

**ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY**

**UTILIZATION OF WASTE FOUNDRY SAND AS HIGHWAY MATERIAL**

**M.Sc. Thesis by  
Abdulgazi GEDIK, B.Sc.**

**Department : CIVIL ENGINEERING**

**Programme : TRANSPORTATION ENGINEERING**

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**M.Sc. Thesis by  
Abdulgazi GEDIK, B.Sc.  
(501051401)**

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**Supervisor of Thesis : Prof. Abdullah Hilmi LAV (ITU)  
Other Jury Members : Prof. Emine AGAR (ITU)  
Prof. Necati KULOGLU (Firat University)**

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**YÜKSEK LİSANS TEZİ  
İnş. Müh. Abdulgazi GEDİK  
(501051401)**

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Tezin Savunulduğu Tarih : 10 Haziran 2008**

**Tez Danışmanı : Prof. Dr. Abdullah Hilmi LAV (İ.T.Ü)  
Diğer Jüri Üyeleri : Prof. Dr. Emine AĞAR (İ.T.Ü)  
Prof. Dr. Necati KULOĞLU  
(Fırat Üniversitesi)**

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## **PREFACE**

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Abdulgazi GEDIK

Civil Engineer

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## **ABBREVIATIONS**

|               |                                                                      |
|---------------|----------------------------------------------------------------------|
| <b>AASHTO</b> | : American Association of State Highway and Transportation Officials |
| <b>AFS</b>    | : American Foundry men's Society                                     |
| <b>ASTM</b>   | : American Society for Testing and Materials                         |
| <b>CBR</b>    | : California Bearing Ratio                                           |
| <b>LOI</b>    | : Loss on Ignition                                                   |
| <b>OMC</b>    | : Optimum Moisture Content                                           |
| <b>UCS</b>    | : Unconfined Compressive Strength                                    |
| <b>UT</b>     | : Ultrasonic Pulse Velocity Test                                     |
| <b>WFS</b>    | : Waste Foundry Sand                                                 |

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## **UTILIZATION OF WASTE FOUNDRY SAND AS HIGHWAY MATERIAL**

### **SUMMARY**

Foundry sand is consumed large amounts by manufacturing industries such as car manufacturing, iron-steel industries, alloy production and various branches of metallurgy industry. Bentonite is mixed with the material to bind the sand. After the molding process, the material is considered as waste stockpiled. Ever increasing stockpile cost is becoming a concern in molding industry; hence, manufacturers are looking for a suitable way of utilization.

The aim of this study is to use waste foundry sand in road construction as subbase or fill material where large amount of the waste may be utilized. The steps of the study are as follows: Firstly, waste foundry sand are categorised based on the manufacturing technique and obtained accordingly. Secondly, each group of material is tested to determine index properties. Then, each group of the material is compacted using various compaction efforts. Stabilization is considered to increase the strength of material and the sand is stabilized with cement and lime by 2%, 4%, 8% and 10% by weight. Stabilized samples are later cured for 7 days, 14 days, 28 days, 3 months and 6 months to observe the effect of stabilization by Ultrasonic Pulse Velocity Test (UT), Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR) tests. Furthermore, triaxial tests are carried out to determine shear strength parameters because of the material is also investigated as fill material in highway constructions, particularly to assess its suitability in high embankments. Finally, an economic analysis is performed whether waste foundry sand is suitable to utilize as subbase or fill material.

# **ATIK DÖKÜM KUMLARININ KARAYOLU MALZEMESİ OLARAK KULLANIMI**

## **ÖZET**

Döküm kumu otomotiv sektörü, demir-çelik sanayisi, alaşım üretimi ve metalurji endüstrisinin çeşitli branşları ve diğer bir çok endüstri alanında büyük miktarlarda kullanılmaktadır. Ayrıca, bentonit kum tanelerini arasında bağlayıcı özellik göstermesi için ilave edilmektedir. Döküm işleminden sonra, kullanılan kum atık malzeme olarak kabul edilmektedir. Atık malzeme olarak depo edilen kullanılmış döküm kumları, döküm endüstrisine ek bir maliyet oluşturmaktadır. Bundan dolayı, döküm endüstrisi atık döküm kumlarının kullanımı için uygun bir alan ve yöntem aramaktadır.

