. An overview of split tensile test with unconfined compression test machine

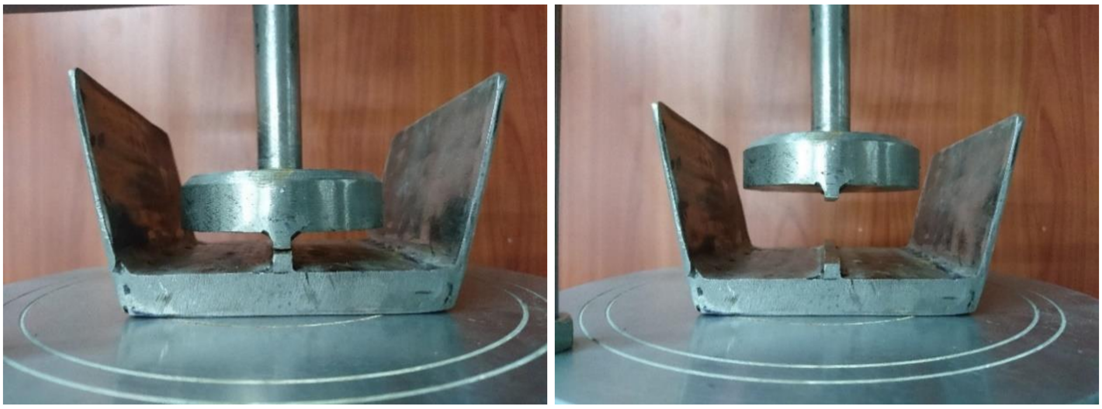


Figure 3.35. Calibration of split tensile testing mold and platens

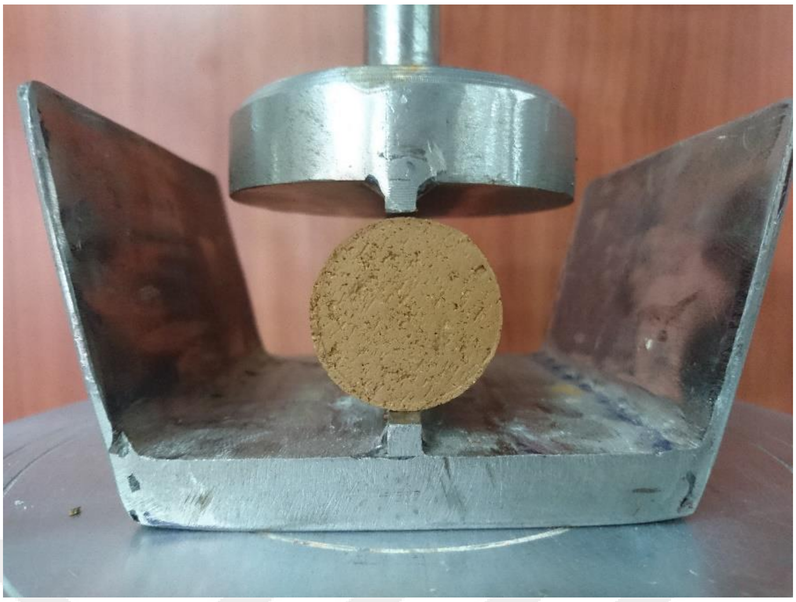


Figure 3.36. Split tensile test specimen before the testing process

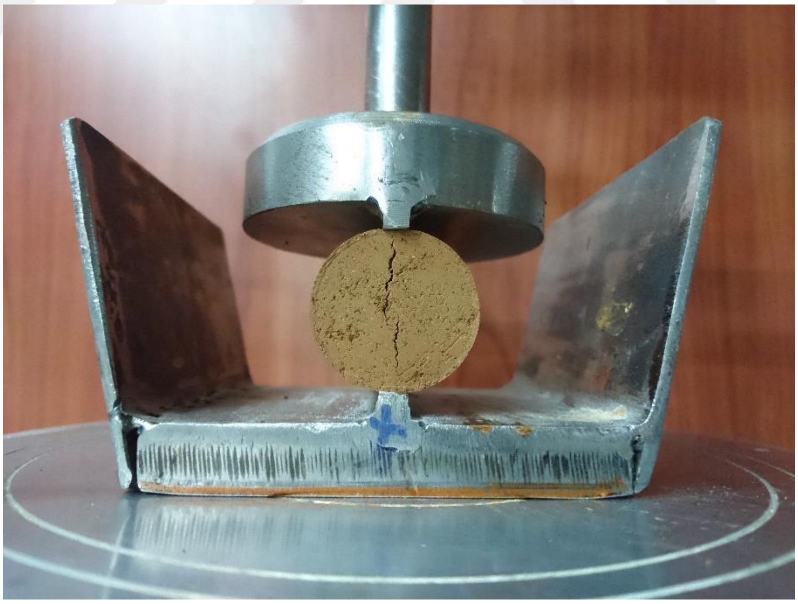


Figure 3.37. Split tensile test specimen after the testing process

3.5.3. Unconfined Compression Test

All of the mixtures were tested for their unconfined compressive strength in this study. ASTM D2166/D2166M-16 standard was followed according to perform unconfined compression tests on the specimens.

The specimens were prepared with the same procedure as they were prepared for the split tensile testing. The specimens were prepared by Harvard miniature compaction apparatus as it was used in split tensile test specimen preparation procedure.

The unconfined compression test specimens were compacted at 95% of their maximum dry density and corresponding wet of optimum moisture content by dynamic compaction. The measurement and calculations were made according to the axial deformation and axial load. Axial strain rate which was used for unconfined compression tests was 0.5 mm/min and a sensitive proving ring was used for reliable measurements. The compressive stress at failure was recorded as unconfined compressive strength for all specimens.

An illustration of specimens used for both unconfined compression test and split tensile test are presented in Figure 3.38. Two pictures of a specimen which are before and after unconfined compression testing process, are presented in Figure 3.39 and Figure 3.40, respectively.

All of the unconfined compression tests on the mixture specimens were repeated two times to assure the reliability of the test result and the study.

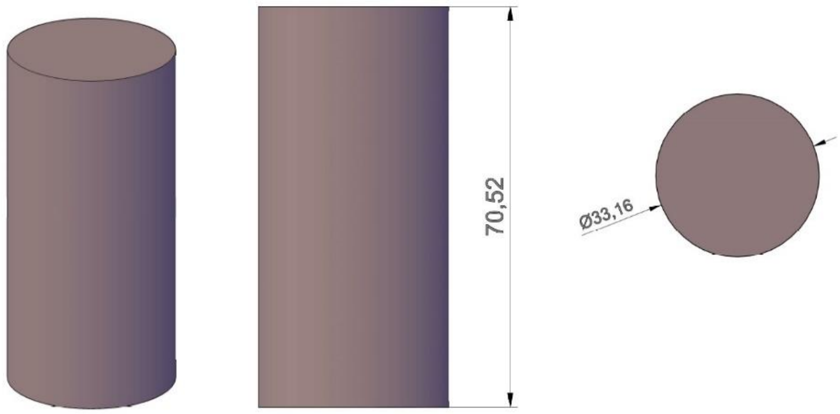


Figure 3.38. Illustration and dimensions of the unconfined compression test and split tensile test specimens (in millimeters)

Figure 3.39. Unconfined compression test specimen before testing process

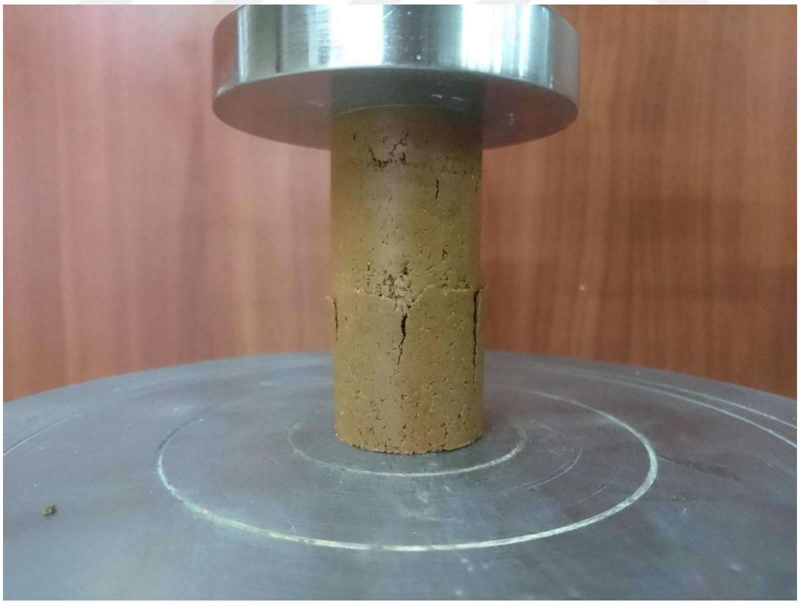


Figure 3.40. Unconfined compression test specimen after testing process

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1. Experimental Results

4.1.1. 8-Shaped Direct Tensile Strength

8-shaped direct tensile tests were performed on all mixtures. For every mixture the direct tensile tests were repeated three times and the average tensile strength value of these triplicate experimentations were expressed as the tensile strength of related mixture design. 8-shaped direct tensile test results are given in Table 4.1 and Figure 4.1.

Different tensile strength values were evaluated from Ankara clay mixtures and Kaolin clay mixtures. For Ankara clay mixtures, material (synthetic fiber, bentonite etc.) percentage which was added on Ankara clay by its dry weight was kept fixed as 5% of the dry weight. For example, a mixture with 95% Ankara clay had either 5% synthetic fiber or 2.5% synthetic fiber and 2.5% bentonite. On the other hand, the Kaolin clay mixtures were prepared with a fixed 5% bentonite addition and various percentages of synthetic fiber, pulverized rubber and metal swarf.

As it can be seen from Table 4.1, the tensile strength of 100% Ankara clay was calculated as 63.44 kPa by 8-shaped direct tensile test. Addition of 5% bentonite on Ankara clay increased the direct tensile strength to 65.19 kPa.

Table 4.1. 8-shaped direct tensile strength of the mixtures

Mixture Design	Mixture Code	8-Shaped Tensile Strength, σ_{t_8} (kPa)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	92,10
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	71,07
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	59,74
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	70,98
Ankara Clay 100% + Water Content 27,2%	AC-01	63,44
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	65,19
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	69,88
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	72,25
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	72,52
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	35,74
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	33,68
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	39,28
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	40,95
Ankara Clay 95% + Shredded Rubber 2,5% + Bentonite 2,5% + Water Content 28%	AC-10	50,16

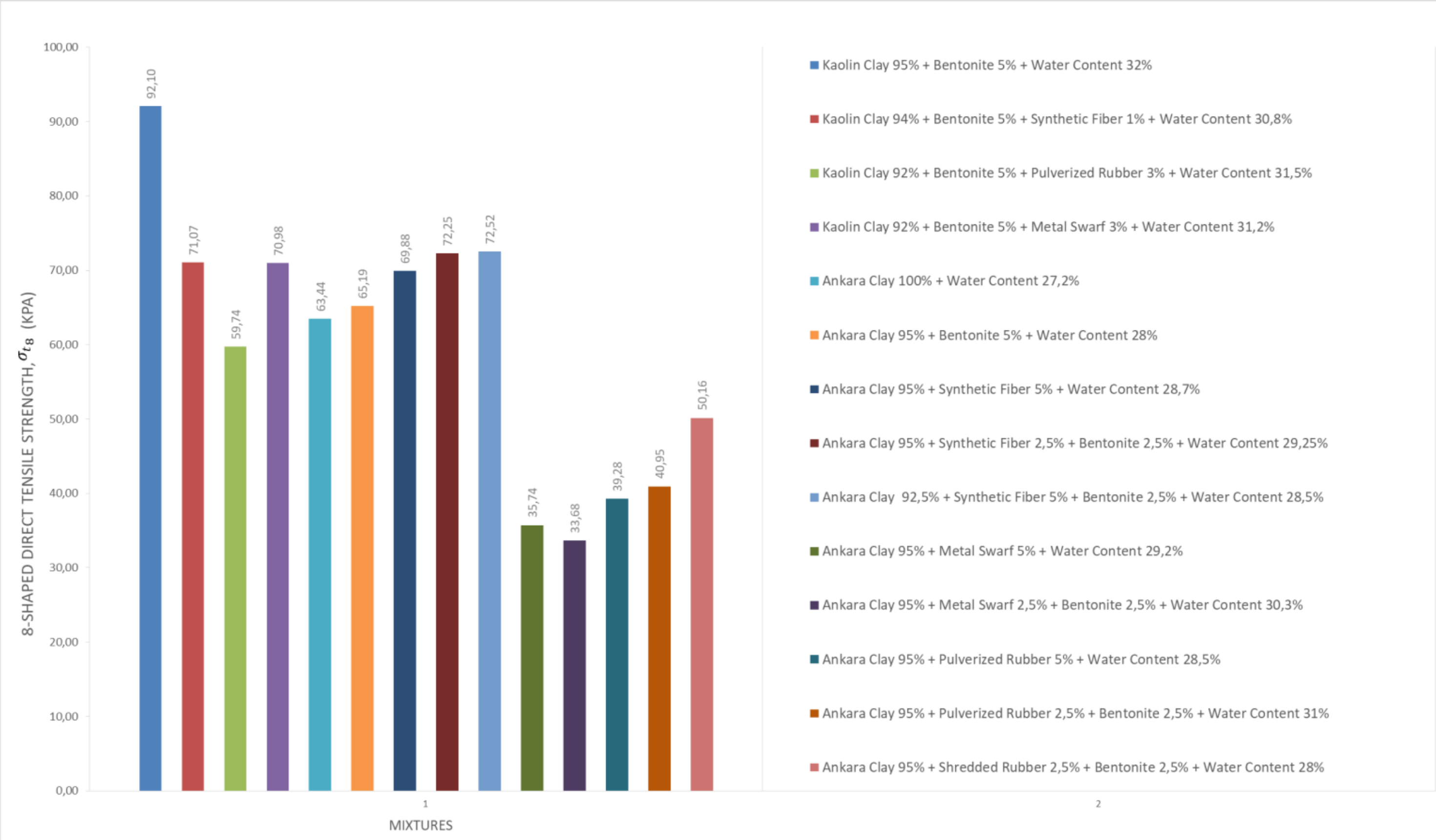


Figure 4.1. 8-shaped direct tensile strength of the mixtures

For the mixtures AC-03, AC-04 and AC-05 which were including synthetic fiber content, it can be stated that, the tensile strength values of these mixtures were determined to have the largest values compared to the other Ankara clay mixture designs. The tensile strength value of AC-04 and AC-05 were approximately same and were determined as 72.25 and 72.52 kPa, respectively.

Metal fiber, pulverized rubber and strip rubber addition to mixtures with both including bentonite content and not, significantly decreased the tensile strength from around 63 kPa to around 35 kPa. It can also be stated that, except the mixtures AC-06 and AC-07 which were the mixtures with metal swarf content, addition of bentonite, increased the direct tensile strength of the mixtures.

It can be concluded that, the addition of synthetic fiber on Ankara clay stabilizes and improves the tensile strength characteristics of the soil. The synthetic fibers, caused soil specimens to be more elastic, durable and increased the ductility of the specimens and this improvement reflected on the tensile strength of the specimens.

The direct tensile strength values of Kaolin mixtures were calculated to be larger than the Ankara clay mixtures. Tensile strength of Kaolin clay with addition of 5% bentonite by its dry weight, was calculated as 92.1 kPa but with addition of synthetic fiber, metal swarf and pulverized rubber the tensile strength significantly decreased.

The 8-shaped tensile strength test specimens which were prepared with addition of pulverized rubber, metal swarf and synthetic fiber are presented in Figures 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7, to illustrate their conditions before and after testing procedure.

Figure 4.2. 8-shaped direct tensile test specimens with pulverized rubber content before testing process

Figure 4.3. 8-shaped direct tensile test specimens with pulverized rubber content after testing process

Figure 4.4. 8-shaped direct tensile test specimens with metal swarf content before testing process

Figure 4.5. 8-shaped direct tensile test specimens with metal swarf content after testing process

Figure 4.6. 8-shaped direct tensile test specimens with synthetic fiber content before testing process

Figure 4.7. 8-shaped direct tensile test specimens with synthetic fiber content after testing process

4.1.2. Split Tensile Strength

Split tensile tests were performed on all mixtures. Every mixture was compacted as their 95% of maximum dry density and corresponding wet of optimum moisture content. For every mixture the split tensile tests were repeated three times and the average tensile strength value of these triplicate experimentations were recorded as the tensile strength value of related mixture. Split tensile test results for both Ankara clay mixtures and Kaolin clay mixtures are provided in Table 4.2 and Figure 4.8.

The split tensile strength values of Ankara clay mixtures and Kaolin clay mixtures were determined to be significantly different. Same mixture designs which were used in 8-shaped direct tensile test, were also tested for their split tensile strengths and calculated tensile strength values were significantly different from each other as one material was decreasing the direct tensile strength but it was increasing the split tensile strength. For example the addition of synthetic fiber, pulverized rubber and metal swarf on Kaolin clay mixtures, decreased the direct tensile strength of soil, on the other hand addition of synthetic fiber and metal swarf, increased the split tensile strength of Kaolin clay mixtures.

The split tensile strength of K-01 mixture was determined to be 39.76 kPa. The addition of 1% synthetic fiber increased the tensile strength by 20 kPa to 59.66 kPa and addition of 3% metal swarf increased the tensile strength by 8 kPa to 47.16 kPa. On the other hand, addition of 3% pulverized rubber on Kaolin clay mixture slightly decreased the tensile by 2 kPa to 37.69 kPa.

Table 4.2. Split tensile strength of the mixtures

Mixture Design	Mixture Code	Split Tensile Strength, σ_{t_s} (kPa)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	39,76
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	59,66
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	37,69
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	47,16
Ankara Clay 100% + Water Content 27,2%	AC-01	34,43
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	38,29
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	50,13
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	46,04
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	36,04
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	14,63
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	12,48
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	21,37
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	17,01

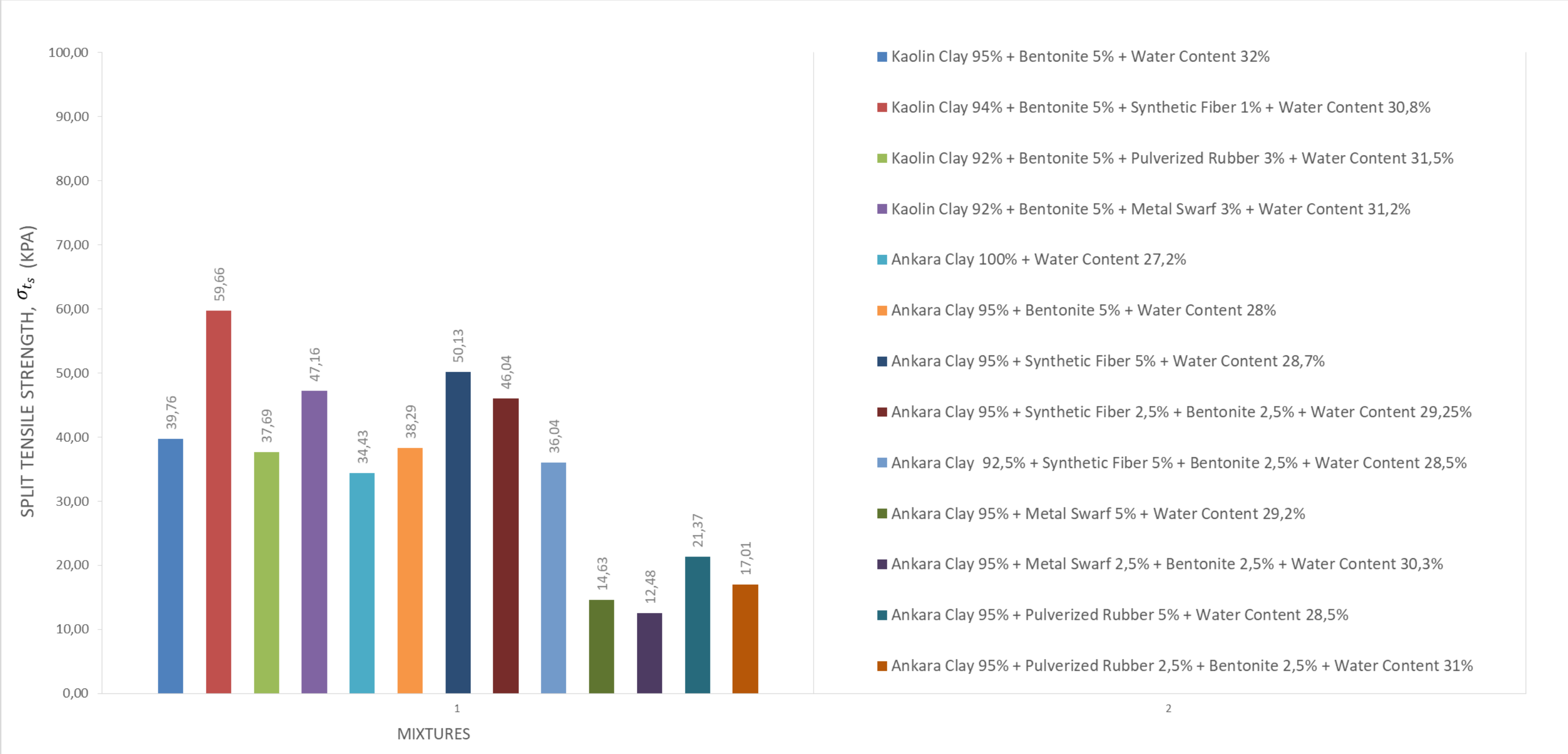


Figure 4.8. Split tensile strength of the mixtures

In the case of Ankara clay mixtures, the tendency of the split tensile strengths was similar to the tendency in 8-shaped direct tensile strengths. Synthetic fiber addition increased the split tensile strength of soil from 34.43 kPa to 50.13 kPa for AC-01 and AC-03 mixtures, respectively. The addition of more than %2.5 synthetic fiber decreased the tensile strength from 50.13 kPa to 46.03 kPa. For AC-05 mixture, 2.5% decrease in Ankara clay content and 2.5% increase in synthetic fiber compared to the AC-03 mixture, vigorously caused a reduction in split tensile strength of the mixture. This reduction of tensile strength may explained by the increased weakness of interfacial mechanical interaction between synthetic fibers and Ankara clay particles as Ankara clay content decreases from 95% to 92.5%.

A drastic reduction in the split tensile strength was observed when metal and pulverized rubber added to the soil mixture. For AC-06 and AC-07 mixtures, the tensile strength decreased approximately by 20 kPa to 14.63 kPa and 12.48 kPa. For AC-08 and AC-09 mixtures, the tensile strength reduction was determined to be around 15 kPa and the tensile strength decreased from 34.43 kPa to 21.37 and 17.01 kPa respectively for AC-08 and AC-09 mixtures.

Typical tension cracks which was responsible for failure of the specimens were observed for all stabilized and non-stabilized Ankara clay and Kaolin clay mixtures. These tension cracks occurred in the central vertical axis of the specimens. None of the specimens tested were split into two halves. All of the specimens showed bulging effect when subjected to split tensile testing. The relatively high young modulus of Ankara clay and Kaolin clay and the confinement provided by synthetic fiber may be the reason of this bulging behavior.

Finally, it can be concluded that addition of synthetic fiber on both Ankara clay and Kaolin clay mixtures significantly increased the tensile strength values. Also it can be stated that as the most important result; the tensile strength values determined from 8-shaped direct tensile test and indirect split tensile test were significantly different from each other. The evaluated results pointed out an average difference around 25 kPa between the tensile strengths determined from both tests which can be considered as a significant difference. This phenomenon and the changing effects of used materials on different tensile strength tests are generally encountered by researchers. And this phenomenon led researchers to investigate the correlations between the direct and indirect tensile strength methods and the reliability of the proposed tensile strength tests. The direction of tensile load, the shape of the compacted specimen and calculation procedures are stated as the main reasons for this difference.

Also as it is stated previously, Kaolin clay mixtures' tensile strengths were evaluated to be higher than the Ankara clay mixtures' tensile strengths. Kaolin clay is considered as a well-packed structure as a result of kaolinite mineral and since the coarse grained soil percentage is close to the zero, the clay impurities cannot be observed. That is why the Kaolin clay mixtures determined to have higher values of tensile strength than the Ankara clay mixtures. Also this phenomenon explained why addition of materials decreased the direct tensile strength of Kaolin clay mixtures. The added materials turned the pure and well packed structure to an impure state and the materials caused a decrease on the tensile strength of the soil.

The split tensile strength test specimens which were prepared with addition of pulverized rubber, metal swarf and synthetic fiber are presented in Figures 4.9, 4.10, 4.11, 4.12, 4.13 and 4.14, to illustrate their conditions before and after testing procedure.

Figure 4.9. Indirect split tensile test specimens with pulverized rubber content before testing process

Figure 4.10. Indirect split tensile test specimens with pulverized rubber content after testing process

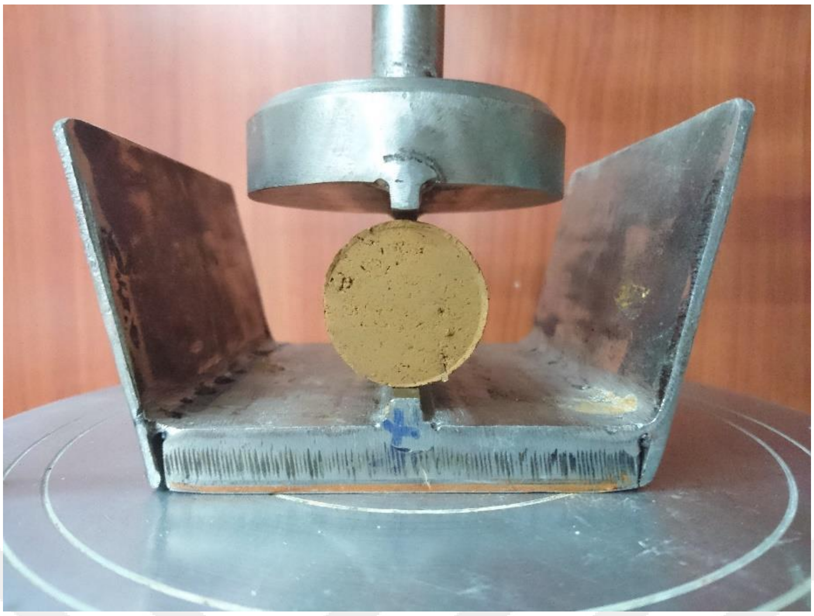


Figure 4.11. Indirect split tensile test specimens with metal swarf content before testing process

Figure 4.12. Indirect split tensile test specimens with metal swarf content after testing process

Figure 4.13. Indirect split tensile test specimens with synthetic fiber content before testing process

Figure 4.14. Indirect split tensile test specimens with synthetic fiber content after testing process

4.1.3. Unconfined Compressive Strength

Unconfined compression tests were performed on all mixtures and for every mixture the test were repeated two times and the average unconfined compressive strength value from these two repeats were recorded as unconfined compressive strength of the mixtures. Unconfined compressive strength tests results are presented in Table 4.3 and Figure 4.15. Specimens' strain values at failure are also presented in Table 4.3.

For Kaolin clay mixtures unconfined compressive strength increased with addition of synthetic fiber and metal swarf from 237.67 to 277.28 and 257.47 for K-01, K-02 and K-04 mixtures, respectively. On the other hand, when pulverized rubber was incorporated the unconfined compressive strength decreased by 25 kPa to 202.63 kPa.

For Ankara clay mixtures, it can be stated that, unconfined compressive strength decreased drastically with addition of synthetic fiber, pulverized rubber, metal swarf and bentonite for every mixture design. The highest value of unconfined compressive strength was determined from AC-01 mixture as 184.84 kPa and the lowest value was 77.98 which is the unconfined compressive strength determined from AC-07 mixture. Increment of interaction between the synthetic fiber, metal swarf, pulverized rubber and accumulation of these materials may be the reason of reduction of unconfined compressive strength.

Finally, it can be stated that, the addition of synthetic fiber and metal swarf increased the unconfined compressive strength of Kaolin mixtures whereas every material added on Ankara clay soil decreased the unconfined compressive strength of the soil. Ultimately, the reductions in unconfined compressive strength of the specimens may be due to the friction and bonding decrease between clay particles and added synthetic fiber, metal swarf or pulverized rubber content.

Table 4.3. Unconfined compressive strength of the mixtures

Mixture Design	Mixture Code	Strain Values at Failure (%)	Unconfined Compressive Strength, q_u (kPa)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	4,8	237,67
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	3,9	277,28
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	2,8	202,63
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	3,2	257,47
Ankara Clay 100% + Water Content 27,2%	AC-01	5,0	184,84
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	5,6	181,99
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	13,8	161,66
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	8,8	176,09
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	9,2	146,61
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	7,1	95,53
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	7,3	77,98
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	6,3	129,90
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	5,3	105,63

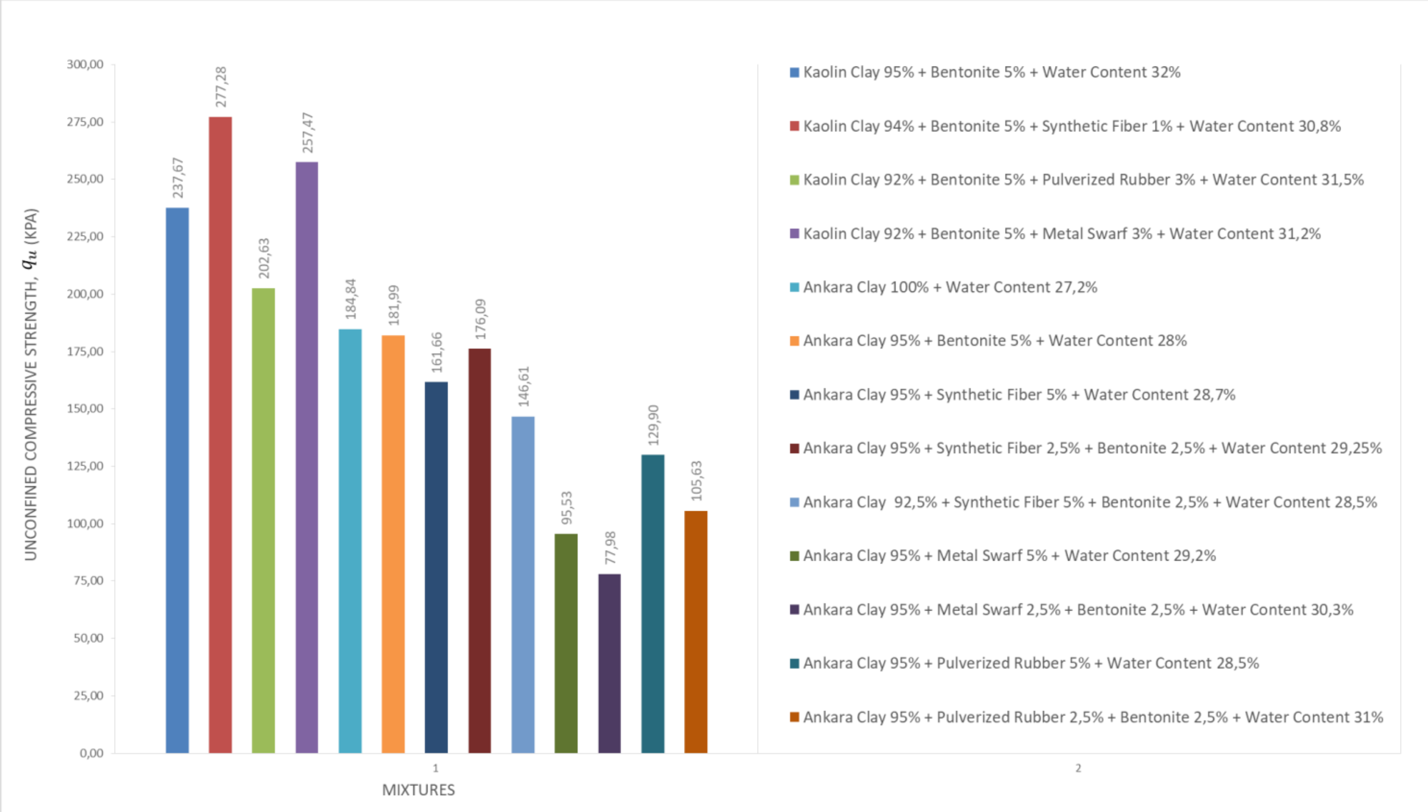


Figure 4.15. Unconfined compressive strength of the mixtures

4.1.4. Secant Modulus of Elasticity

The obtained results from 8-shaped direct tensile test and indirect split tensile test are very useful when probability of tensile crack development is investigated. These results which are found from tensile tests are also significantly important for numerical modelling of the tensile stress zone development in geostructures. The modulus of elasticity in tension which determined from tensile strength tests can also be considered as a significant value when tensile zone widening is investigated. Modulus of elasticity in compression, on the other hand, is an important parameter when the stabilized soils' mechanical properties are investigated as it points out the effects of the added materials on the elasticity of soil. In this study, only the secant modulus of elasticities from unconfined compression tests were calculated since 8-shaped direct tensile strength test did not propose any displacement measurement and radial deformations in split tensile testing did not observed.

The modulus of elasticity values of Ankara clay and Kaolin clay mixtures from unconfined compression test are tabulated in Table 4.4 and stress–strain curves of all mixtures are provided in Appendix C. The secant modulus of elasticities of the mixtures were calculated from the slope of linear straight line prior to the yield point of the stress-strain curves of mixtures. For AC-01 mixture the modulus of elasticity was determined to be 6.38 MPa. With addition of 5% bentonite to the Ankara clay the modulus of elasticity increased to 8.60 MPa. On the other hand, addition of 5% synthetic fiber and 2.5% bentonite to Ankara clay soil increased the modulus of elasticity to 7.18 MPa. Except AC-02 and AC-04 mixtures, a reduction on modulus of elasticity was observed on Ankara clay mixtures. It was observed that addition of metal swarf and pulverized rubber significantly decreased the ductility of the mixture.

For Kaolin clay mixtures, modulus of elasticity increased with the addition of synthetic fiber, metal swarf and pulverized rubber. Modulus of elasticity of K-01 was determined to be 8.46 MPa. K-02 and K-04 mixtures' modulus of elasticity values were determined to be highest as 10.95 MPa and 11.34 MPa, respectively. It can be stated that, modulus of elasticity values of Kaolin clay mixtures were determined to be higher than the modulus of elasticity values of Ankara clay mixtures.

All of the Ankara clay and Kaolin clay mixtures exhibited bulging failure patterns with multiple crack formations. The bulging failure patterns of the AC-01, AC-03, AC-06 and AC-07 mixtures are presented in Figures 4.16, 4.18, 4.20 and 4.22, and their stress-strain curves are presented in Figures 4.17, 4.19, 4.21 and 4.23. It can be inferred from the stress-strain curves and the failure patterns of the specimens, the smooth reduction in stress-strain curve indicates the bulging failure of the specimen. Also this relation between the bulging failure and smooth reduction in stress-strain curve can be observed from Figure 2.24 and Figure 2.25. As it was stated previously, all mixtures designs in this study exhibited bulging failure with multiple cracks and when the Figures 2.24 and 2.25 were examined, it was determined that all of the stress–strain curves illustrates a smooth reduction of peak unconfined compressive stress. This smooth reduction in stress–strain curve and bulging failure pattern may be due to the effect of confining which was induced by synthetic fiber, metal swarf and pulverized rubber or mobilization of tensile strength and shear strength along the failure surface. Multiple crack development, on the other hand, may be due to tensile stress development at the surfaces of synthetic fiber, metal swarf and pulverized rubber.

Ultimately, it can be stated that, for Kaolin clay mixtures synthetic fiber, metal swarf and pulverized rubber addition decreased the stiffness of the soil and the soil become relatively more ductile. For Ankara clay mixtures, synthetic fiber was the only material which increased the ductility of soil.

Table 4.4. Modulus of elasticity values of mixtures from unconfined compressive strength tests (UCS)

Mixture Design	Mixture Code	Modulus of Elasticity - UCS (MPa)
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	8,46
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	10,95
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	8,99
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	11,34
Ankara Clay 100% + Water Content 27,2%	AC-01	6,38
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	8,60
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	4,70
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	5,90
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	7,18
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	3,18
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	1,92
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	2,92
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	4,02

Figure 4.16. Unconfined compression test specimen of AC-01 mixture after the testing process

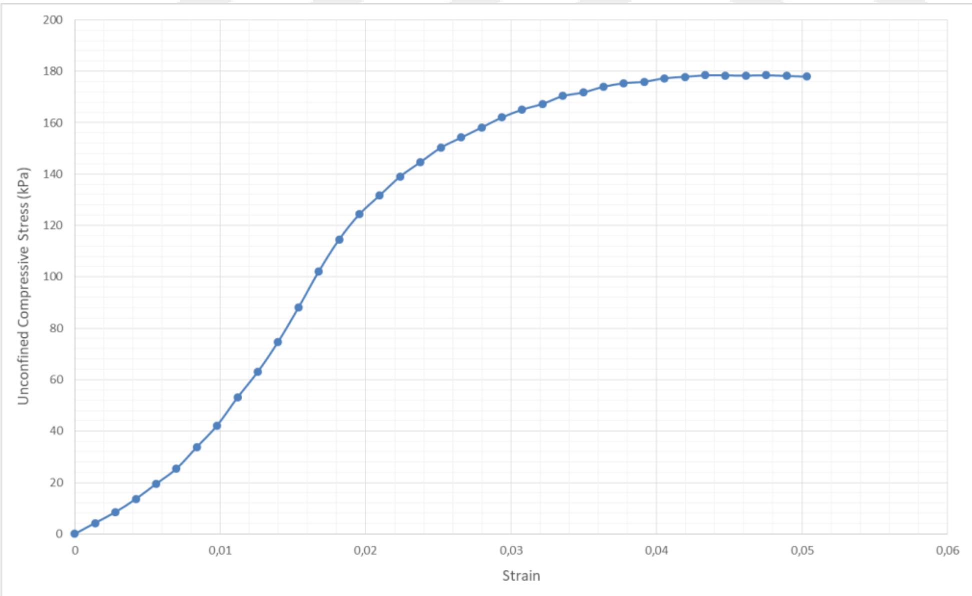


Figure 4.17. Unconfined compressive stress-strain curve of AC-01 mixture

Figure 4.18. Unconfined compression test specimen of AC-03 mixture after the testing process

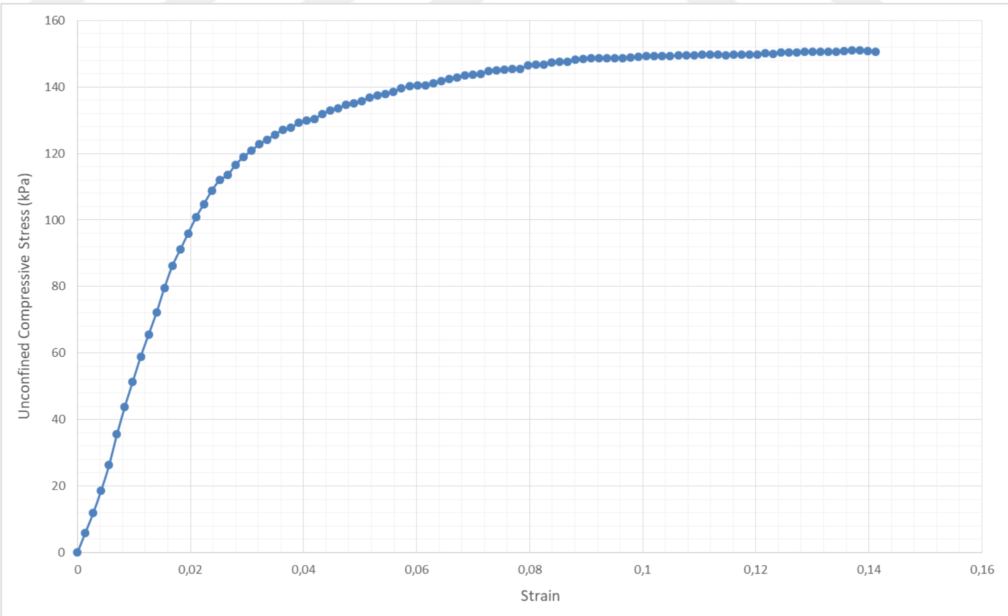


Figure 4.19. Unconfined compressive stress-strain curve of AC-03 mixture

Figure 4.20. Unconfined compression test specimen of AC-06 mixture after the testing process

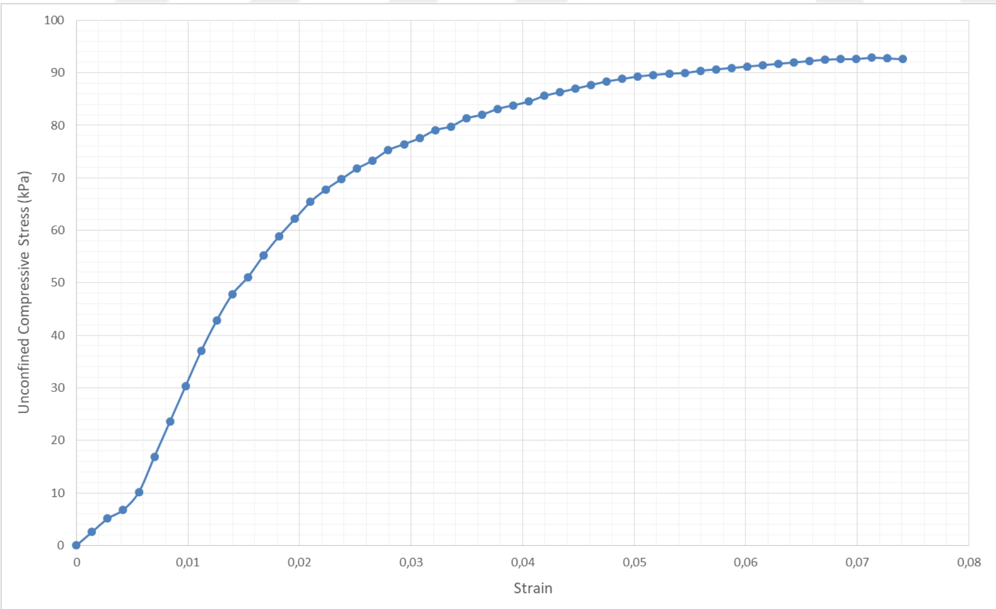


Figure 4.21. Unconfined compressive stress-strain curve of AC-06 mixture

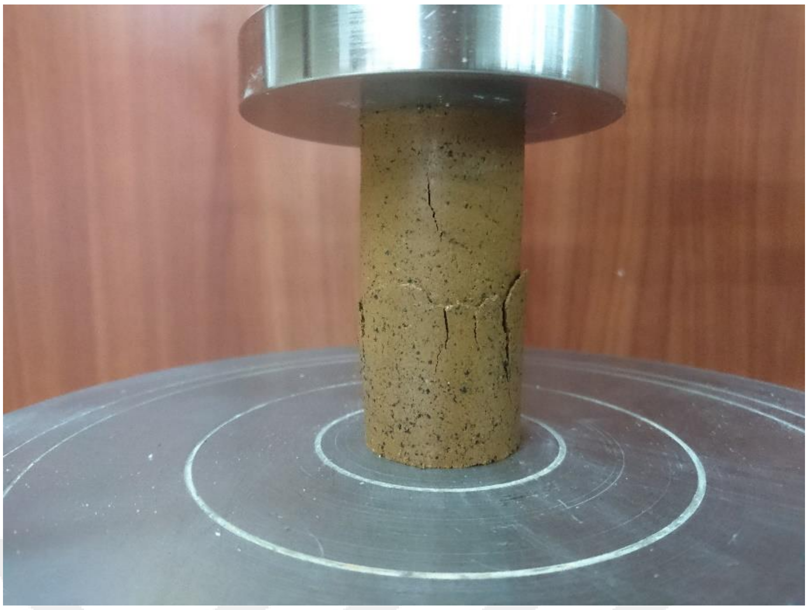


Figure 4.22. Unconfined compression test specimen of AC-08 mixture after the testing process

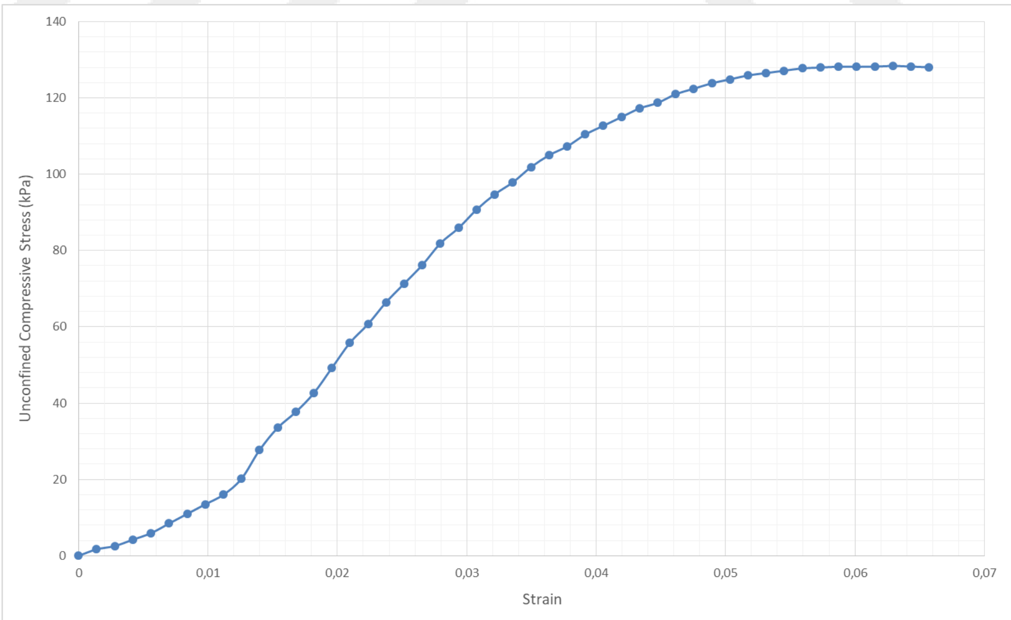


Figure 4.23. Unconfined compressive stress-strain curve of AC-08 mixture

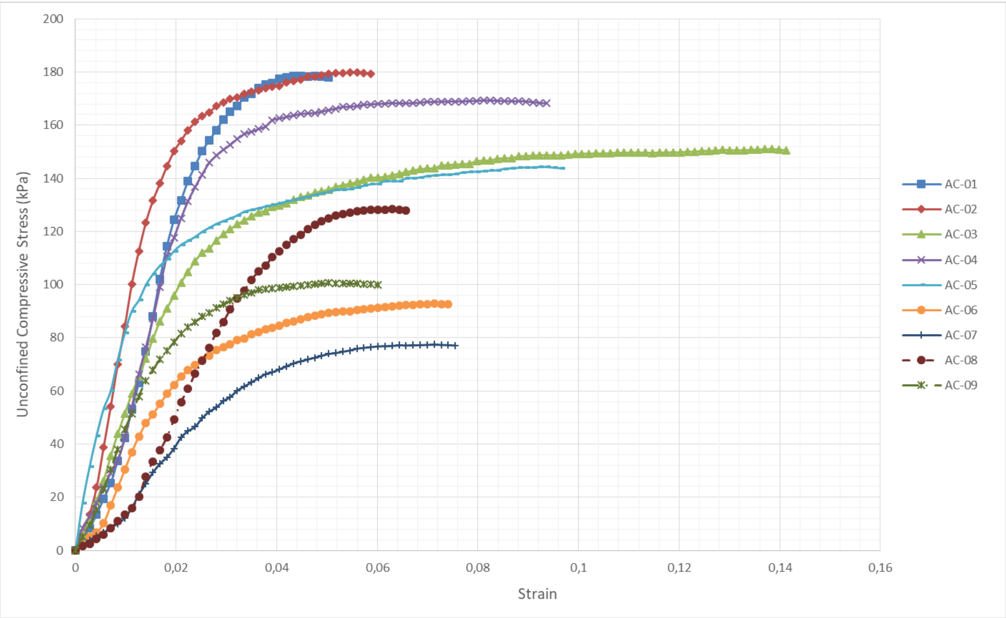


Figure 4.24. Combined unconfined compressive stress-strain curve of Ankara clay mixtures

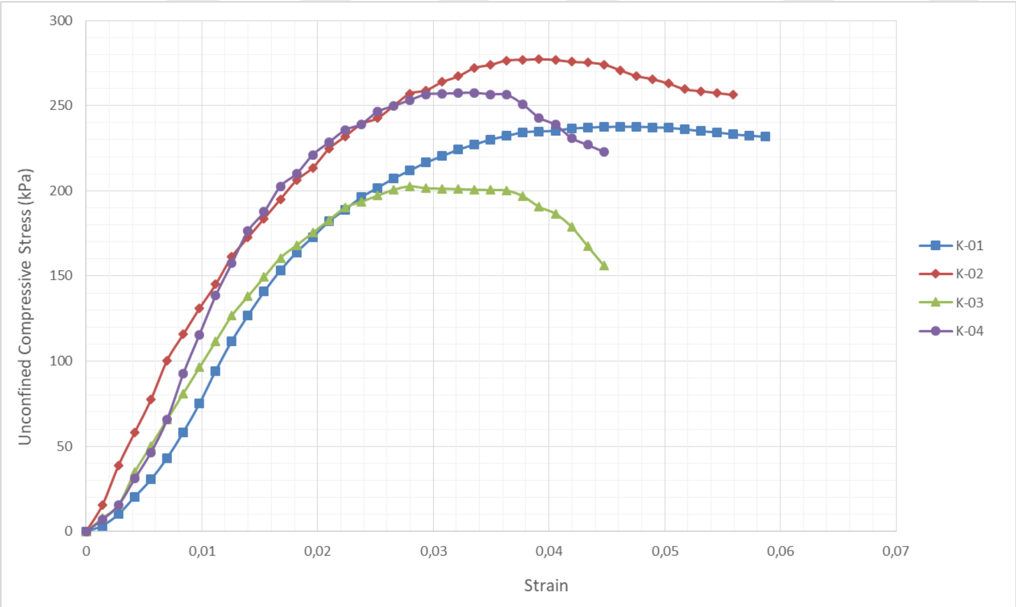


Figure 4.25. Combined unconfined compressive stress-strain curve of Kaolin clay mixtures

4.2. Correlations

In this study, thirteen mixtures (four Kaolin clay mixtures and nine Ankara clay mixtures) were tested for their 8-shaped direct tensile strengths, indirect split tensile strengths and unconfined compressive strengths. As it is stated in Subsection 4.1.2, when the results are evaluated for direct tensile test and indirect tensile test, it can be clearly seen that the tensile strength values significantly differs when the tensile strength determined from 8-shaped direct tensile test and split tensile test. This determination pointed out that correlations must be existed between the tensile strength values. In order to determine these correlations; 8-shaped direct tensile strength versus split tensile strength, 8-shaped direct tensile strength versus unconfined compressive strength and split tensile strength versus unconfined compressive strength graphics were established from the test results. With the established correlation charts, it is possible to determine direct and indirect tensile strength from unconfined compressive strength and to determine direct tensile strength from indirect tensile strength and vice versa.