Bu çalışmanın amacı karayolu malzemesi olarak büyük miktarda atık döküm kumunun kullanılabilirliğini araştırmaktır. Böylelikle, yüksek miktarda atık malzemenin değerlendirilmesi mümkün olacaktır. Bu bağlamda; ilk olarak üretim tekniği ve şekline göre atık döküm kumları sınıflara ayrıldı ve indeks özellikleri tespit edildi. Daha sonra bu malzeme çeşitli kompaksiyon metodları kullanılarak sıkıştırıldı. Stabilizasyonun malzeme özelliklerini iyileştireceği düşünüldüğünden, atık döküm kumu ağırlıkça %2, %4, %8 ve %10 oranında çimento ve kireçle ayrı ayrı stabilize edildi. Stabilize edilen numuneler 7-gün, 14-gün, 28-gün, 3-ay ve 6-ay süre boyunca nem odasında kür edildi. Hazırlanan numunelere stabilizasyonun etkisini araştırmak için 3 farklı deney (Ultrasyon Dalga Hızı Testi, Serbest Basınç Mukavamet deneyi, ve Kaliforniya Taşıma Oranı deneyi) yapıldı. Deney sonuçlarının ışığında atık döküm kumlarının klasik yol malzemeleriyle ekonomik karşılaştırılması yapıldı ve amaca uygunluğu irdelendi.

## 1. INTRODUCTION

Foundry industry produces metal castings. The metal castings can be categorized into two groups according to their origin [12]. One of which is ferrous group including iron and steel. Another is non-ferrous group including aluminum, beryllium, cobalt, copper, zinc, lead, tin, nickel, magnesium, and titanium. All over the world, foundries produced over 80 million tones castings especially in the automotive industry. Addition to peak casting; ferrous casting, sfero casting, aluminum casting and magnesium casting are also played a major role through this development. Along with automotive industry, casting productions are used in various industries such as cement, agriculture, health, naval construction, white goods, defense, iron and steel industry [9,14].

Figure 1.1 indicates that Turkish foundry industry has been playing a major role in Europe as well as in the whole world. In Turkey, amounts of production of peak casting exceeded as compared with other casting.

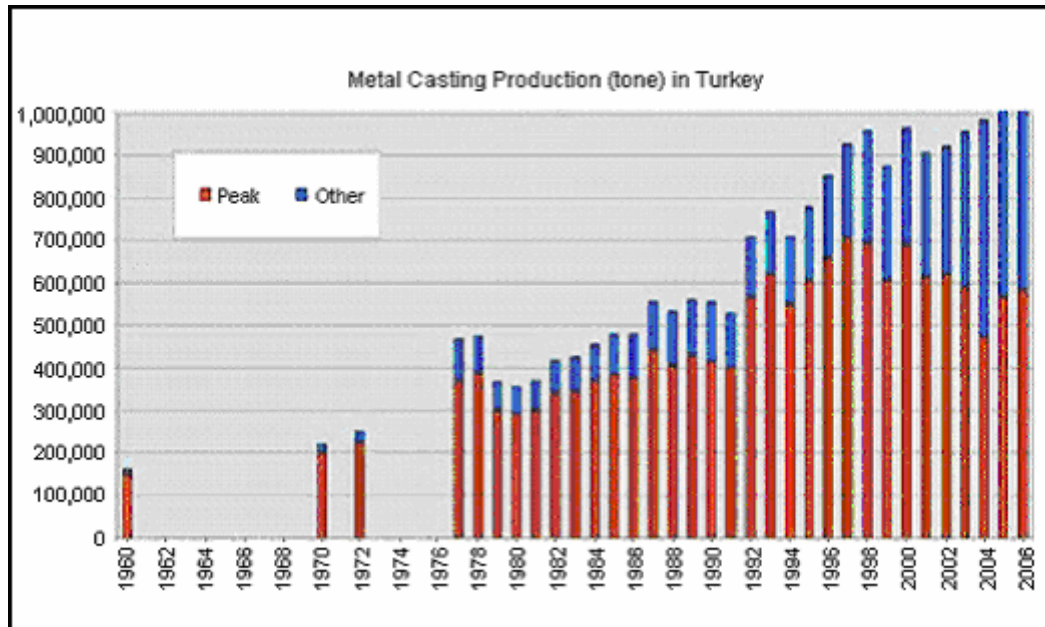


**Figure 1.1 :** The Metal Casting Production in Turkey Between 1960-2006 [27].

In Turkey, according to 2006 figures, there were over 1300 foundries with 1.2 million tone productions, worth 3 billion-dollar. Additionally, exportation was over

1.3 billion dollar and the number of employees was about 30.000. Turkey, having 1.21 million tone casting production in 2005, has come 6<sup>th</sup> among European countries and has come 15<sup>th</sup> in the world. Furthermore, in the same year, Turkey accounted for 1.4 percentage of total production in the world [27]. Table 1.1 shows the amount of ferrous casting production in Turkey between 1960-2006.