4.2.1. 8-Shaped Direct Tensile Strength versus Indirect Split Tensile Strength

In order to determine the correlation between the 8-shaped direct tensile strength and indirect split tensile strength several graphs were established as presented in Figures 4.26, 4.27, 4.28 and 4.29. Since there were thirteen mixture designs (nine Ankara clay mixture and four Kaolin clay mixture), three main graphs were established for Ankara clay mixtures, Kaolin clay mixtures and combination of all mixtures. Also the graphics with outlying points removed are presented for reliable presentation of correlations between the tensile strengths. The coefficient of determination and the equation of best fitting line are provided on the presented graphs. It can be stated from the graphs provided, indirect split tensile strength increases with increasing 8-shaped direct tensile strength.

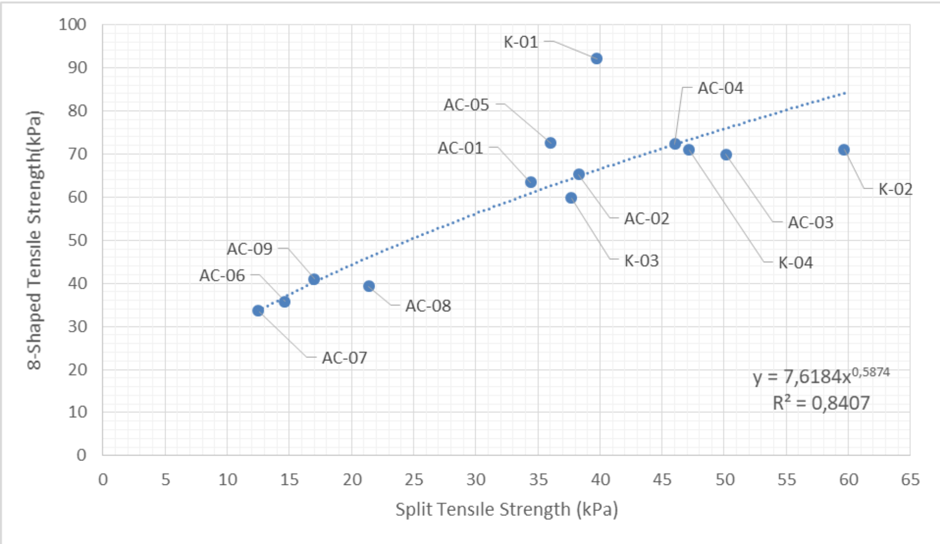


Figure 4.26. 8-shaped tensile strength versus split tensile strength graph

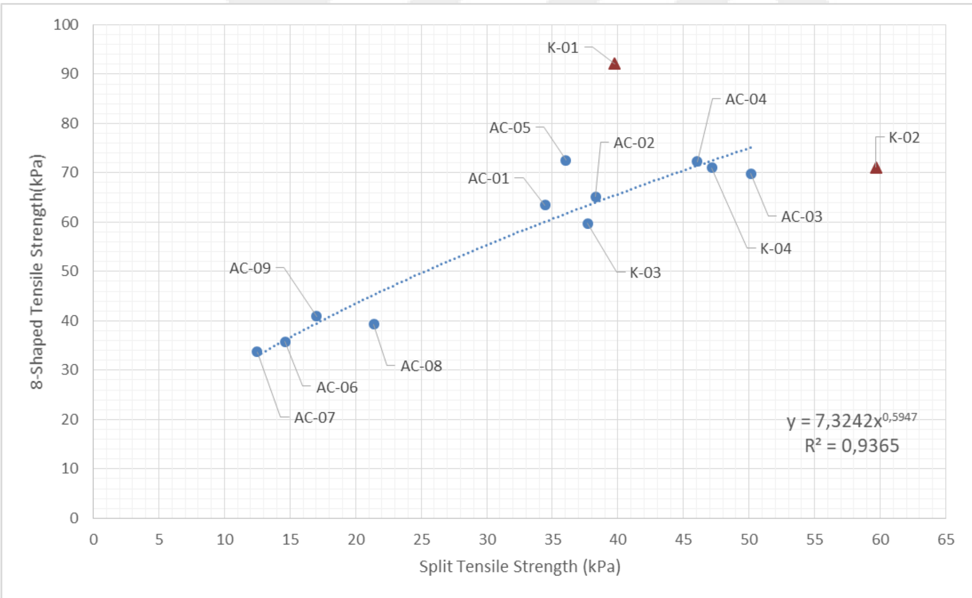


Figure 4.27. 8-shaped tensile strength versus split tensile strength graph with points K-01 and K-02 excluded

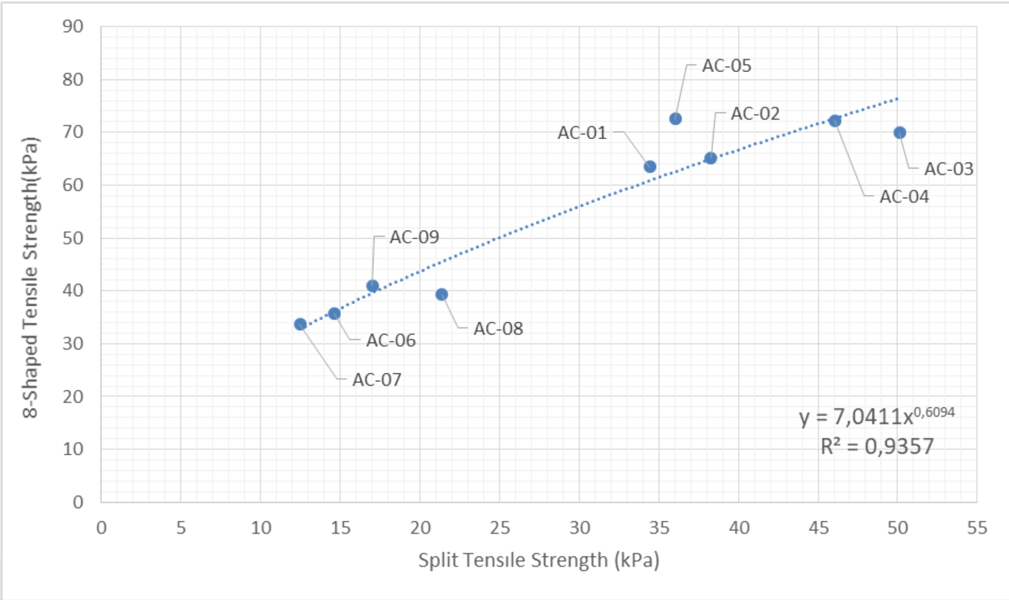


Figure 4.28. 8-shaped tensile strength versus split tensile strength graph for Ankara clay mixtures

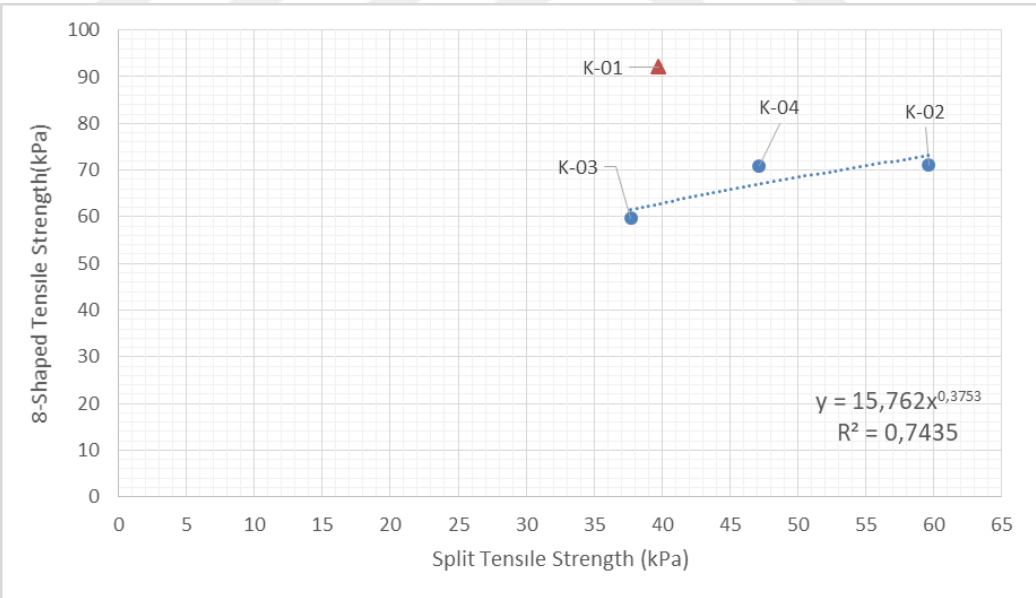


Figure 4.29. 8-shaped tensile strength versus split tensile strength graph for Kaolin clay mixtures excluding point K-01

4.2.2. 8-Shaped Direct Tensile Strength versus Unconfined Compressive Strength

In order to determine the correlation between the 8-shaped direct tensile strength and unconfined compressive strength several graphs were established as presented in Figures 4.30, 4.31, 4.32 and 4.33. Since there were thirteen mixture designs (nine Ankara clay mixture and four Kaolin clay mixture), three main graphs were established for Ankara clay mixtures, Kaolin clay mixtures and combination of all mixtures. Also the graphs with outlying points removed are presented for reliable presentation of correlations between direct tensile strength and unconfined compressive strength values. The coefficient of determination and the equation of best fitting line are provided on the graphs. It can be concluded from the graphs that, the direct tensile strength increases with increasing unconfined compressive strength.

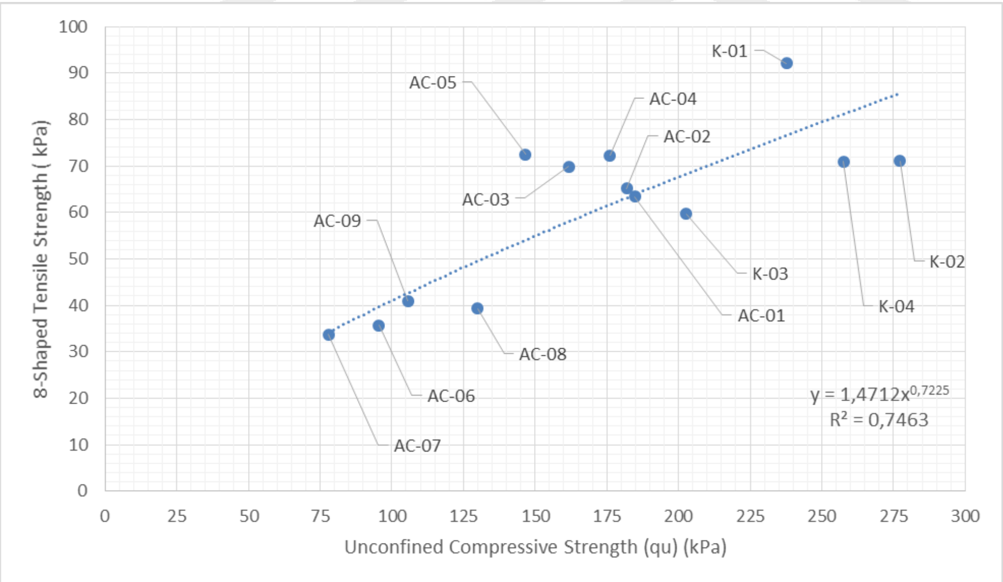


Figure 4.30. 8-shaped tensile strength versus unconfined compressive strength graph for all mixtures

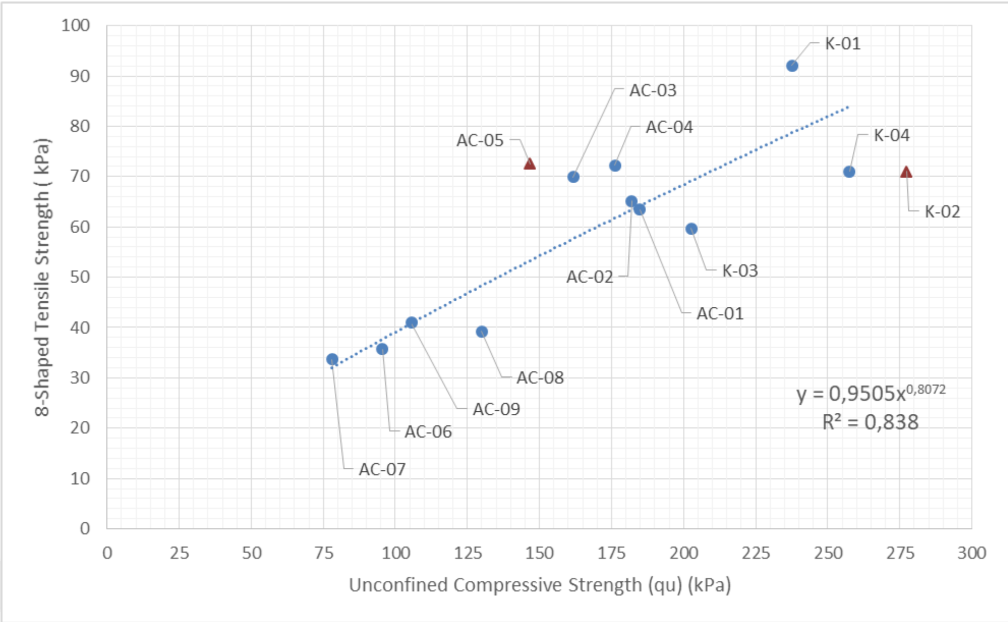


Figure 4.31. 8-shaped tensile strength versus unconfined compressive strength graph for all mixtures excluding points AC-05 and K-02

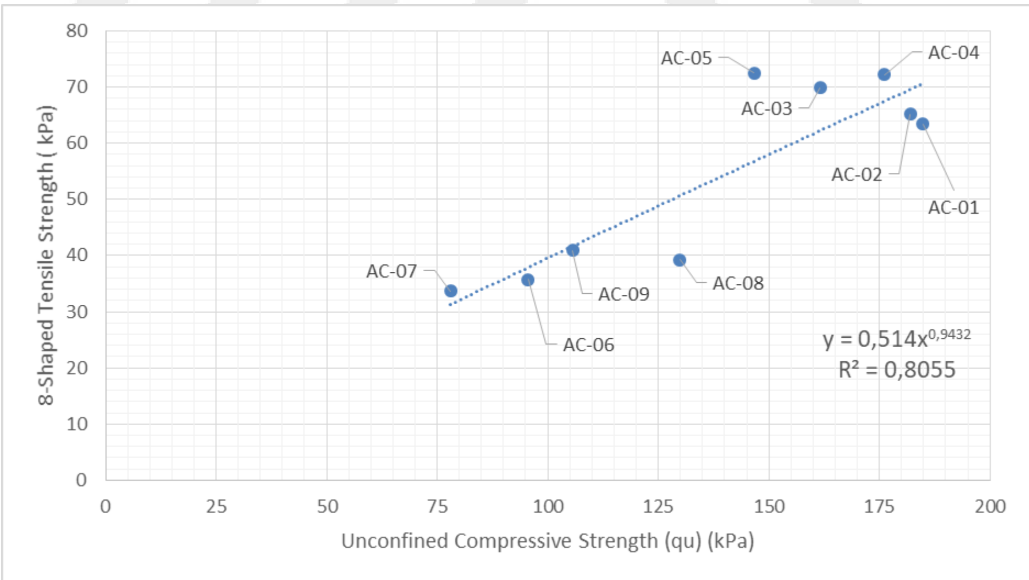


Figure 4.32. 8-shaped tensile strength versus unconfined compressive strength graph for Ankara clay mixtures

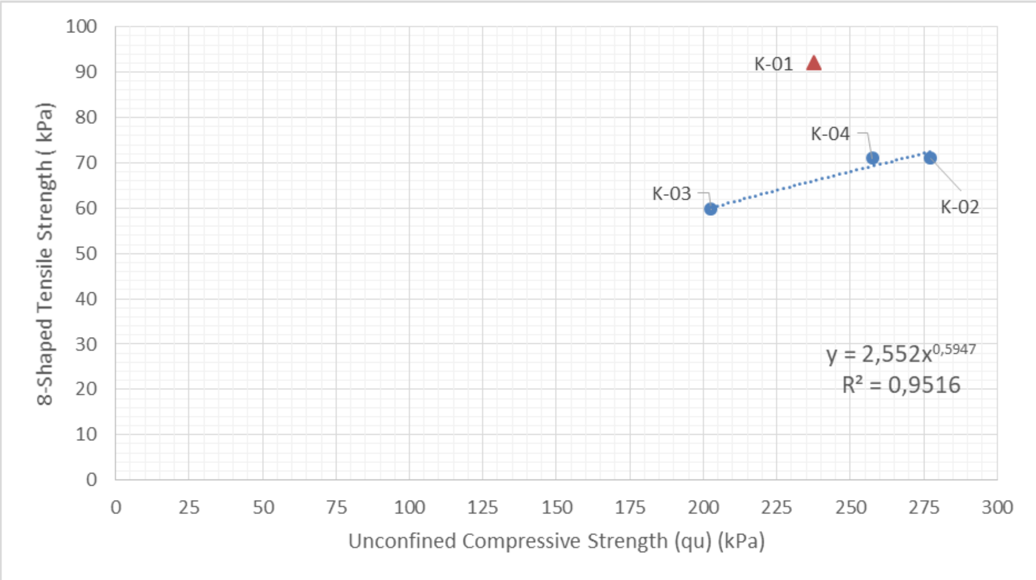


Figure 4.33. 8-shaped tensile strength versus unconfined compressive strength graph for Kaolin clay mixtures excluding point K-01

4.2.3. Indirect Split Tensile Strength versus Unconfined Compressive Strength

In order to determine the correlation between the indirect split tensile strength and unconfined compressive strength several graphs were established as presented in Figures 4.34, 4.35, 4.36 and 4.37. Since there were thirteen mixture designs (nine Ankara clay mixture and four Kaolin clay mixture), three main graphs were established for Ankara clay mixtures, Kaolin clay mixtures and combination of all mixtures. Also the graphs with outlying points removed are presented for reliable presentation of correlations between indirect split tensile strength and unconfined compressive strength values. The coefficient of determination and the equation of best fitting line are provided on the graphs. It can be concluded from the graphs that, the indirect split tensile strength increases with increasing unconfined compressive strength.

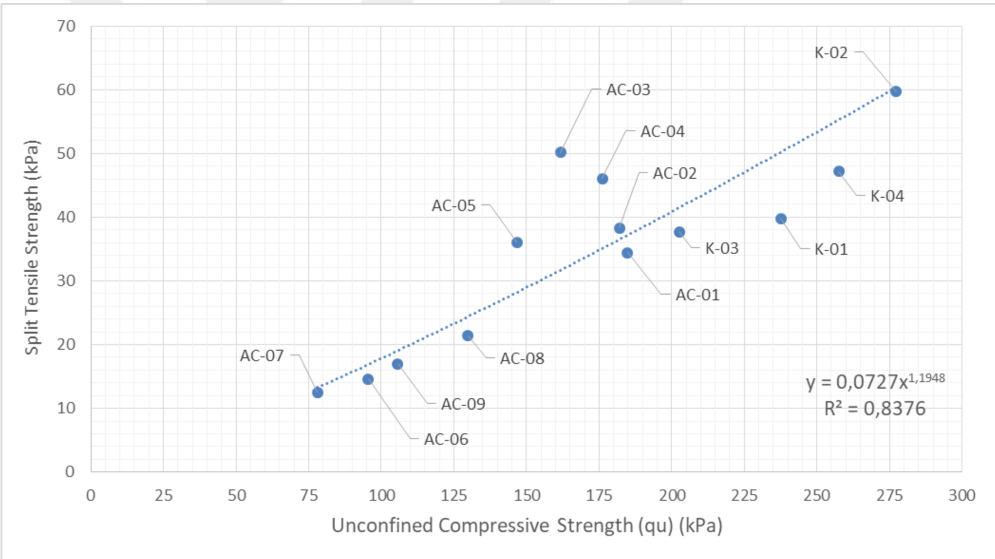


Figure 4.34. Split tensile strength versus unconfined compressive strength graph for all mixtures

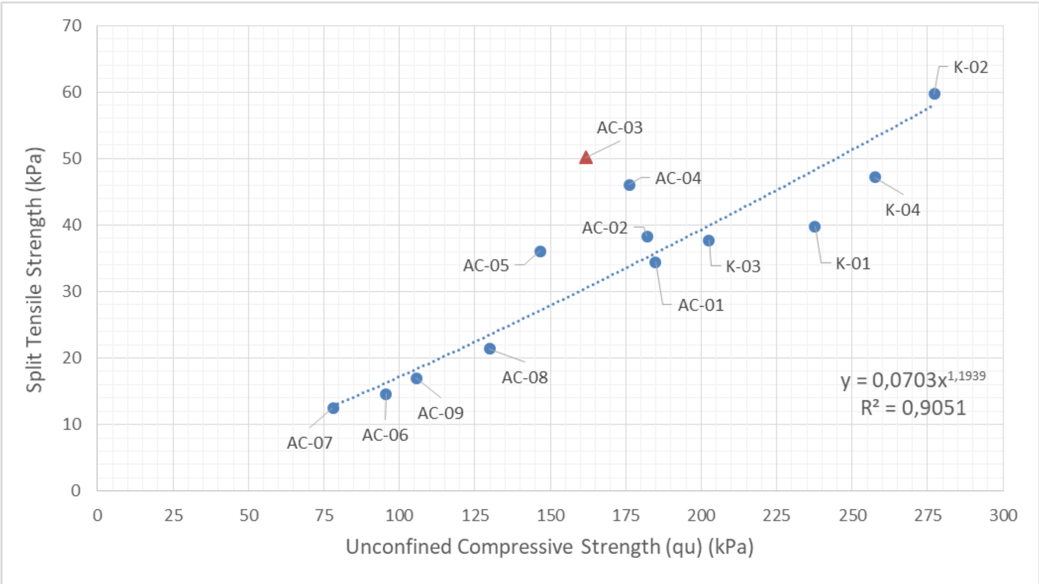


Figure 4.35. Split tensile strength versus unconfined compressive strength graph for all mixtures excluding point AC-03

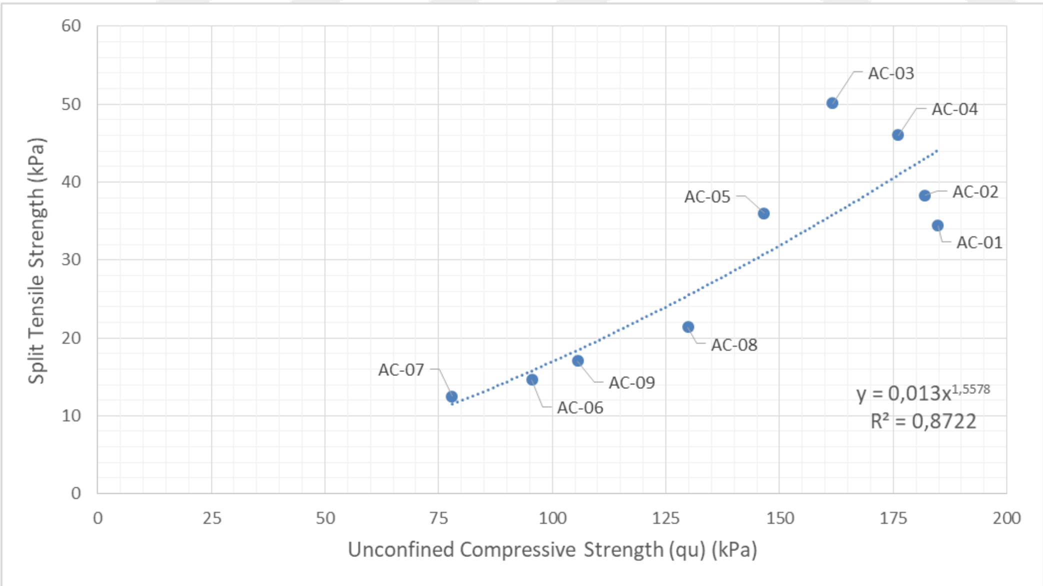


Figure 4.36. Split tensile strength versus unconfined compressive strength graph for Ankara clay mixtures

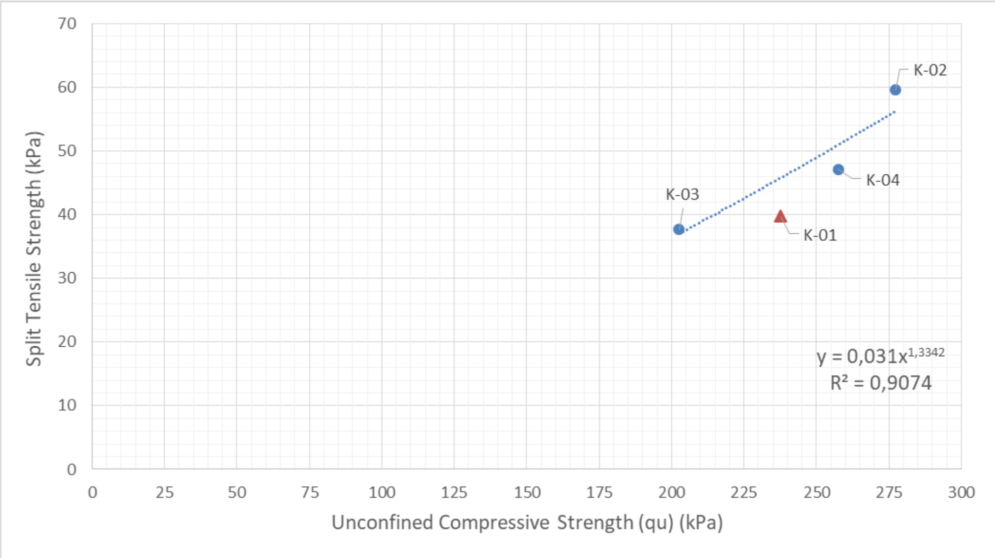


Figure 4.37. Split tensile strength versus unconfined compressive strength graph for Kaolin clay mixtures excluding point K-01

4.2.4. Ratios between the Results of the Strength Tests

Table 4.5, shows the ratios between the results of the 8-shaped direct tensile tests, split tensile tests and unconfined compression tests. The average ratios of the, unconfined compressive strength to the 8-shaped direct tensile strength, unconfined compressive strength to the split tensile strength, 8-shaped direct tensile strength to the unconfined compressive strength, split tensile strength to the unconfined compressive strength, 8-shaped direct tensile strength to the split tensile strength and split tensile strength to the 8-shaped direct tensile strength were calculated as 2.8, 5.2, 0.4, 0.2, 1.9 and 0.6, respectively. Also, the average ratios of the 8-shaped direct tensile strength to the undrained shear strength (c_u) and split tensile strength to the undrained shear strength (c_u) were calculated as 0.8 and 0.4, respectively when the angle of internal friction values (ϕ_u) were assumed to be zero. These significant ratios which were determined from the strength tests can be expressed by following equations:

$$\frac{(\sigma_{t_{8-\mathrm{shaped}}})_{\mathrm{ave}}}{(\sigma_{t_{\mathrm{split}}})_{\mathrm{ave}}} \cong 1.9$$

$$\frac{(\sigma_{t_{8-\mathrm{shaped}}})_{\mathrm{ave}}}{(q_u)_{\mathrm{ave}}} \cong 0.4$$

$$\frac{(\sigma_{t_{\mathrm{split}}})_{\mathrm{ave}}}{(q_u)_{\mathrm{ave}}} \cong 0.2$$

Table 4.5. Ratios between the results of the strength tests

Mixture Design	q_u/σ_{t_8}	q_u/σ_{t_s}	σ_{t_8}/q_u	σ_{t_s}/q_u	$\sigma_{t_8}/\sigma_{t_s}$	$\sigma_{t_s}/\sigma_{t_8}$
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	2,6	6,0	0,4	0,2	2,3	0,4
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	3,9	4,6	0,3	0,2	1,2	0,8
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	3,4	5,4	0,3	0,2	1,6	0,6
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	3,6	5,5	0,3	0,2	1,5	0,7
Ankara Clay 100% + Water Content 27,2%	2,9	5,4	0,3	0,2	1,8	0,5
Ankara Clay 95% + Bentonite 5% + Water Content 28%	2,8	4,8	0,4	0,2	1,7	0,6
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	2,3	3,2	0,4	0,3	1,4	0,7
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	2,4	3,8	0,4	0,3	1,6	0,6
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	2,0	4,1	0,5	0,2	2,0	0,5
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	2,7	6,5	0,4	0,2	2,4	0,4
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	2,3	6,2	0,4	0,2	2,7	0,4
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	3,3	6,1	0,3	0,2	1,8	0,5
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	2,6	6,2	0,4	0,2	2,4	0,4
Average Value	2,8	5,2	0,4	0,2	1,9	0,6

4.3. Equations for Estimation of Tensile Strength

4.3.1. Evaluation of Equations Proposed by Earlier Researchers for Tensile Strength Estimation

Earlier researchers who studied on tensile strength quantification of soils proposed various empirical relations for determination of the tensile strength of soils. By employing the equations which are presented in Table 4.6, the tensile strength values of Ankara clay and Kaolin clay mixtures were computed. The determined results are tabulated in Table 4.7 and a comparison of mixtures' measured and estimated tensile strength values from the tensile strength tests and proposed tensile strength equations are presented in Figure 4.38. It must be stated that, the equations listed requires the values of liquid limit, plasticity index, clay content and water content to estimate the tensile strength values of the related mixtures. For Ankara clay and Kaolin clay mixtures, the values of LL, PI, CC and water content are presented in related subsections of Chapter 3.

Table 4.6. Equations proposed by earlier researchers for estimation of tensile strength of soils

Equations for Estimation of Tensile Strength of Soils	Equation Code	References
σ_t = (1,2748*LL) - 4,827	I	Win (2006)
σ_t = (2,1446*PI) + 9,3421	II	Win (2006)
σ_t = (1,15*CL) + 9,0813	III	Win (2006)
σ_t = 31,44 + (1,24*PI) - (0,018*PI^2) + (0,00011*PI^3)	IV	Fang and Chen (1971)
log (σ_t) = 5,12 - (2,32*log(w))	V	Zeh and Witt (2005a)

Table 4.7. Determined results from equations proposed by earlier researchers for estimation of tensile strength of soils

Mixture Design	Measured Tensile Strength Values (kPa)		Average Measured Tensile Strength (kPa)	Equations for Estimation of Tensile Strength of Soils				
	8-Shaped Tensile Strength (kPa)	Split Tensile Strength (kPa)		I	II	III	IV	V
K-01	92,10	39,76	65,93	64,99	34,71	61,98	43,77	42,47
K-02	71,07	59,66	65,36	67,34	43,21	61,98	46,97	46,40
K-03	59,74	37,69	48,71	62,74	37,69	59,68	44,94	44,05
K-04	70,98	47,16	59,07	63,37	29,66	59,68	41,67	45,04
AC-01	63,44	34,43	48,94	66,43	71,49	58,53	54,94	61,92
AC-02	65,19	38,29	51,74	71,66	87,51	65,43	58,05	57,89
AC-03	69,88	50,13	60,01	93,09	79,57	56,23	56,61	54,67
AC-04	72,25	46,04	59,14	84,22	83,83	63,13	57,40	52,31
AC-05	72,52	36,04	54,28	89,93	84,38	60,83	57,50	55,56
AC-06	35,74	14,63	25,18	63,37	65,32	55,08	53,50	52,52
AC-07	33,68	12,48	23,08	69,11	88,27	63,13	58,18	48,20
AC-08	39,28	21,37	30,33	60,19	64,39	55,08	53,27	55,56
AC-09	40,95	17,01	28,98	67,84	89,96	63,13	58,46	45,71
Average Value	60,52	34,98	47,75	71,10	66,15	60,30	52,71	50,95

Figure 4.38. A comparison of mixtures' average measured and estimated tensile strength values from the tensile strength tests and proposed tensile strength equations

It can be inferred from the estimated tensile strength results from the proposed equations that, even though the estimated tensile strength results did not exhibit a significant agreement with the measured 8-shaped and split tensile strength values, equations were able to estimate the tensile strength values approximately on same order. Incidentally, Equation I which correlates LL with the tensile strength of soil exhibited an average tensile strength value of 71.70 kPa, Equation II which correlates PI with the tensile strength of soil exhibited an average tensile strength value of 66.15 kPa, Equation III which correlates CC and the tensile strength of soil exhibited an average tensile strength value of 60.30 kPa, Equation IV which correlates PI and the tensile strength of soil exhibited an average tensile strength value of 52.71 kPa and Equation V which correlates water content and the tensile strength of soil exhibited a tensile strength value of 50.95 while the average measure tensile strength was determined to be 47.75 kPa.

Ultimately, the soils exhibit different characteristics and properties and the proposed equations are generalized in nature. As a result, these proposed equations by the researchers can be used to easily, rapidly and roughly estimate the fine grained soils' tensile strength values by inputting the CC, LL, PI and water content values of the related soil.

4.3.2. Developed Equations According to the Conducted Tensile Strength Experimentation

Tensile strength estimation according to the soils' index properties has been a significant research area by the researchers as it is stated in the previous subsection. In this study, two tensile strength tests were used to determine the tensile strength of Ankara clay and Kaolin clay mixtures, namely 8-shaped tensile test and split tensile test. 13 mixtures were designed by using Ankara clay and Kaolin clay with addition of synthetic fiber, metal swarf, pulverized rubber and bentonite. All 13 mixtures' index properties including consistency limits, clay contents, maximum dry densities and optimum water contents were determined and presented in Chapter 3 of this thesis. According to the conducted tensile strength test results and index properties two empirical equation for 8-shaped direct tensile testing and one empirical equation for split tensile testing were developed and proposed. The equations which are listed in Table 4.8 and Table 4.9 were developed by conducting regression and statistical analyses on the tensile strength test results and the index properties of the mixtures. Equations coefficient of determination and significance F values are also tabulated in the equation tables. Figures 4.39, 4.40, 4.41, 4.42 and 4.43 are provided for better visualization of the data which determined from the equations, the measured tensile strength values from the tensile strength tests and the confidence limits of the equations proposed.

Table 4.8. Developed tensile strength equations from 8-shaped direct tensile strength test results

8-Shaped Direct Tensile Strength Equations	R^2	Significance F	Equation Code
σ_{t_8} = -100,158 ($\gamma_{d_{max}}$) + 2,461 (PL) - 0,942 (LL) - 6,623 (w) + 3,656 (CC) - 0,477 (SL) + 230,96	0,90	0,0089	I (Direct)
σ_{t_8} = -0,3528 (LL) + 2,0977 (CC) - 5,8545 (w_{opt}) + 4,229 (PL) - 2,554 (SL) + 61,335	0,91	0,001822	II (Direct)

Table 4.9. Developed tensile strength equation from indirect split tensile strength test results

Indirect Split Tensile Strength Equation	R^2	Significance F	Equation Code
σ_{t_s} = -100,12 ($\gamma_{d_{max}}$) + 1,1267 (PL) - 0,8874 (LL) - 6,851 (w) + 3,457 (CC) + 0,8424 (SL) + 226,3613	0,87	0,02347	I (Indirect)

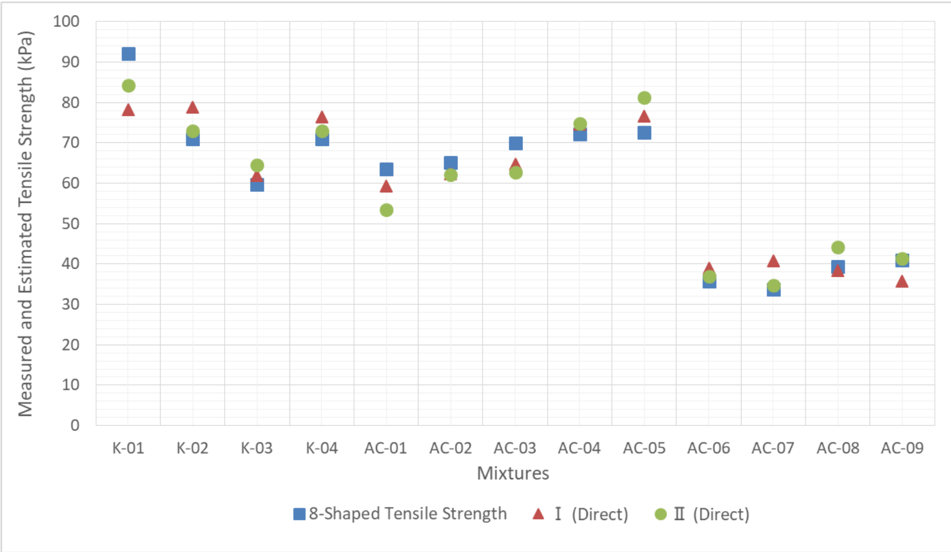


Figure 4.39. A comparison of mixtures' measured and estimated tensile strength values from the 8-shaped tensile strength tests and developed tensile strength equations

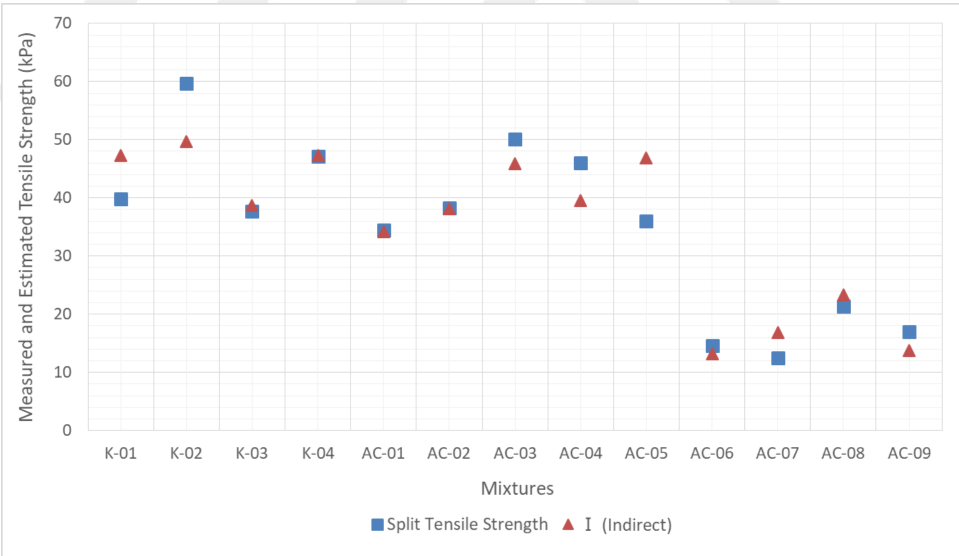


Figure 4.40. A comparison of mixtures' measured and estimated tensile strength values from the split tensile strength tests and developed tensile strength equation

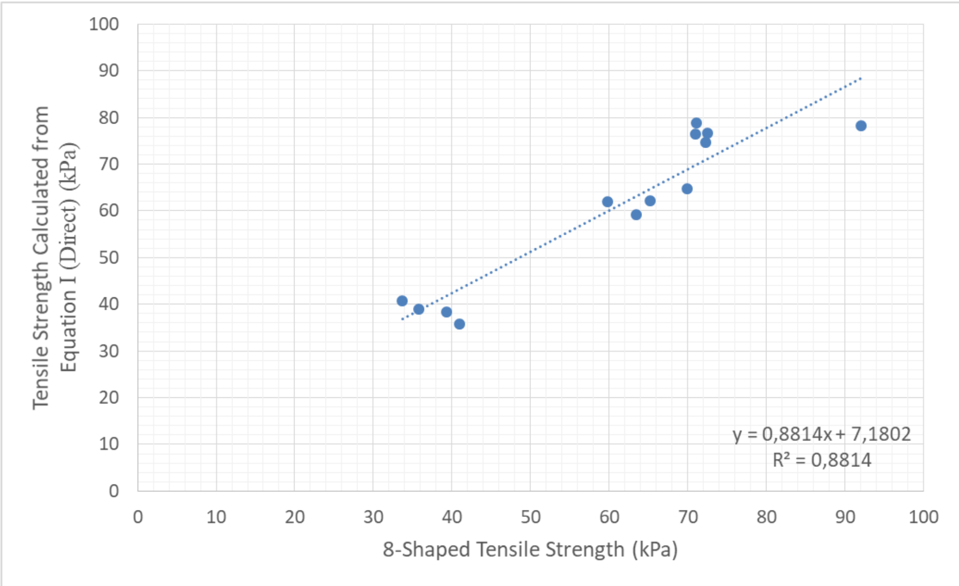


Figure 4.41. Measured 8-shaped tensile strength versus estimated tensile strength from Equation I (Direct)

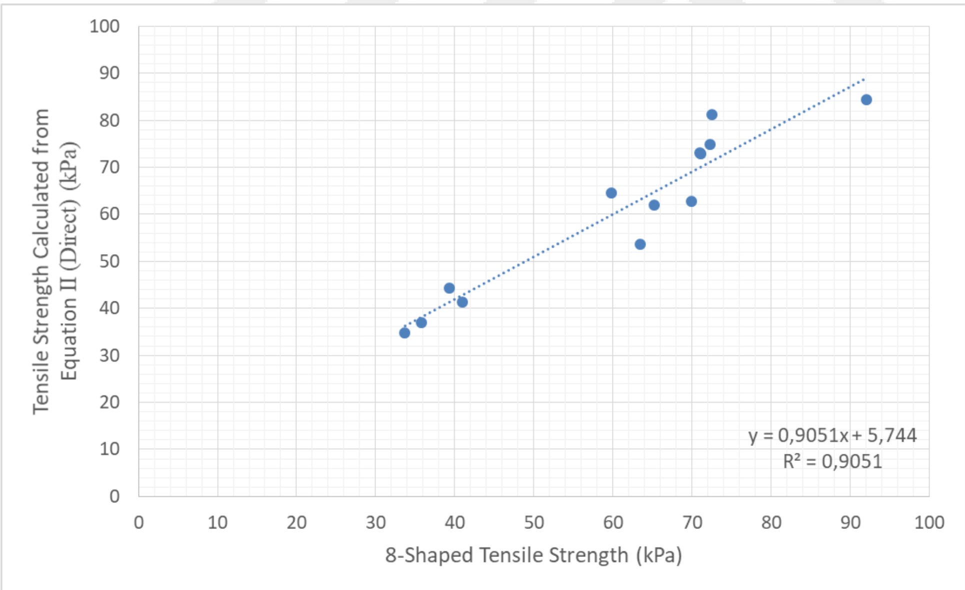


Figure 4.42. Measured 8-shaped tensile strength versus estimated tensile strength from Equation II (Direct)

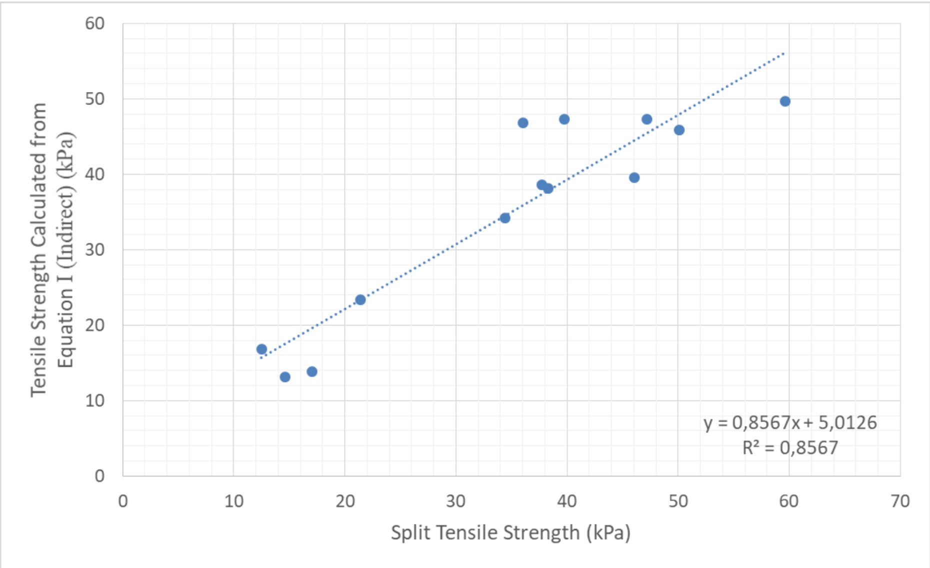


Figure 4.43. Measured split tensile strength versus estimated tensile strength from Equation I (Indirect)

Equations I (Direct) and II (Direct) were developed from the 8-shaped direct tensile strength results and the data obtained from the equations fall within 90% confidence limits as it can be seen from the graphs provided. Equation I (Indirect), on the other hand, was developed from indirect split tensile strength test results and the data obtained from the equation fall within 85% confidence limits. These developed equations can be used to easily and rapidly determine the fine grained soils' tensile strength values by inputting the maximum dry density, liquid limit, plastic limit, shrinkage limit, water content and clay content values of the soil tested.

The equations developed in this study can be employed to measure fine grained soils' tensile strength values, in general. However, extensive researches should be conducted on different kind of stabilized and non-stabilized fine grained soils following the proposed methodology, to develop generalized empirical relations between the tensile strength and index properties of soils.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary of Research and Contributions

Aim of this study was to investigate and stabilize the tensile strength characteristics of Ankara clay and Kaolin clay. Two tensile strength measurement methods were used in this study, namely, direct tensile testing method and indirect tensile testing method.

A new direct tensile set up was developed to investigate the tensile strength of compacted 8-shaped Ankara clay soil. As an indirect tensile testing method, split tensile test or Brazilian tensile test was used on the same mixtures. Every mixture design was also tested for their unconfined compressive strength.

Beside Ankara clay soil, all strength tests were also conducted on Kaolin clay soil to investigate the stabilization effects for a different kind of fine grained soil since it would provide a unique standpoint for the study.

Synthetic fiber, metal swarf, pulverized rubber and bentonite were used to stabilize the tensile and unconfined compressive strength of Ankara clay and Kaolin clay. In order to investigate the stabilization effects, thirteen mixtures were tested; nine Ankara clay mixtures and four Kaolin clay mixtures with different percentages of additives by soils dry weights.

Maximum amount of additives was kept fixed as 5% for Ankara clay mixtures. For Kaolin clay mixtures, bentonite content was kept fixed as 5% whereas other additives' percentages are changed.

Every specimen which was prepared from related mixture, was compacted to its 95% of maximum dry density and corresponding wet of optimum water content as it is suggested by previous researchers to demonstrate better tensile strength characteristics and better workability on the specimens.

Sieve analysis and hydrometer tests were conducted on every mixture design to obtain grain size distribution curve of the mixtures.

Fall cone test was used beside the Casagrande liquid limit test and rolling thread test to obtain the liquid limit and plastic limit values of the mixtures since Casagrande liquid limit testing and rolling thread testing methods were unable to give reliable results for mixture designs consist of additives. All mixtures' shrinkage limits were obtained from shrinkage limit tests by using mercury method.

All mixture designs were classified according to the USCS and AASHTO Soil Classification system by considering LL, PL and gradation curves of the mixtures.

Effects of added synthetic fiber, metal swarf and pulverized rubber content on modulus of elasticities of Ankara clay and Kaolin clay mixtures were investigated and failure patterns with their stress-strain curves were investigated for better understanding of the relation between the failure patterns and stress-strain curves.

The experimental results obtained from 8-shaped direct tensile tests, indirect split tensile tests and unconfined compression tests were evaluated and analyzed for the differences and relations between them. Then formulated correlations were developed between the strength tests for better understanding and illustration of the experimental study.

Empirical equations proposed by earlier researchers for tensile strength estimation were employed to estimate the Ankara clay and Kaolin clay mixtures' tensile strengths by using their index properties. The estimated tensile strength results from proposed equations and measured tensile strengths from the 8-shaped tensile tests and split tensile tests were compared.

Equations, according to the Ankara clay and Kaolin clay mixtures' tensile strengths and index properties were developed, and proposed to estimate the tensile strength of fine-grained soils from their index properties.

5.2. Conclusions

Following main conclusions are summarized according to the experimental results from 8-shaped direct tensile test, indirect split tensile test, unconfined compression tests and index property tests:

- Metal fiber, pulverized rubber and strip rubber addition to mixtures with both bentonite and without bentonite, significantly decreased the direct tensile strength.

- The direct tensile strength values of Kaolin mixtures were calculated to be larger than Ankara clay mixtures.

- Direct tensile strength of Kaolin clay with addition of 5% bentonite by its dry weight was calculated to be 92.09 kPa but addition of synthetic fiber, metal swarf and pulverized rubber decreased the direct tensile strength.

- Synthetic fiber addition to Ankara clay increased the split tensile strength of soil from 34.42 kPa to 50.13 kPa.

- The evaluated results pointed out an average difference around 25 kPa between the tensile strength determined from 8-shaped direct tensile test and indirect split tensile test. This analysis indicated that the significant difference between the testing methods which should be considered with great attention. The direction of tensile load, the shape of the compacted specimen and calculation procedures are stated as the main reasons for this difference.

- Unconfined compressive strength for Ankara clay mixtures decreased significantly with addition of synthetic fiber, pulverized rubber and metal swarf. The unconfined compressive strength for 100% Ankara clay determined to be 184.83 kPa.

- The addition of synthetic fiber and metal swarf increased the unconfined compressive strength of Kaolin mixtures whereas every material added on Ankara clay soil decreased the unconfined compressive strength of the soil. Ultimately, the reductions in unconfined compressive strength of the specimens may be due to the friction and bonding decrease between clay particles and added synthetic fiber, metal swarf or pulverized rubber content.

- It was observed that addition of metal swarf and pulverized rubber significantly decreased the ductility of the mixture.

- It can be stated that, modulus of elasticity values of Kaolin clay mixtures were determined to be higher than the modulus of elasticity values of Ankara clay mixtures.

- All of the Ankara clay and Kaolin clay mixtures exhibited bulging failure patterns with multiple crack formations. It was inferred from the stress-strain curves and the failure patterns of the specimens that, the smooth reduction in stress-strain curve indicated the bulging failure of the specimen.

This smooth reduction in stress–strain curve and bulging failure pattern may be due to the effect of confining which was induced by synthetic fiber, metal swarf and pulverized rubber or mobilization of tensile strength and shear strength along the failure surface. Multiple crack development, on the other hand, may be due to tensile stress development at the surfaces of synthetic fiber, metal swarf and pulverized rubber.

- Addition of synthetic fiber, metal swarf and pulverized rubber decreased the stiffness of the soils and the soil become relatively more ductile with the addition of these materials.

- Ultimately, synthetic fiber can be considered as the most influential material effecting the tensile strength of fine grained soils as it demonstrated considerable stabilization effects on both Ankara clay and Kaolin clay. It can be stated that, the addition of synthetic fiber on Ankara clay and Kaolin clay stabilizes and improves the tensile strength characteristics of the soil. The synthetic fibers, caused soil specimens to be more elastic, durable and increased the ductility of the specimens and this improvement reflected on the tensile strength of the specimens.

- Developed correlations graphs between the results of 8-shaped direct tensile tests, indirect split tensile tests and unconfined compression tests pointed out significant relations between the test results. The correlated data fall within the 85% - 90% confidence limits and the ratio of 8-shaped tensile strength to split tensile strength was calculated to be 1.9, the ratio of 8-shaped tensile strength to unconfined compressive strength was calculated to be 0.4 and the ratio of split tensile strength to unconfined compressive strength was calculated to be 0.2. It should be stated that, these significant relations can be used to estimate the fine-grained soils tensile strengths from their unconfined compressive strengths.