**Table 1.1 : Amount of Ferrous Casting Production [27].**

| <b>Ferrous Casting Production (tone) in Turkey Between 1960-2006</b> |             |              |               |              |              |              |
|----------------------------------------------------------------------|-------------|--------------|---------------|--------------|--------------|--------------|
| <b>Years</b>                                                         | <b>Peak</b> | <b>Sfero</b> | <b>Temper</b> | <b>Steel</b> | <b>Other</b> | <b>Total</b> |
| 1960                                                                 | 150.000     |              | 1.000         | 10.000       | 100          | 161.100      |
| 1970                                                                 | 200.000     |              | 2.000         | 15.000       | 5.000        | 222.000      |
| 1972                                                                 | 223.000     |              | 3.000         | 18.000       | 6.000        | 250.000      |
| 1977                                                                 | 371.500     | 2.500        | 2.500         | 85.000       | 7.000        | 468.500      |
| 1978                                                                 | 389.000     | 3.000        | 7.000         | 70.000       | 8.000        | 477.000      |
| 1979                                                                 | 300.000     | 2.500        | 7.000         | 50.000       | 9.000        | 368.500      |
| 1980                                                                 | 291.000     | 6.000        | 4.000         | 46.000       | 10.000       | 357.000      |
| 1981                                                                 | 299.500     | 5.500        | 5.000         | 50.000       | 10.000       | 370.000      |
| 1982                                                                 | 340.000     | 11.000       | 6.000         | 50.000       | 10.000       | 417.000      |
| 1983                                                                 | 345.000     | 13.000       | 7.000         | 51.000       | 10.000       | 426.000      |
| 1984                                                                 | 370.000     | 15.000       | 8.000         | 53.000       | 10.000       | 456.000      |
| 1985                                                                 | 385.000     | 18.000       | 9.000         | 56.000       | 10.000       | 478.000      |
| 1986                                                                 | 375.000     | 22.000       | 11.000        | 61.500       | 10.000       | 479.500      |
| 1987                                                                 | 442.000     | 32.000       | 13.000        | 59.500       | 10.000       | 556.500      |
| 1988                                                                 | 405.000     | 46.000       | 12.000        | 62.000       | 10.000       | 535.000      |
| 1989                                                                 | 428.000     | 48.500       | 13.200        | 61.500       | 10.000       | 561.200      |
| 1990                                                                 | 415.000     | 60.200       | 10.500        | 58.000       | 12.000       | 555.700      |
| 1991                                                                 | 400.000     | 55.000       | 10.500        | 53.000       | 10.000       | 528.500      |
| 1992                                                                 | 568.000     | 58.000       | 11.600        | 59.000       | 11.000       | 707.600      |
| 1993                                                                 | 620.000     | 69.500       | 11.600        | 56.000       | 12.000       | 769.100      |
| 1994                                                                 | 550.000     | 75.000       | 11.200        | 61.000       | 12.000       | 709.200      |
| 1995                                                                 | 606.000     | 79.700       | 12.960        | 65.690       | 14.000       | 778.350      |
| 1996                                                                 | 658.000     | 90.600       | 15.200        | 70.600       | 20.000       | 854.400      |
| 1997                                                                 | 706.000     | 86.500       | 14.000        | 94.400       | 24.350       | 925.250      |
| 1998                                                                 | 695.000     | 123.000      | 12.000        | 101.000      | 28.700       | 959.700      |
| 1999                                                                 | 605.500     | 136.000      | 7.550         | 88.350       | 36.720       | 874.120      |
| 2000                                                                 | 690.000     | 130.000      | 7.000         | 98.000       | 40.000       | 965.000      |
| 2001                                                                 | 615.000     | 132.000      | 7.800         | 107.000      | 44.000       | 905.800      |
| 2002                                                                 | 620.000     | 139.000      | 7.500         | 110.000      | 45.000       | 921.500      |
| 2003                                                                 | 592.000     | 187.000      | 6.000         | 112.000      | 58.000       | 955.000      |
| 2004                                                                 | 475.000     | 308.000      | 6.000         | 121.000      | 72.000       | 982.000      |
| 2005                                                                 | 567.000     | 327.000      | 6.500         | 125.000      | 95.700       | 1.121.200    |
| 2006                                                                 | 586.000     | 368.000      | 6.500         | 132.000      | 117.000      | 1.209.500    |

Casting is the manufacturing of shaped metals by pouring molten metal into molds. In casting process, sand mold is most commonly used to resist against pressure and heat of molten metal. When temperature of metal has decreased, the sand is separated

from the casting. After process, major amount of used sand is no longer suitable to reuse for a new cycle because of physical and chemical breakdown. This amount is approximately between 90 and 95 percent of the initial sand. Therefore, foundries have to replace used sand by virgin sand as new sand contains unburned binder, whereas spent sand contains burned binder. That is the reason why spent sand is considered as waste and defined as waste foundry sand (WFS) [12].