- According to the conducted tensile strength test results and index properties, two empirical equation for 8-shaped direct tensile testing and one empirical equation for split tensile testing were developed and proposed. Equations which are listed below were developed from the 8-shaped direct tensile strength results and the data obtained from the equations fall within 90% confidence limits.

$$\sigma_{t_8} = -100{,}158\ (\gamma_{d_{max}}) + 2{,}461\ (PL) - 0{,}942\ (LL) - 6{,}623\ (w) + 3{,}656\ (CC) - 0{,}477\ (SL) + 230{,}96$$

$$\sigma_{t_8} = -0{,}3528\ (LL) + 2{,}0977\ (CC) - 5{,}8545\ (w_{opt}) + 4{,}229\ (PL) - 2{,}554\ (SL) + 61{,}335$$

- Equation which is presented below, was developed from indirect split tensile strength test results and the data obtained from the equation fall within 85% confidence limits.

$$\sigma_{t_s} = -100{,}12\ (\gamma_{d_{max}}) + 1{,}1267\ (PL) - 0{,}8874\ (LL) - 6{,}851\ (w) + 3{,}457\ (CC) + 0{,}8424\ (SL) + 226{,}3613$$

- The equations developed in this study, can be used to easily and rapidly determine the fine grained soils' tensile strength values by inputting the maximum dry density, liquid limit, plastic limit, shrinkage limit, water content and clay content values of the soil tested. However, extensive researches should be conducted on different kind of stabilized and non-stabilized fine grained soils following the proposed methodology, to develop generalized empirical relations between the tensile strength and index properties of soils.

- There are significant amounts of industrial waste materials which can be reclaimed for construction of various geo-structures like lightweight backfill for retaining walls, landfill liners and capping systems etc. It should be stated that, the leachate generation on landfill and lateral pressures of soil-fiber mixtures should be investigated before field applications carried out.

5.3. Recommendations for Future Studies

Following suggestions can be examined for future studies related with the tensile strength of soils;

- In this study, mainly synthetic fiber, metal swarf, pulverized rubber and bentonite were used to stabilize soil with fixed percentages. Various percentages of additives can be examined on the same soil to determine the effects of additives on the tensile strength of soil. Also different additives, for example; chemical additives etc. can be used to investigate the stabilization effects on tensile strength of soils.

- Synthetic fibers with various lengths can be used to investigate the improvement effects of fiber length on tensile strength of soils.

- Proposed direct tensile tests and indirect tensile tests can be performed on different kinds of fine grained soils, sands and rocks.

- Effects of water content and curing time on the tensile strength of stabilized soils can be examined.

- Various correlations between the consistency limits, tensile strength characteristics and other strength characteristics of soils can be investigated.

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APPENDIX A

MAXIMUM DRY DENSITIES VERSUS OPTIMUM MOISTURE CONTENT CURVES

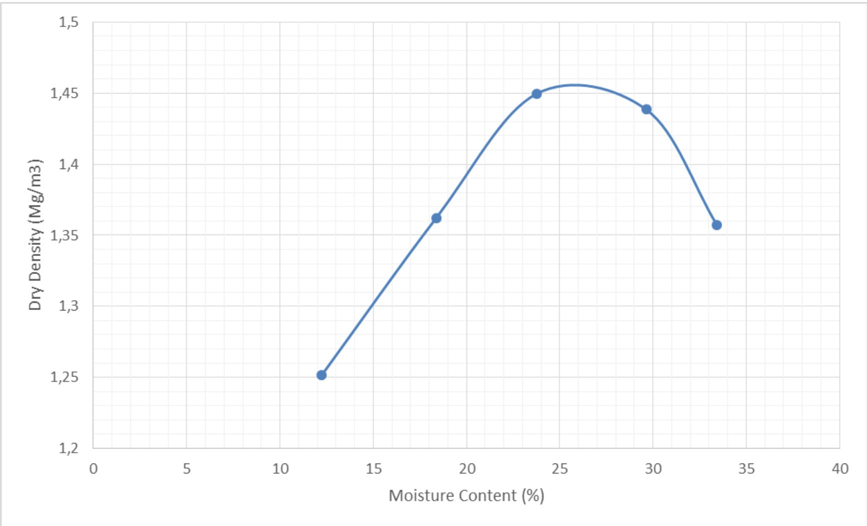

Figure A.1. Compaction curve of K-01 mixture

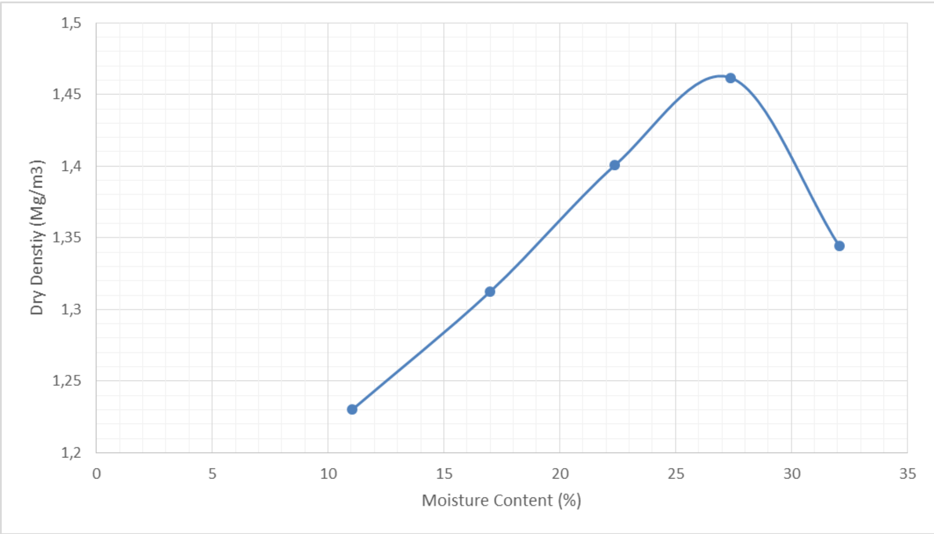

Figure A.2. Compaction curve of K-02 mixture

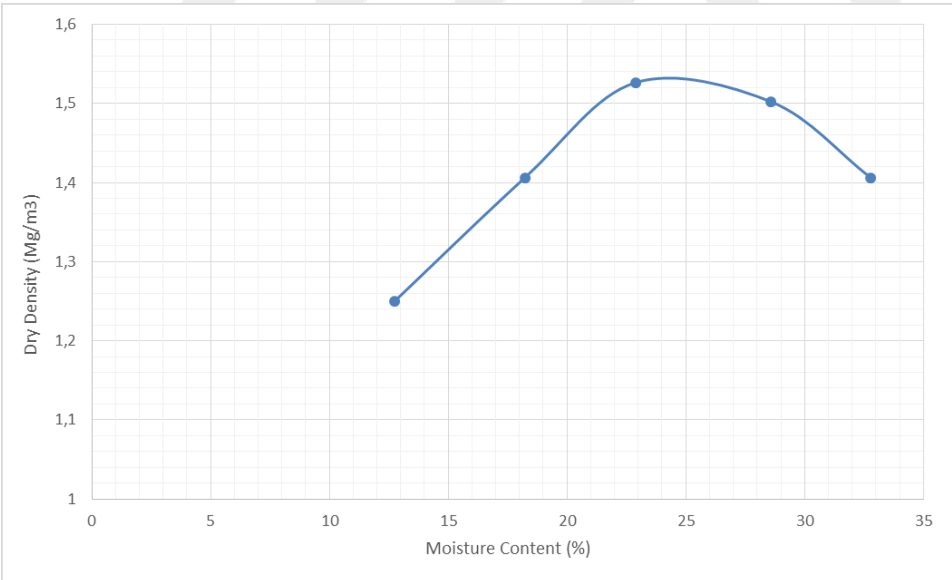

Figure A.3. Compaction curve of K-03 mixture

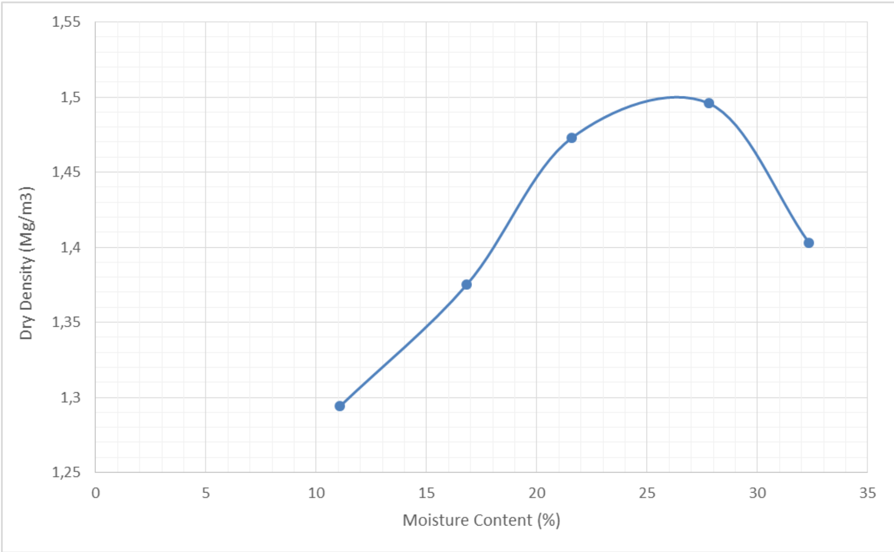

Figure A.4. Compaction curve of K-04 mixture

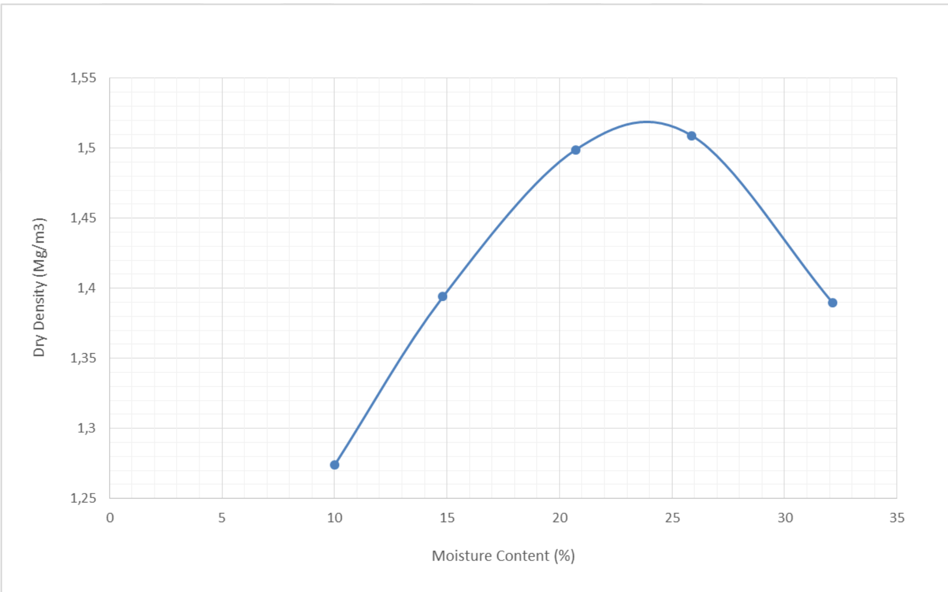

Figure A.5. Compaction curve of AC-01 mixture

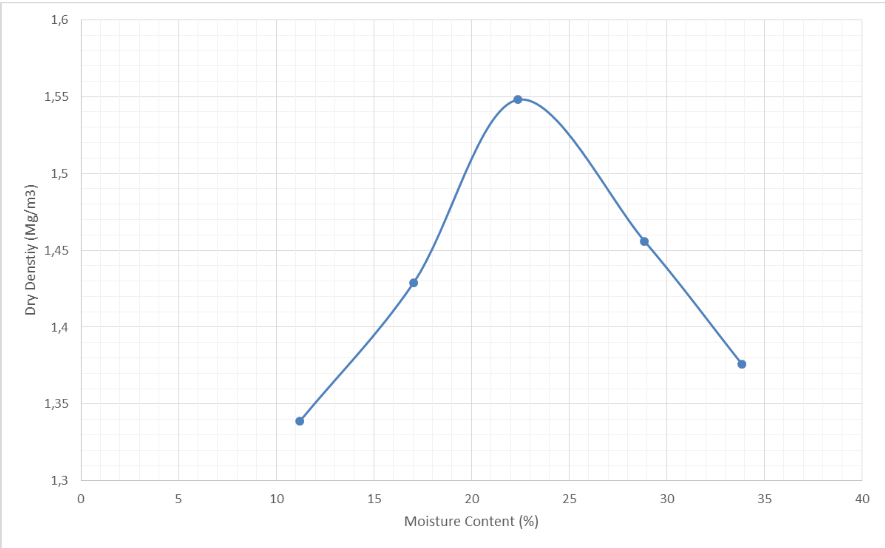

Figure A.6. Compaction curve of AC-02 mixture

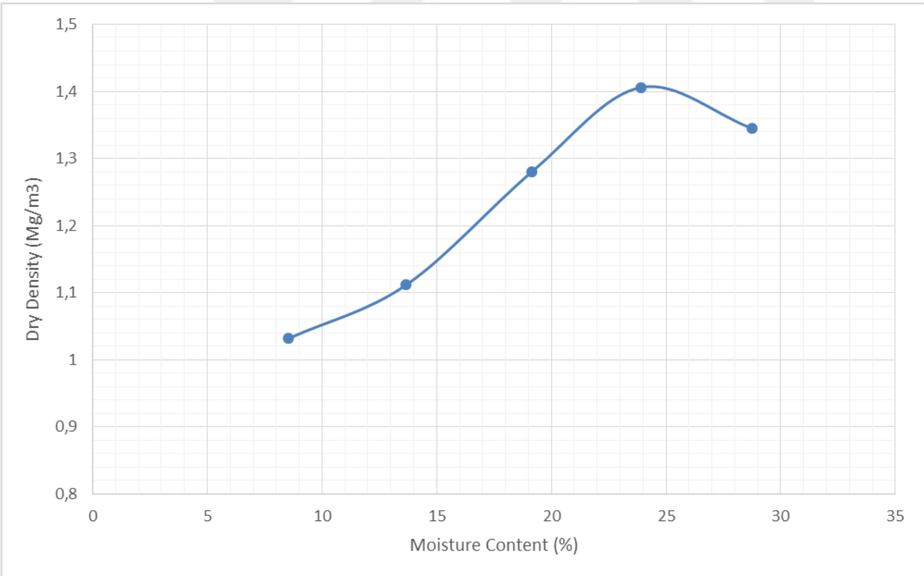

Figure A.7. Compaction curve of AC-03 mixture

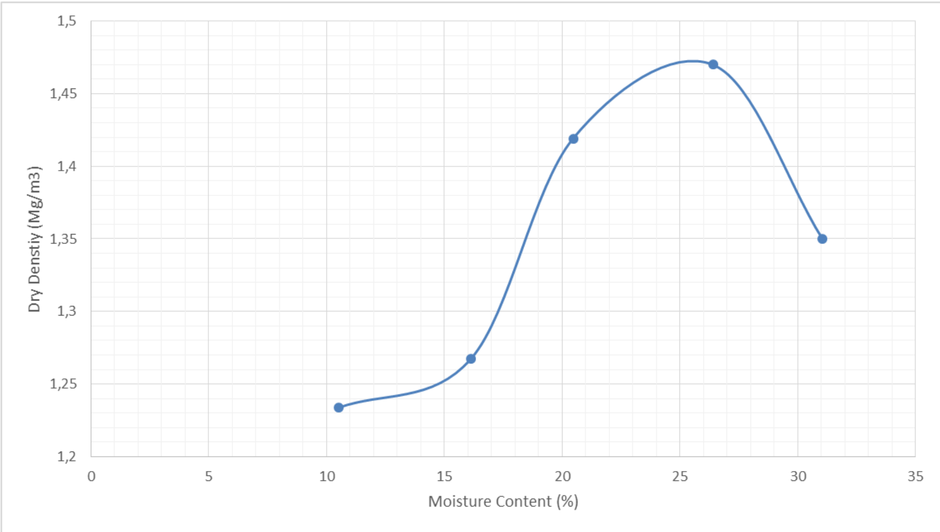

Figure A.8. Compaction curve of AC-04 mixture

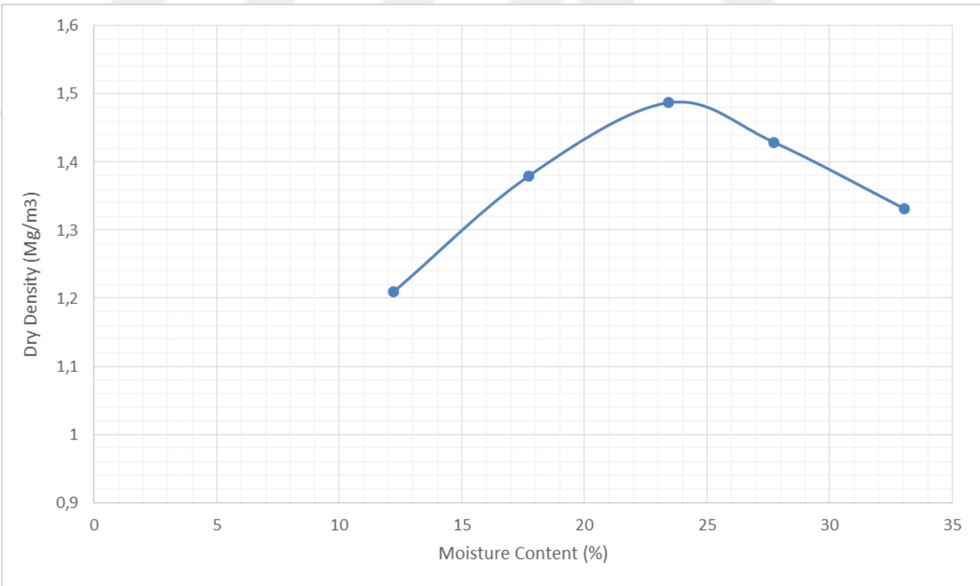

Figure A.9. Compaction curve of AC-05 mixture

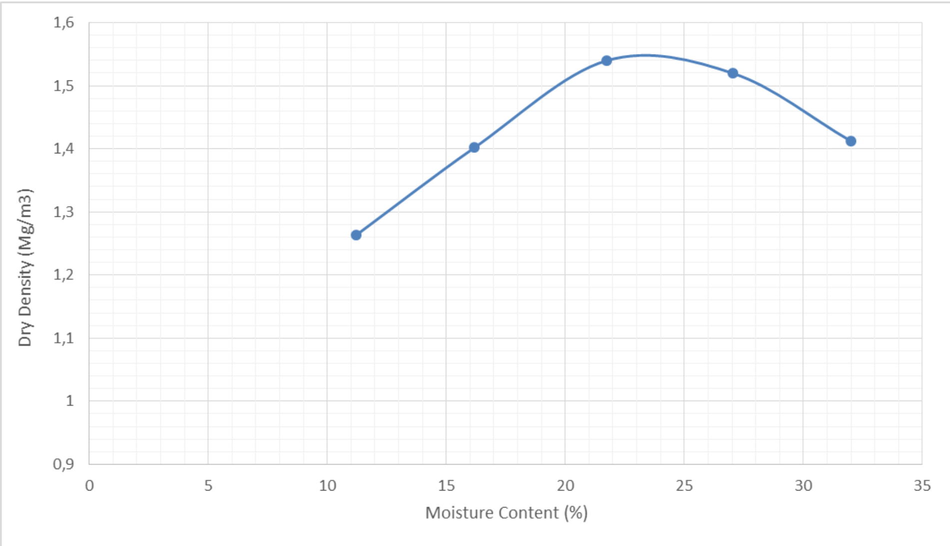

Figure A.10. Compaction curve of AC-06 mixture

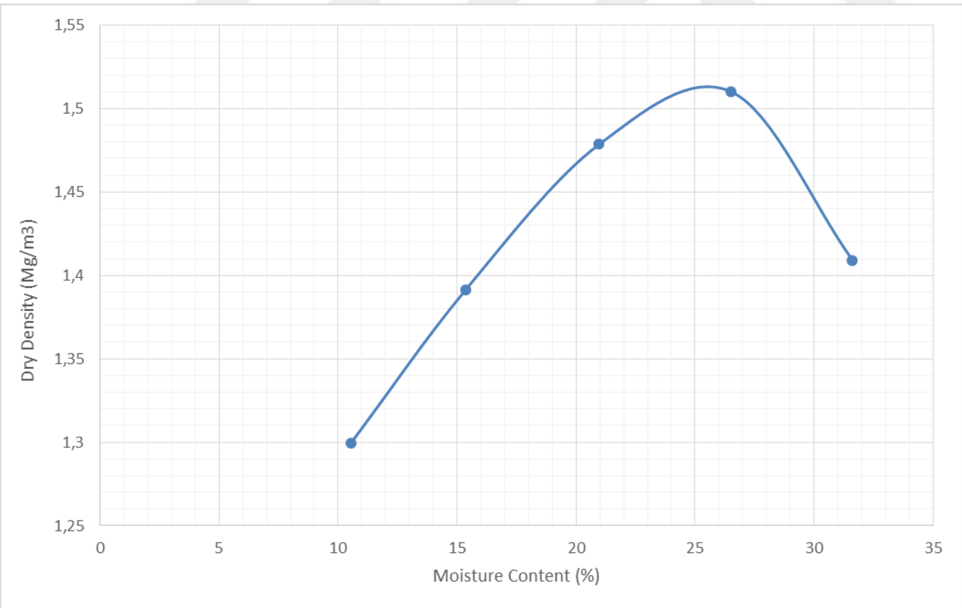

Figure A.11. Compaction curve of AC-07 mixture

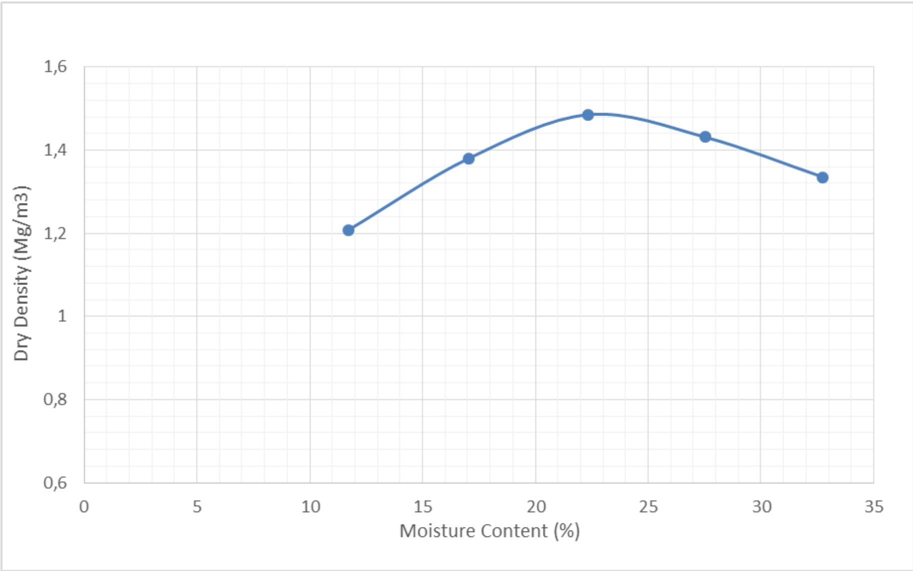

Figure A.12. Compaction curve of AC-08 mixture

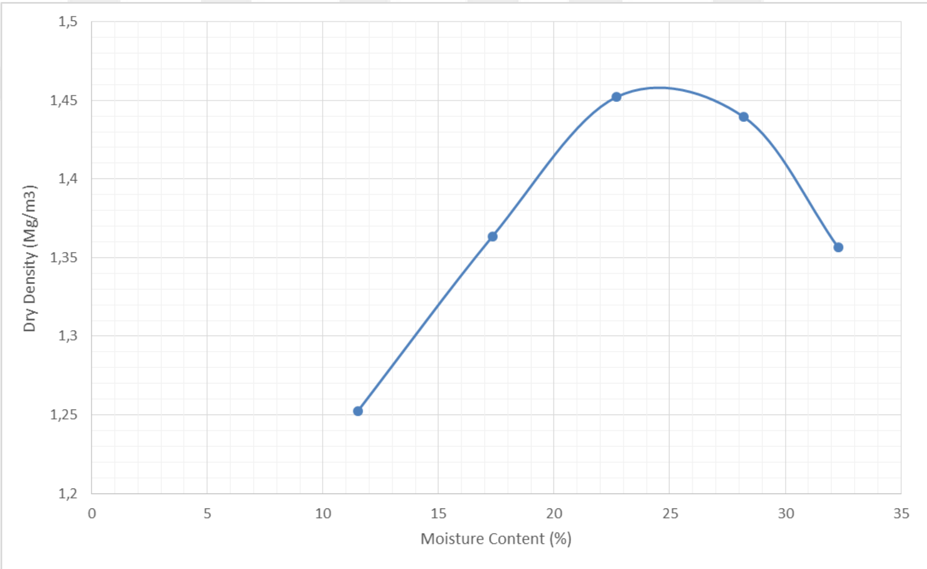

Figure A.13. Compaction curve of AC-09 mixture

Table A.1. Wet of optimum percentages of the Ankara clay and Kaolin clay mixtures

Mixture Design	Mixture Code	Optimum Water Content (%)	Water Content (%)	% Wet of Optimum
Kaolin Clay 95% + Bentonite 5% + Water Content 32%	K-01	26	32	6
Kaolin Clay 94% + Bentonite 5% + Synthetic Fiber 1% + Water Content 30,8%	K-02	27	30,8	3,8
Kaolin Clay 92% + Bentonite 5% + Pulverized Rubber 3% + Water Content 31,5%	K-03	24,5	31,5	7
Kaolin Clay 92% + Bentonite 5% + Metal Swarf 3% + Water Content 31,2%	K-04	26,5	31,2	4,7
Ankara Clay 100% + Water Content 27,2%	AC-01	24	27,2	3,2
Ankara Clay 95% + Bentonite 5% + Water Content 28%	AC-02	22,5	28	5,5
Ankara Clay 95% + Synthetic Fiber 5% + Water Content 28,7%	AC-03	24	28,7	4,7
Ankara Clay 95% + Synthetic Fiber 2,5% + Bentonite 2,5% + Water Content 29,25%	AC-04	25,5	29,25	3,75
Ankara Clay 92,5% + Synthetic Fiber 5% + Bentonite 2,5% + Water Content 28,5%	AC-05	24	28,5	4,5
Ankara Clay 95% + Metal Swarf 5% + Water Content 29,2%	AC-06	24,5	29,2	4,7
Ankara Clay 95% + Metal Swarf 2,5% + Bentonite 2,5% + Water Content 30,3%	AC-07	25,5	30,3	4,8
Ankara Clay 95% + Pulverized Rubber 5% + Water Content 28,5%	AC-08	22,2	28,5	6,3
Ankara Clay 95% + Pulverized Rubber 2,5% + Bentonite 2,5% + Water Content 31%	AC-09	24,5	31	6,5

APPENDIX B

GRAIN SIZE DISTRIBUTION CURVES

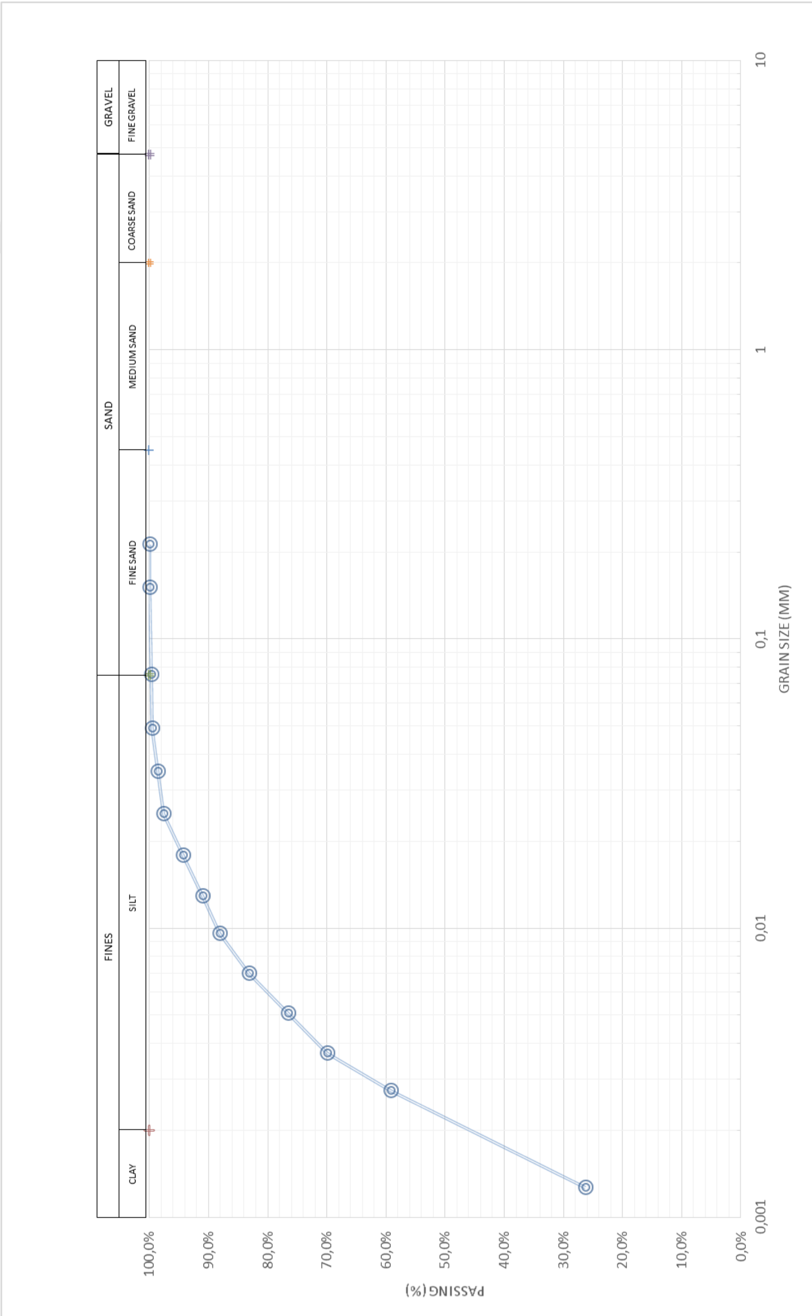

Figure B.1. Grain Size Distribution of K-01 mixture

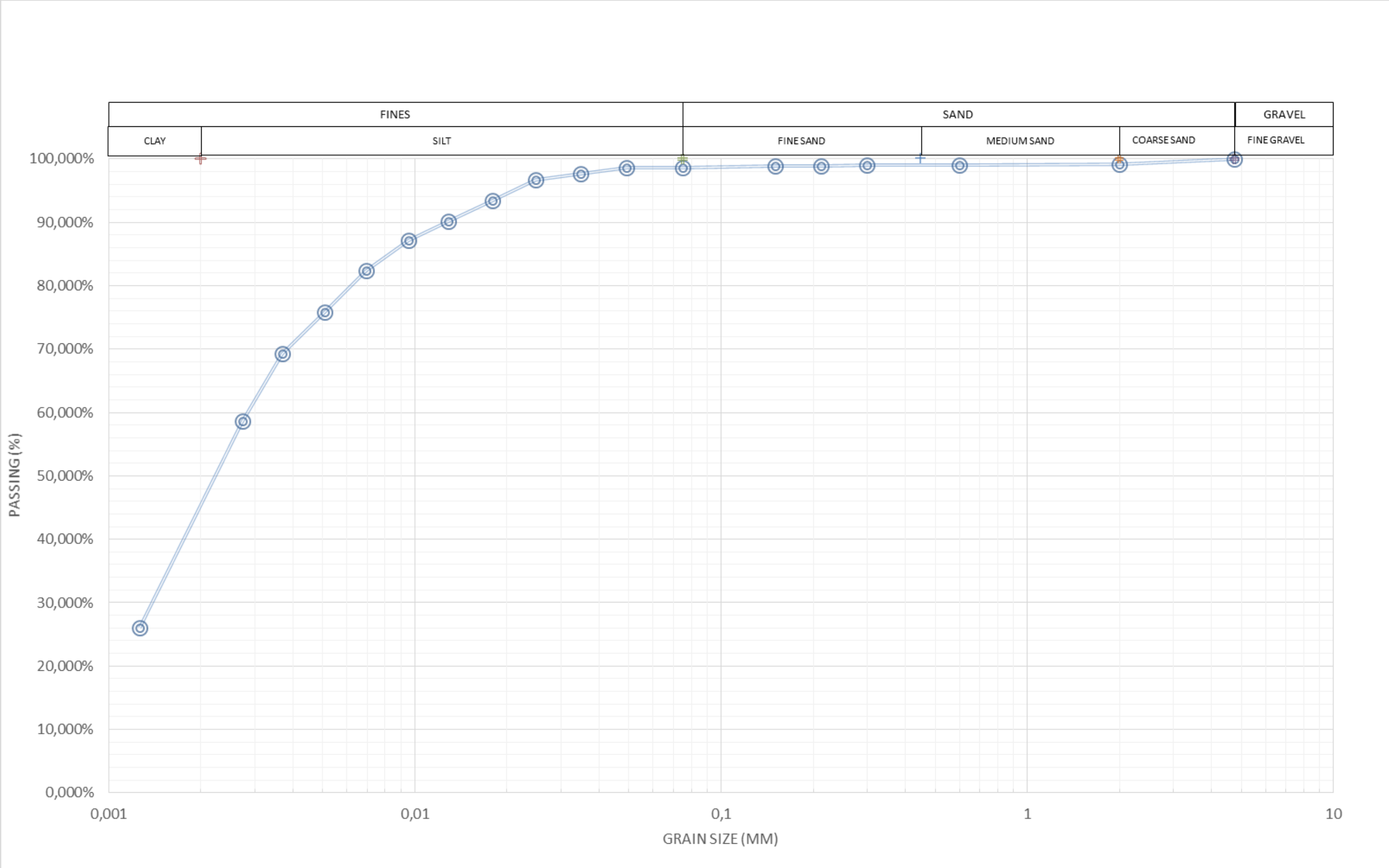

Figure B.2. Grain Size Distribution of K-02 mixture

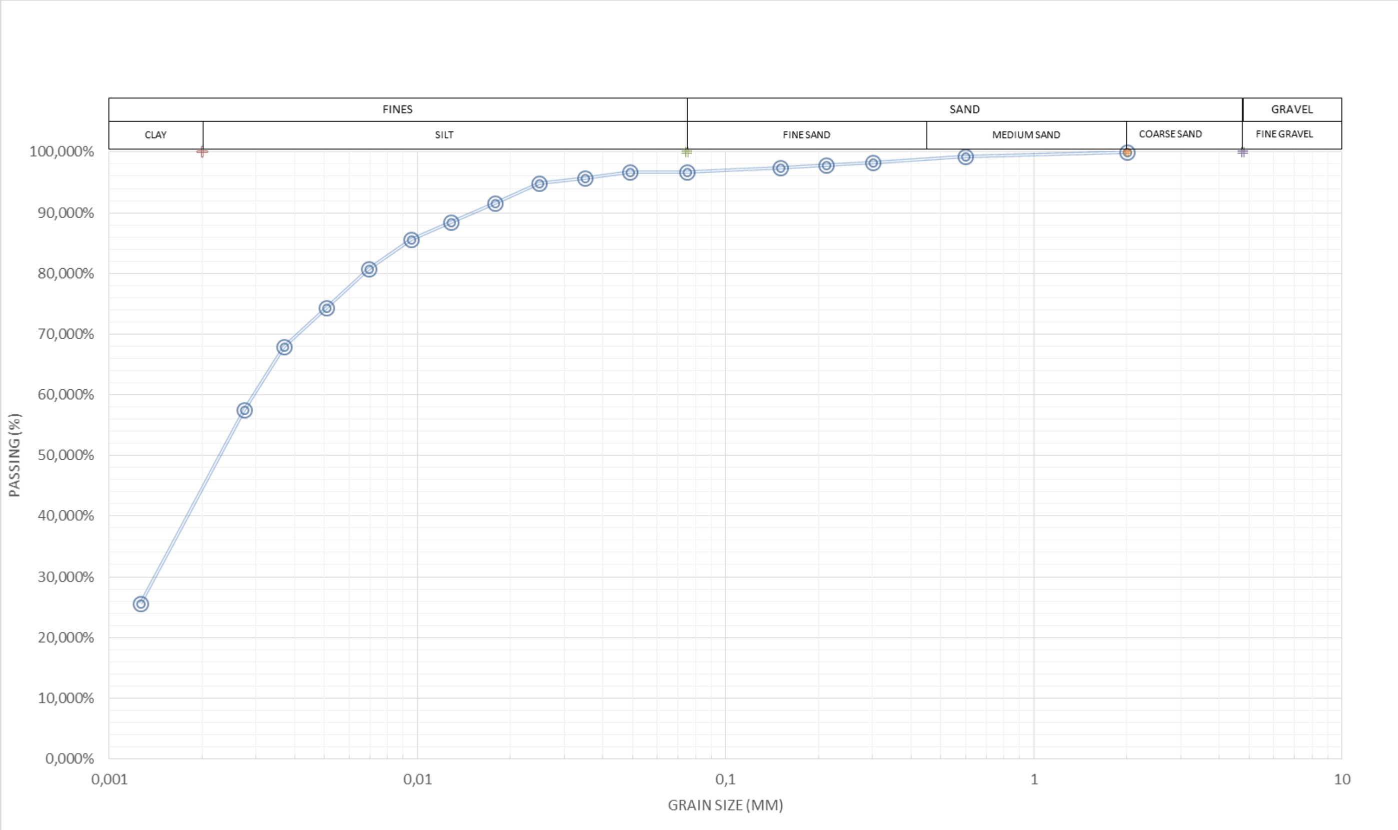

Figure B.3. Grain Size Distribution of K-03 mixture

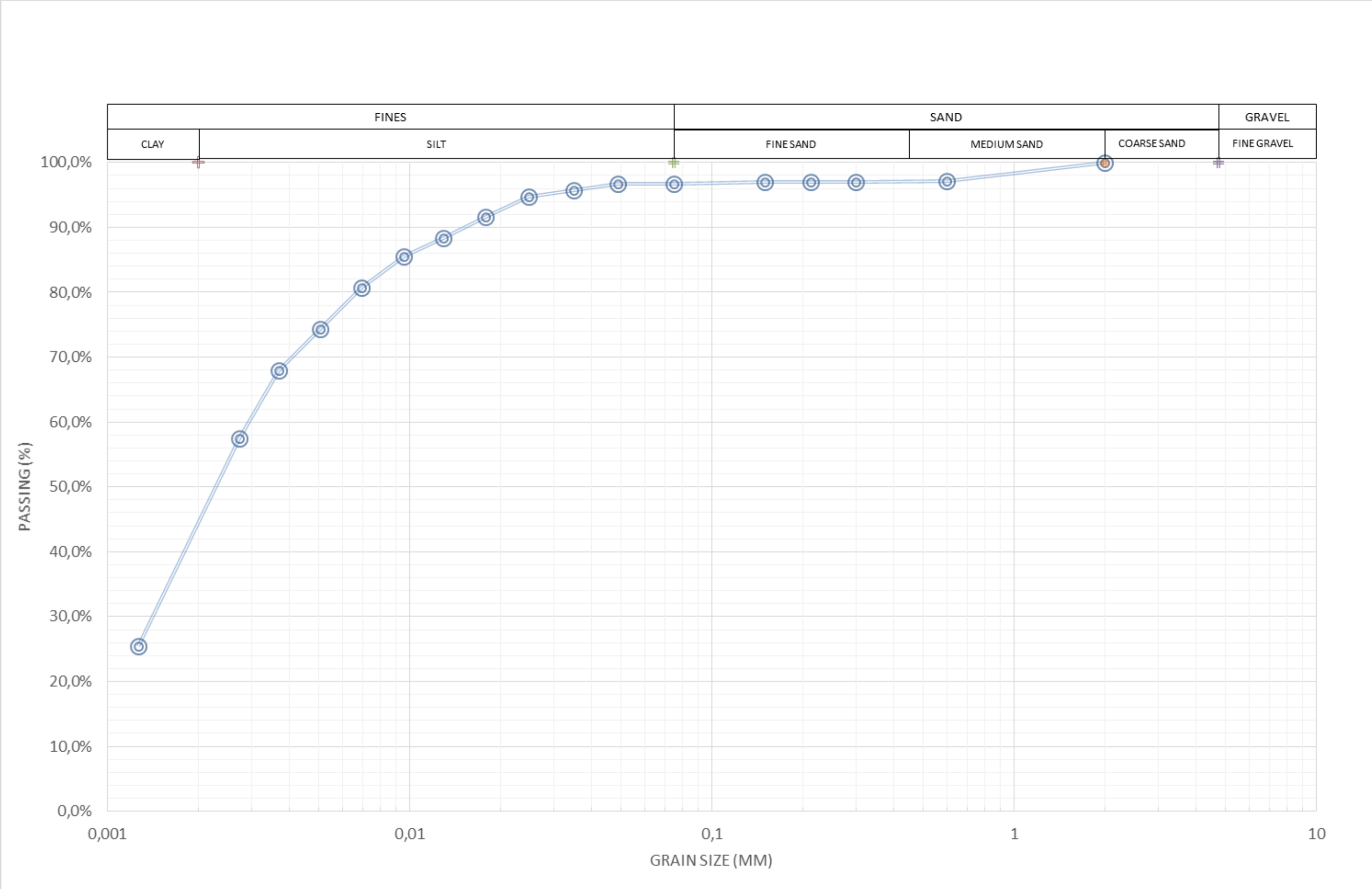

Figure B.14. Grain Size Distribution of K-04 mixture

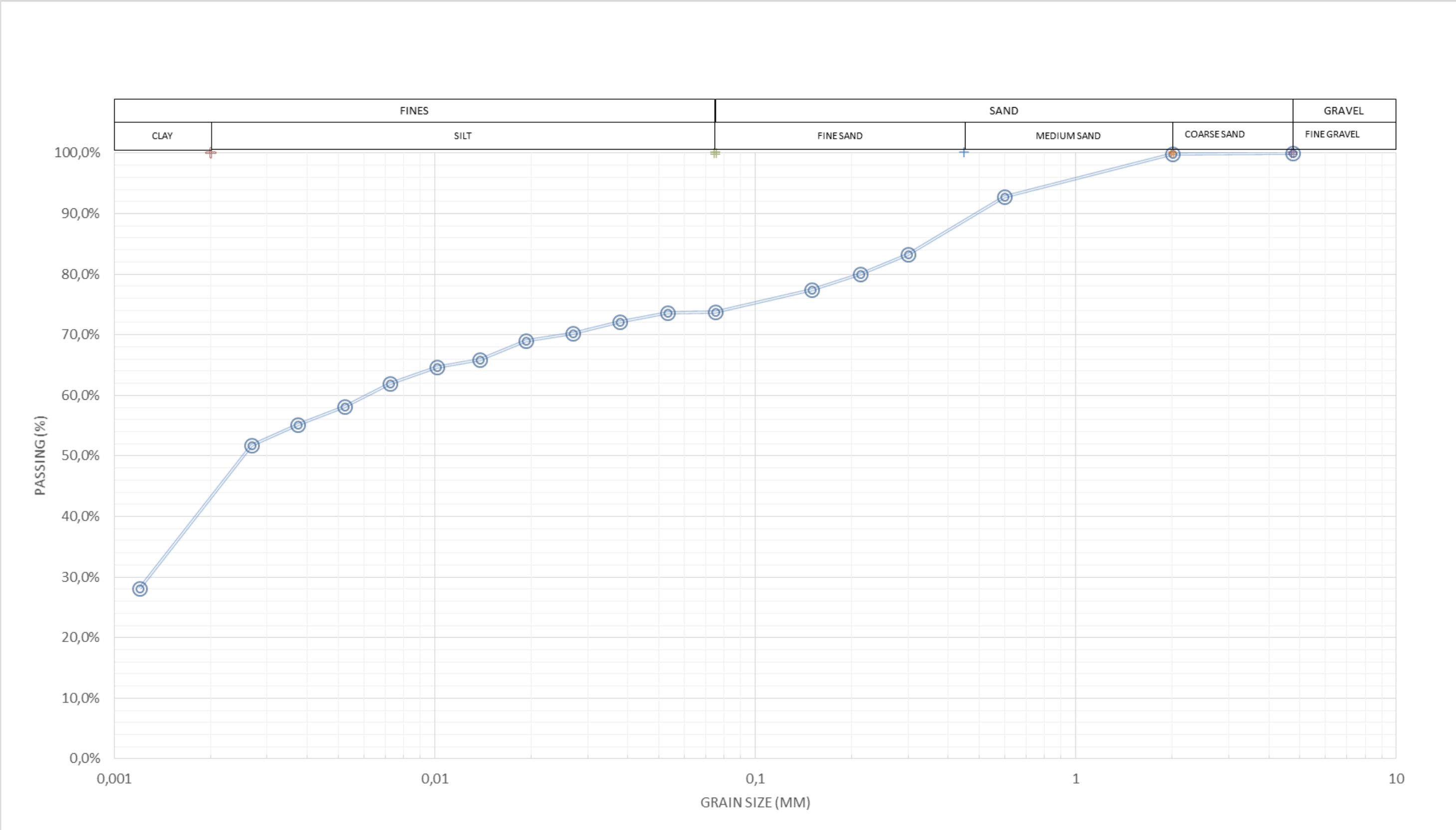

Figure B.5. Grain Size Distribution of AC-01 mixture

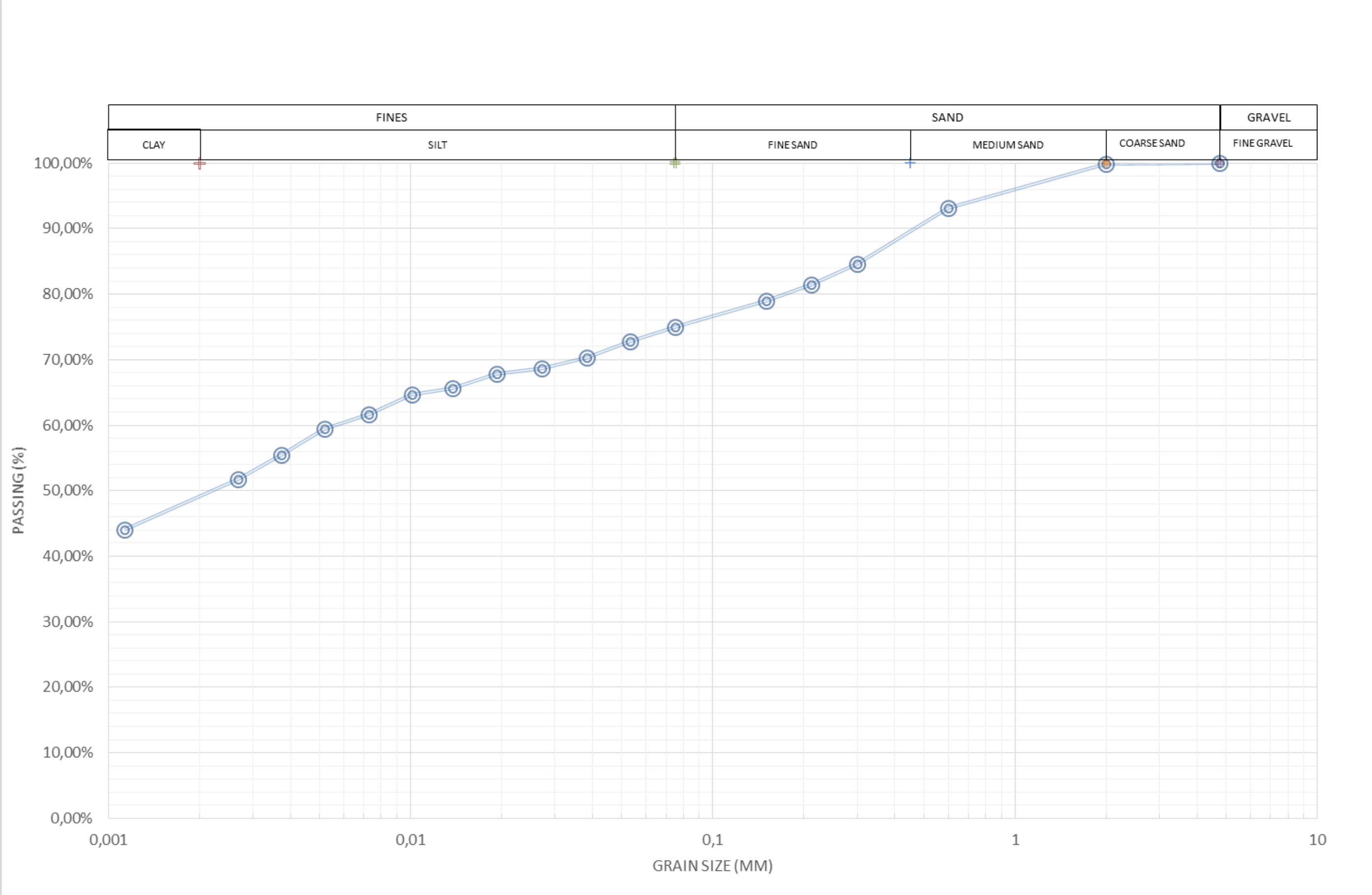

Figure B.6. Grain Size Distribution of AC-02 mixture

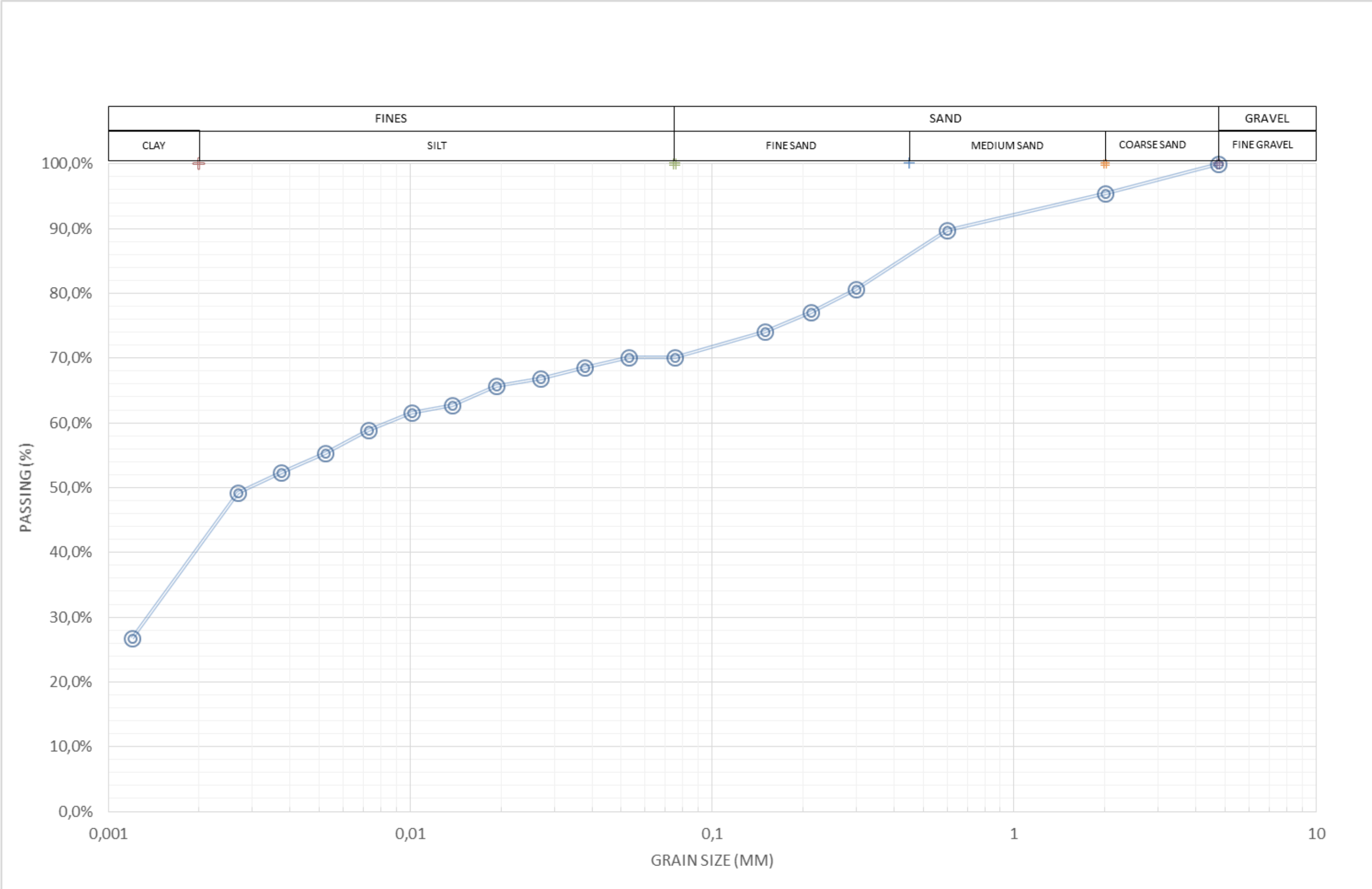

Figure B.7. Grain Size Distribution of AC-03 mixture

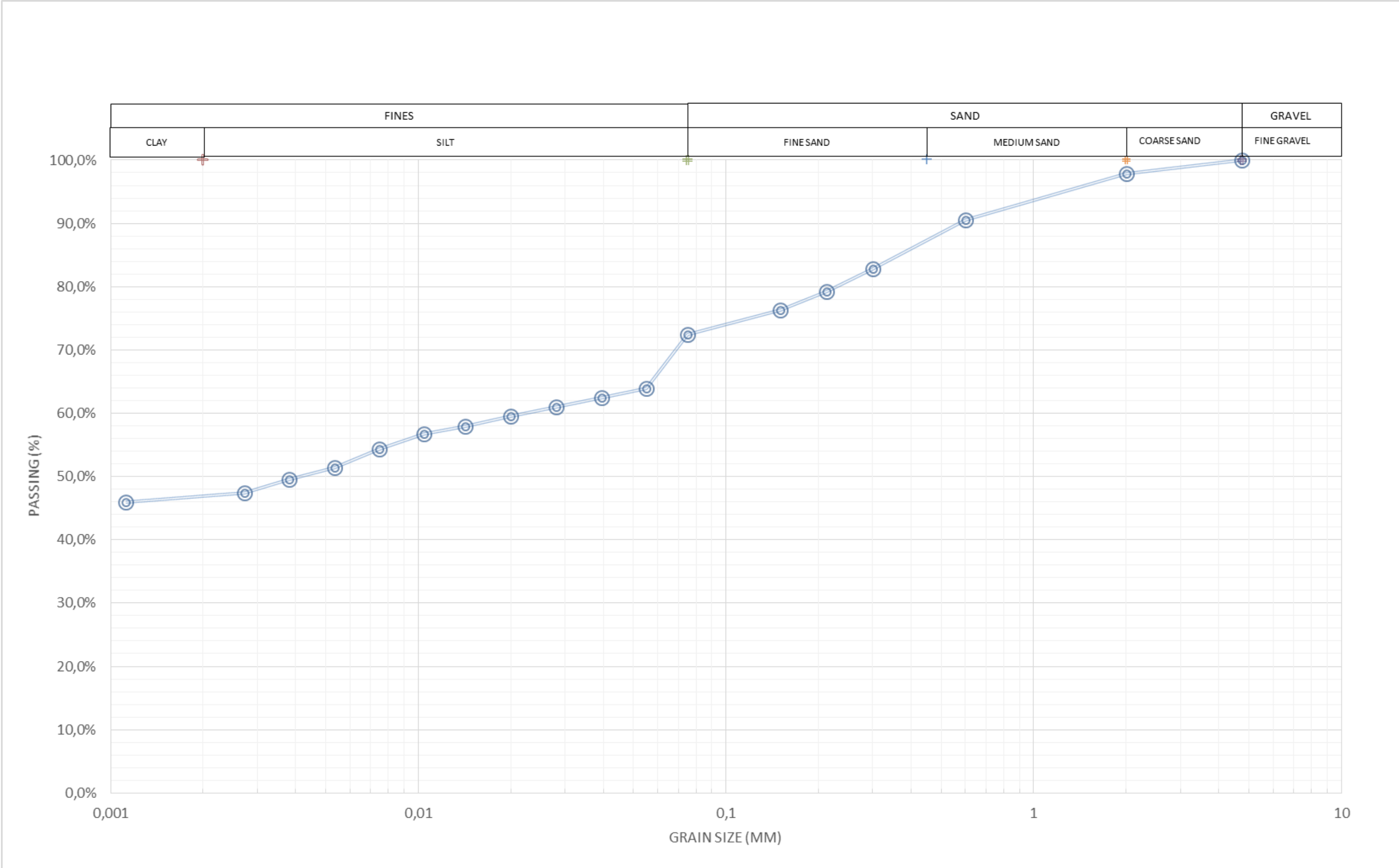

Figure B.8. Grain Size Distribution of AC-04 mixture

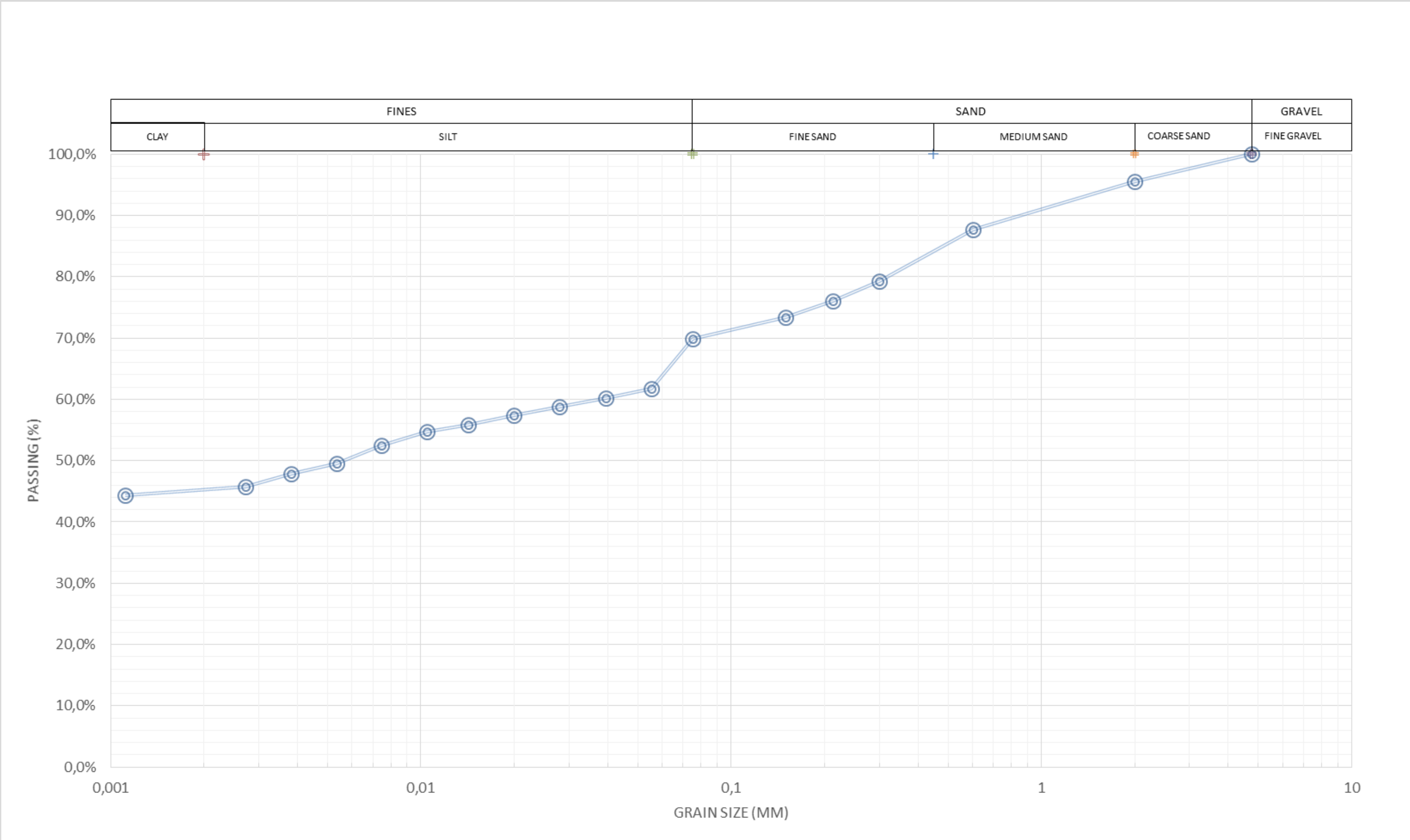

Figure B.9. Grain Size Distribution of AC-05 mixture

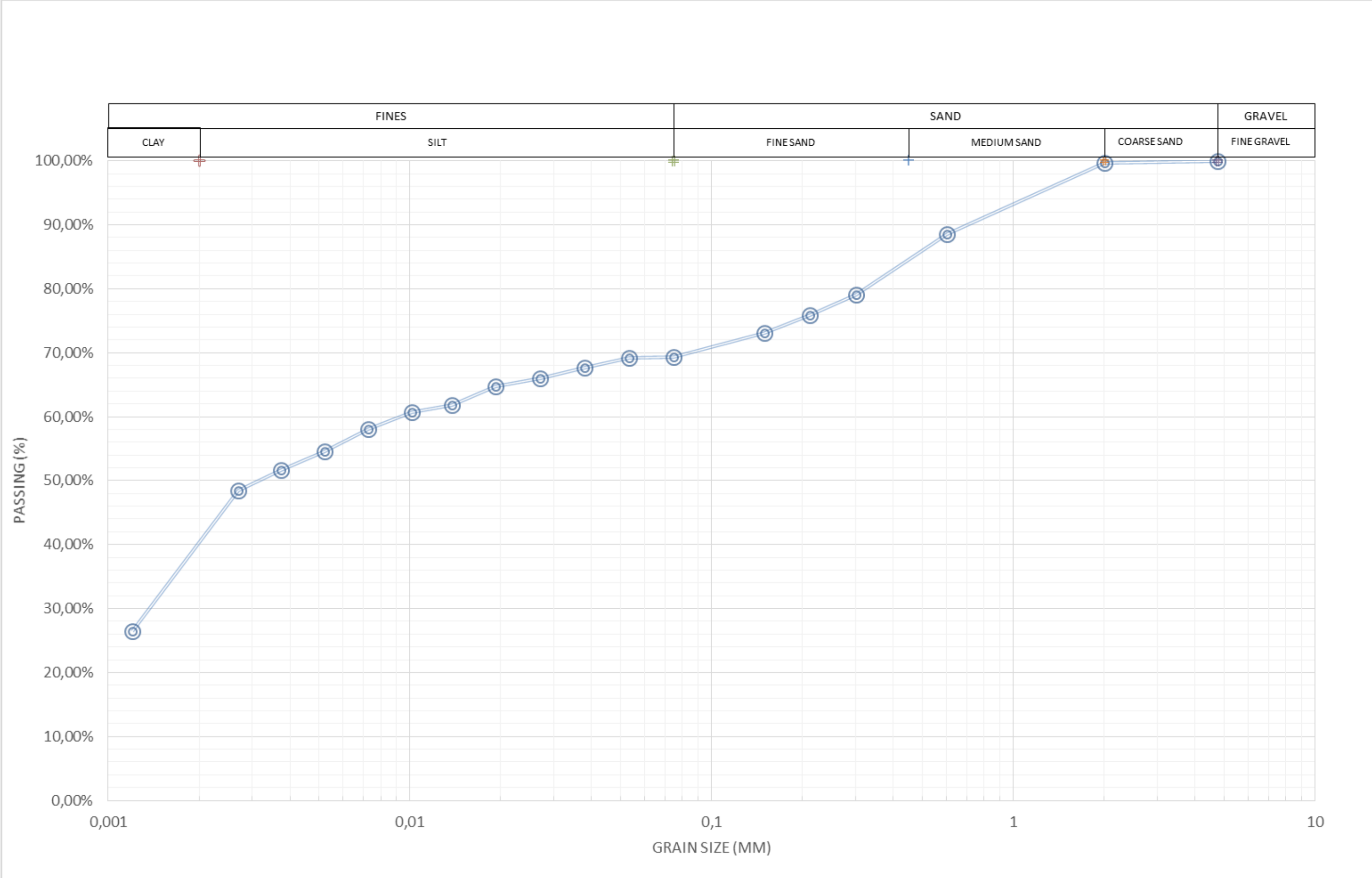

Figure B.10. Grain Size Distribution of AC-06 mixture

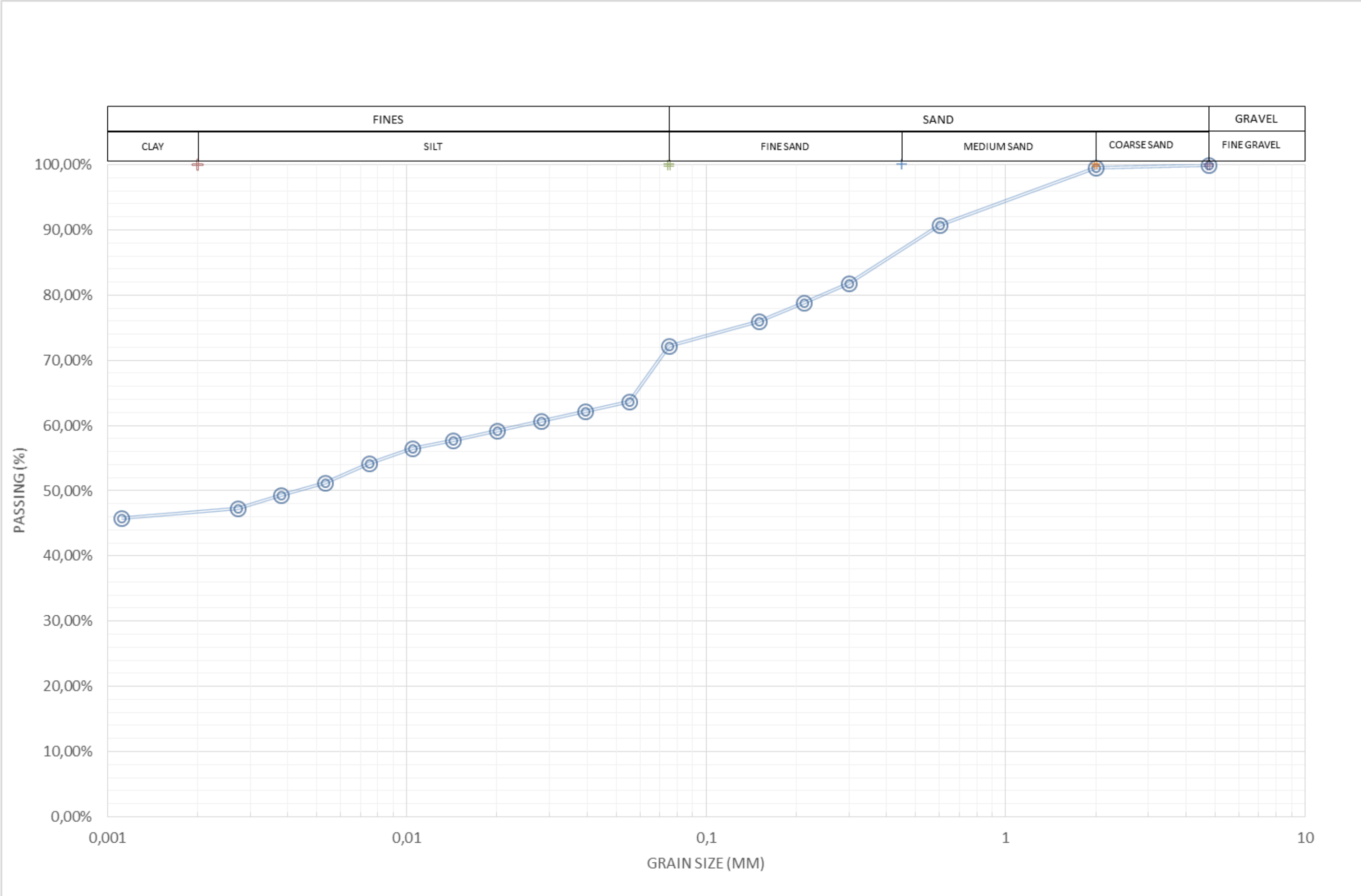

Figure B.11. Grain Size Distribution of AC-07 mixture

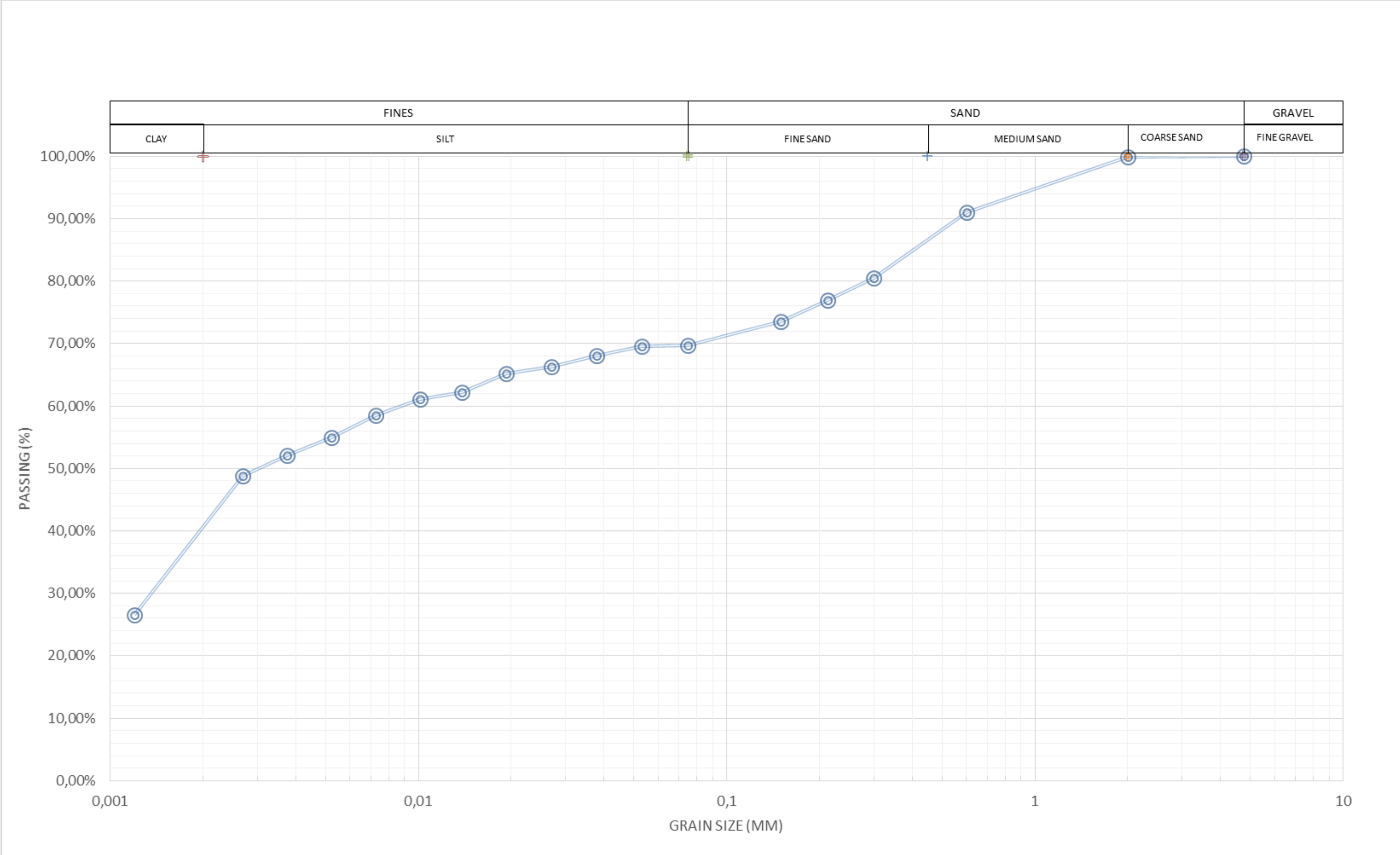

Figure B.12. Grain Size Distribution of AC-08 mixture

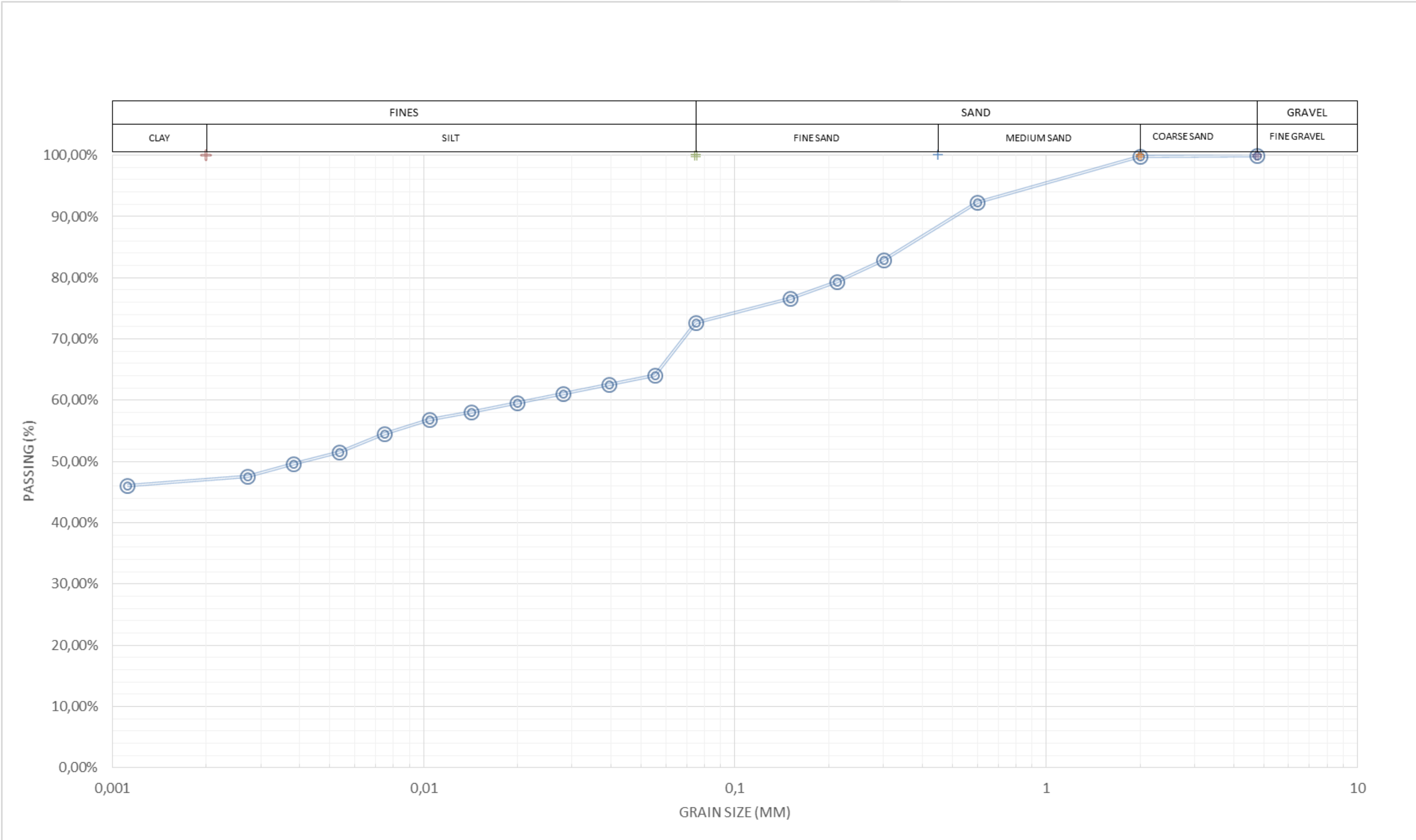

Figure B.13. Grain Size Distribution of AC-09 mixture

APPENDIX C

STRESS-STRAIN CURVES

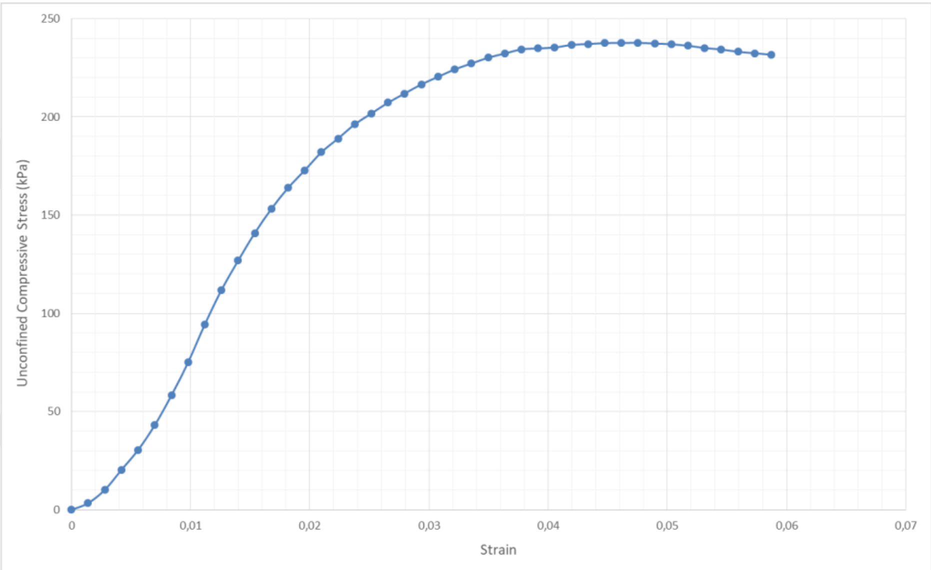

Figure C.1. Unconfined compressive stress-strain curve of K-01 mixture

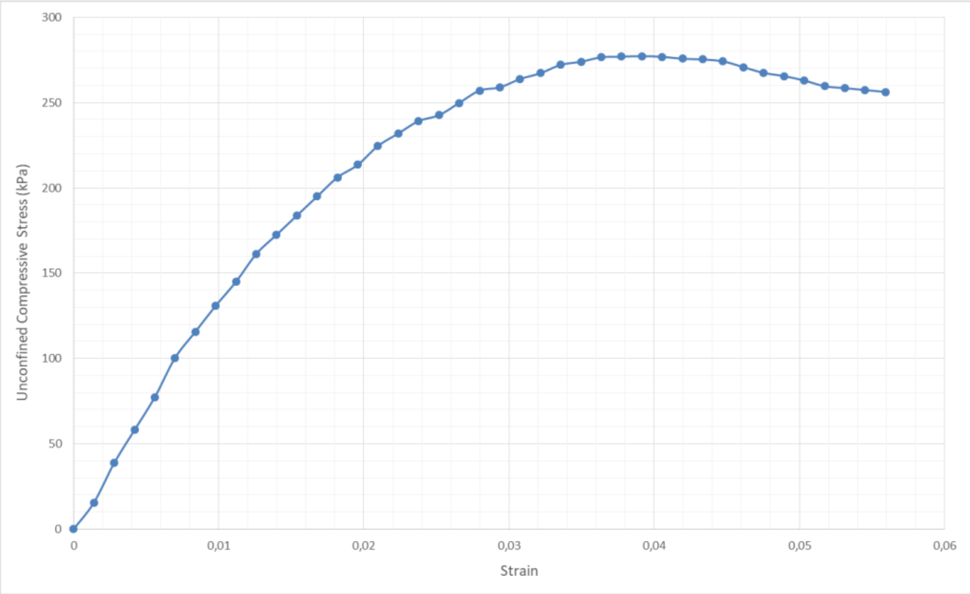

Figure C.2. Unconfined compressive stress-strain curve of K-02 mixture

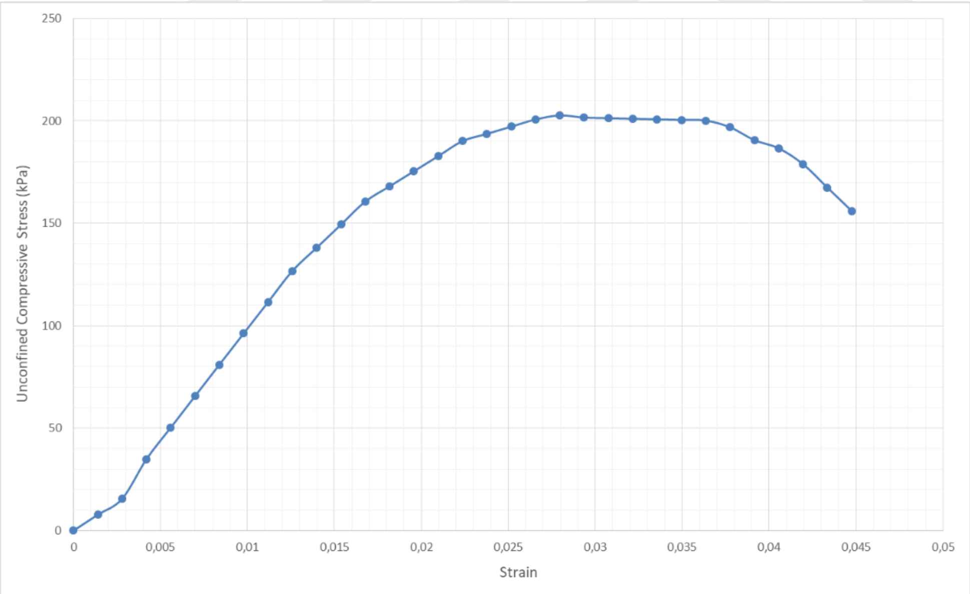

Figure C.3. Unconfined compressive stress-strain curve of K-03 mixture

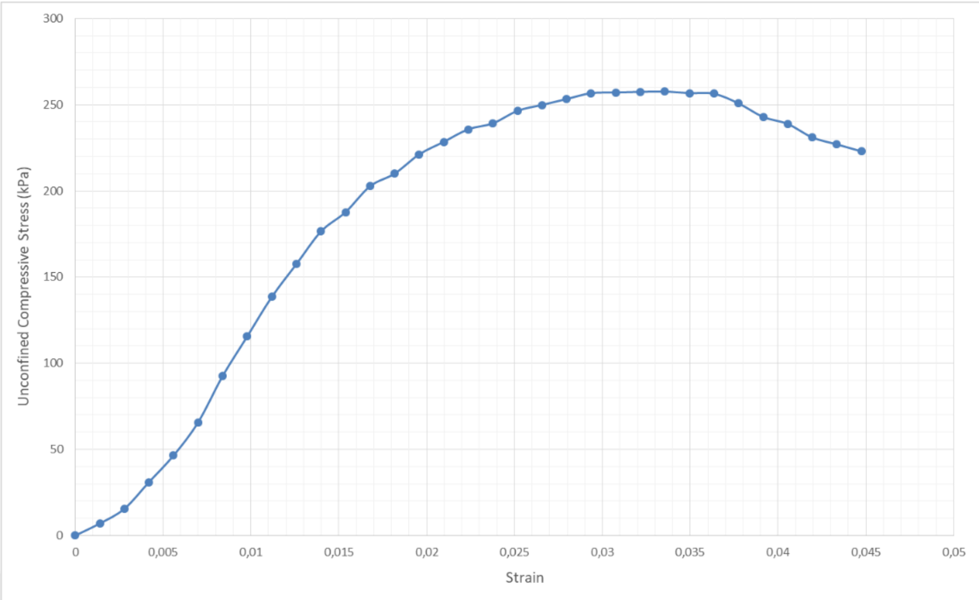

Figure C.4. Unconfined compressive stress-strain curve of K-04 mixture

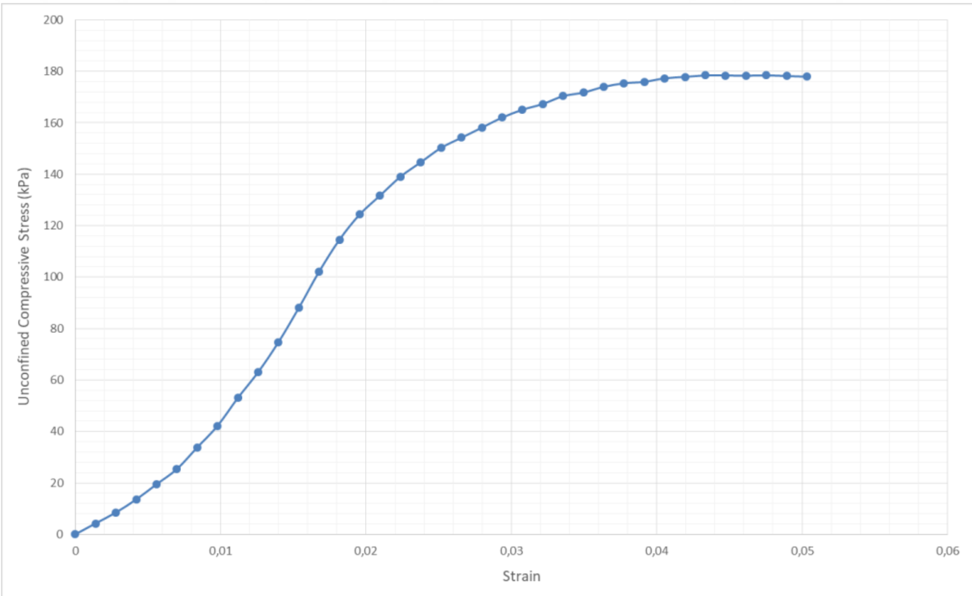

Figure C.5. Unconfined compressive stress-strain curve of AC-01 mixture

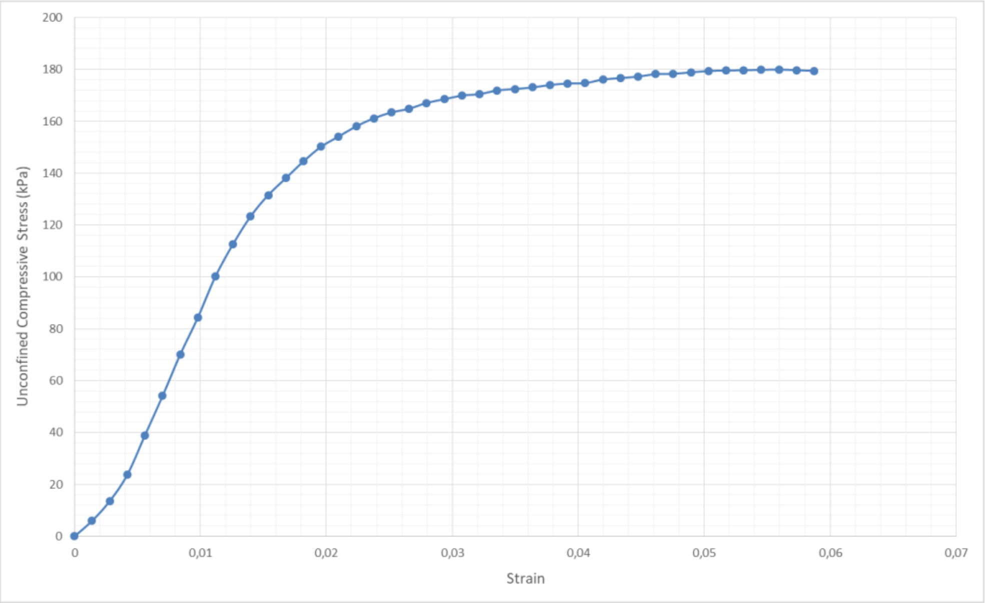

Figure C.6. Unconfined compressive stress-strain curve of AC-02 mixture

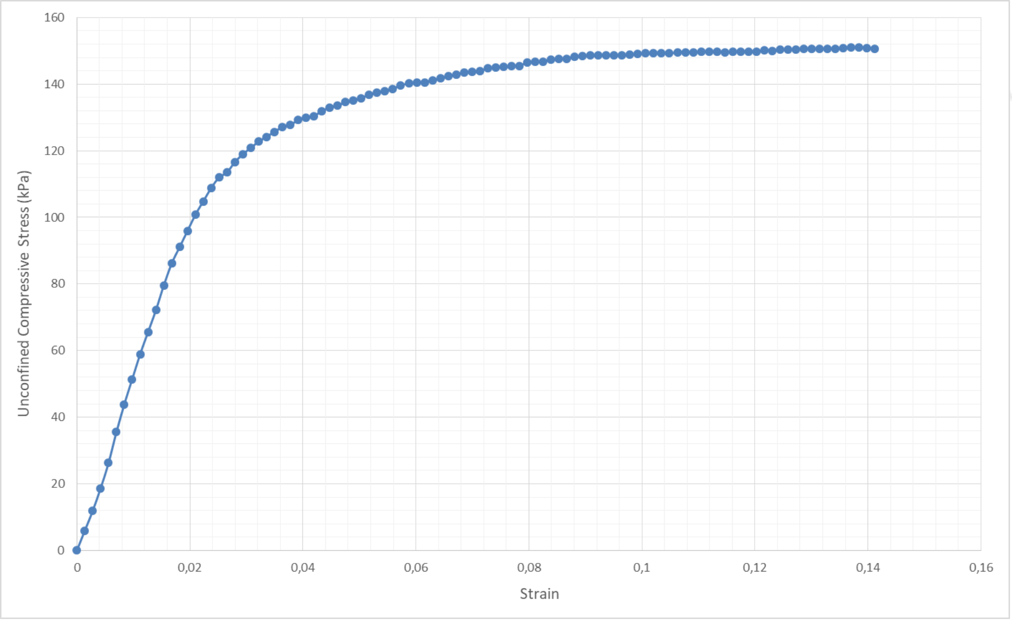

Figure C.7. Unconfined compressive stress-strain curve of AC-03 mixture

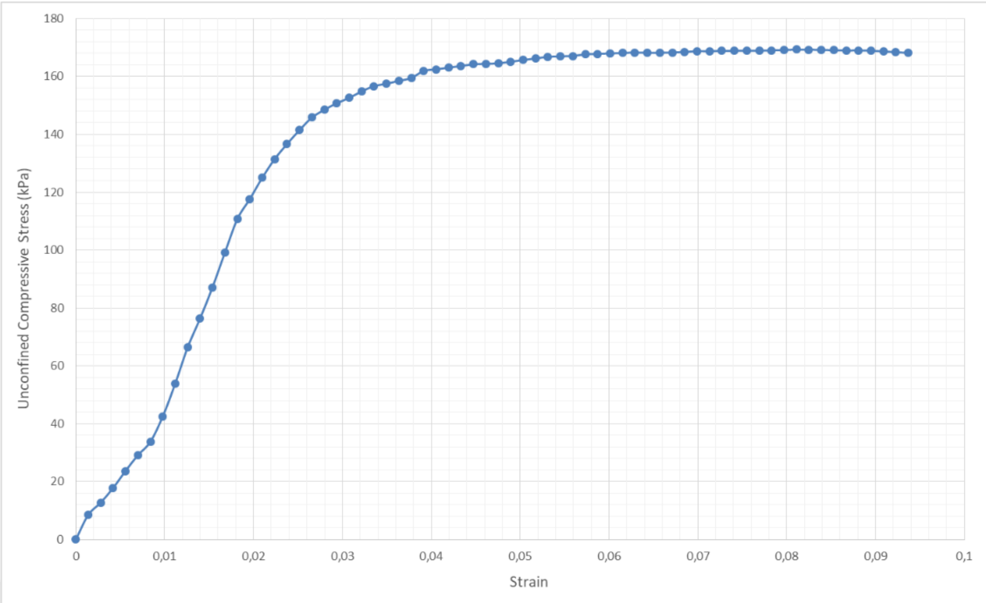

Figure C.8. Unconfined compressive stress-strain curve of AC-04 mixture

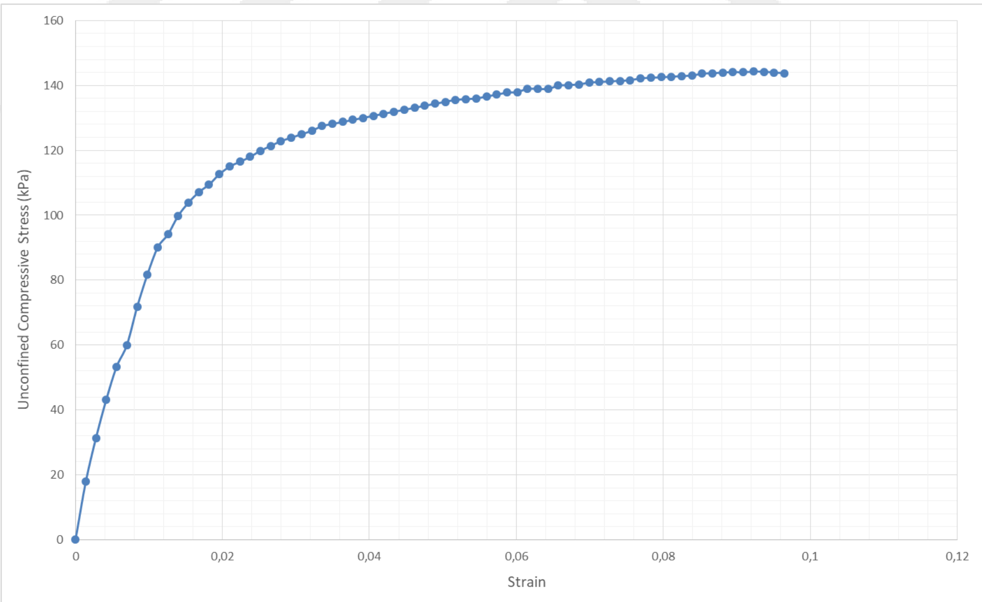

Figure C.9. Unconfined compressive stress-strain curve of AC-05 mixture

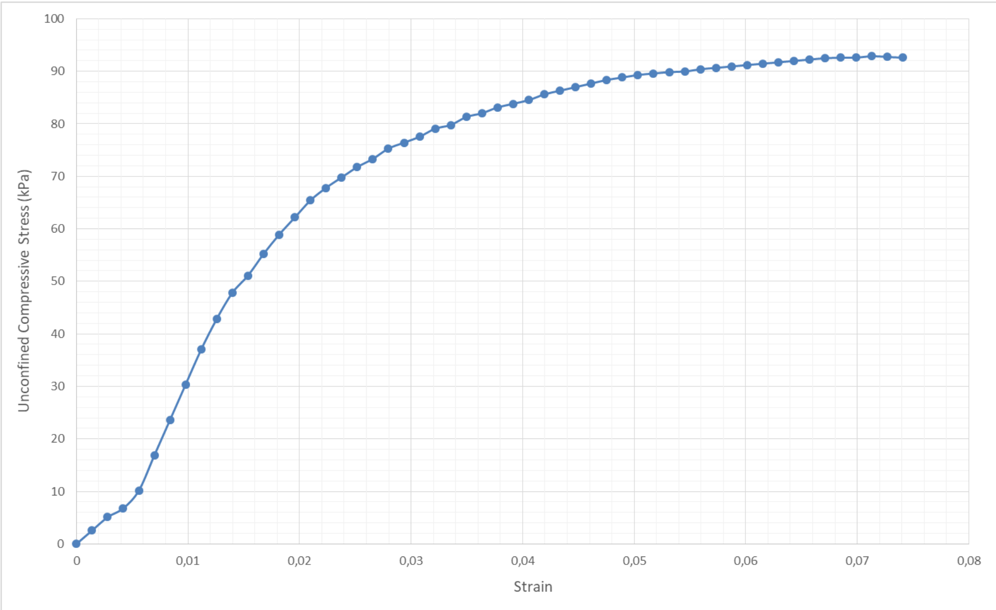

Figure C.10. Unconfined compressive stress-strain curve of AC-06 mixture

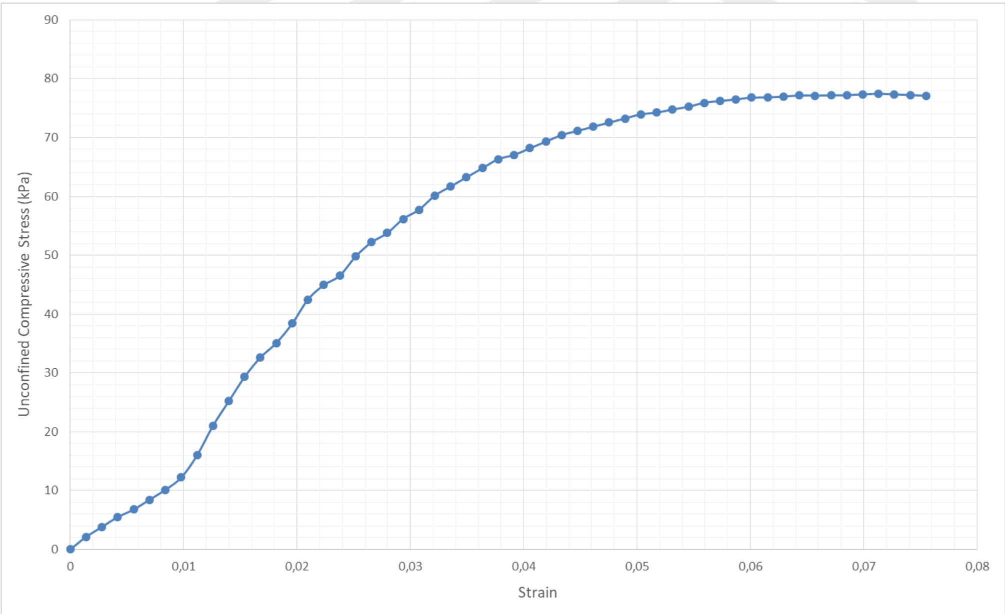

Figure C.11. Unconfined compressive stress-strain curve of AC-07 mixture

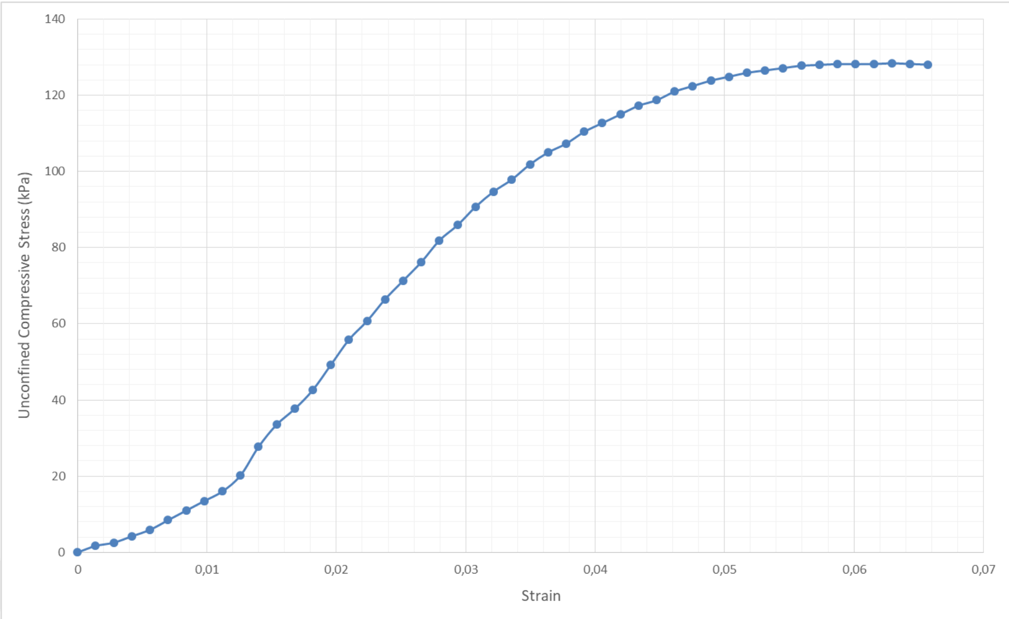

Figure C.12. Unconfined compressive stress-strain curve of AC-08 mixture

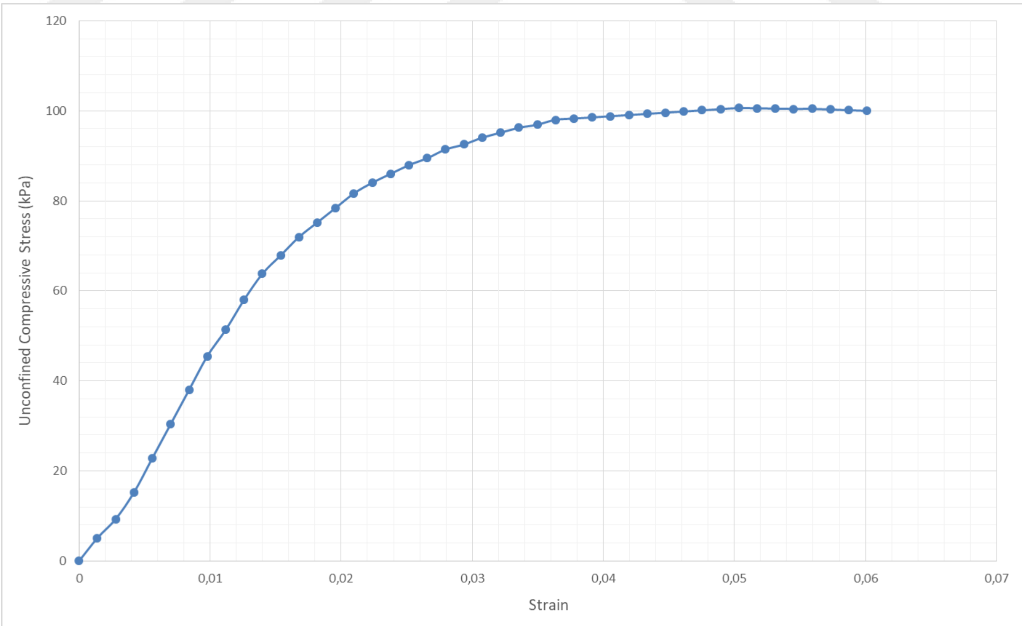

Figure C.13. Unconfined compressive stress-strain curve of AC-09 mixture