Clay and chemical binders perform bonding process in foundry sand. In case of utilization of clay as binder, surface interactions produce the bonding forces between sand and clay particles. The amount of binder depends on casting temperatures and binder performance. It was specified that too much binder resulted in clumping, generating contaminants in WFS, and preventing the reclamation WFS. Besides, too less binder causing performing the casting disintegrated due to low strength [18].

The physical and chemical characteristics of foundry sand will depend on the type of casting process. There are two basic types of foundry sand currently being used, green sand (often referred to as molding sand) that contains clay (generally bentonite) as the binder material, and chemically bonded sand that comprises polymers for the same purpose. Green sand consists of 85–95% silica, 0–12% clay, 2–10% carbonaceous additives, such as seacoal, and 2–5% water. WFS used in this study has 5.43% bentonite as a binder. Green sand is the most commonly used molding sources by various foundries. As shown in Figure 1.2, actually, green sands are typically black, or gray not green. Chemically bonded sand is typically a medium tan or off - white color [13,25].

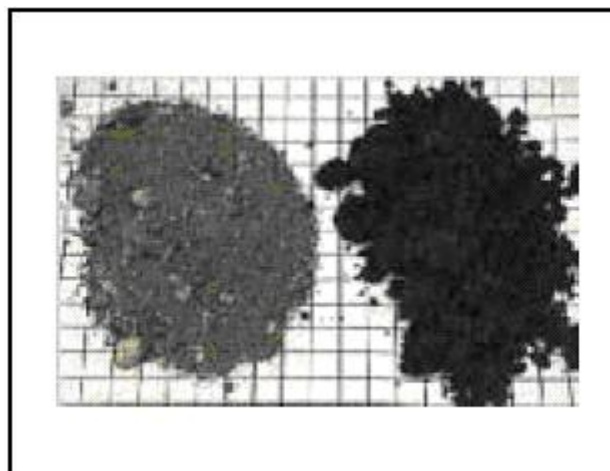


**Figure 1.2 : Two Different Colours of Green Sand [25].**

The silica sand resists high temperatures, while the clay binds the sand together and water adds plasticity. The carbonaceous additives prevent the “burn-on” or fusing of sand onto the casting surface. Green sands also contain trace chemicals such as MgO, K<sub>2</sub>O, and TiO<sub>2</sub>. Chemically bonded sand consists of 93–99% silica and 1–3% chemical binder by weight. Silica sand is thoroughly mixed with the chemicals; a catalyst initiates the reaction that cures and hardens the mass. There are various chemical binder systems used in the foundry industry. The most common chemical binder systems used are mixtures of organic chemical such as phenolic-urethanes, epoxy-resins, furfuryl alcohol, and sodium silicates.

Enormous source of solid waste must be discarded by the foundry industry. The majority of WFS are deposited in restricted (non-hazardous, solid waste) or sanitary waste landfills [7,13].

### **1.1 Definition of Recycling and Reuse**

“Recycling” can be defined as the re-processing of materials into new products. In the other words, it is the breaking down of the used materials into raw materials that are used to make new items. Recycling does not always mean re-use, as this term generally used for utilization of existing materials for a different purpose. The aims of recycling are as follows;

- Preventing the disposal of potentially beneficial materials.
- Decreasing the consumption of new materials.
- Reducing energy usage.
- Become environmentally sensible.

The materials which have a potential to be recycled are also known as recyclables. There are very various recyclables such as glass, paper, asphalt, iron, plastic and iron.

“Reuse” is using a material more than once. This includes conventional reuse where an item is used again for the same purpose and new-life reuse where it is used for a new function. An EPA (Environmental Protection Agency) guide “Reuse Resources of New England” specifies reuse as “the use of a product or material again in its original unmodified form or with little enhancement or change to be utilized again for the same purpose” [15].

Reuse process can provide the following economical and enviromental benefits:

- Savings on energy and raw materials.
- Decreasing disposal needs and costs.
- Savings on business and consumers as reused products are generally cheaper.

## 1.2 Waste Foundry Sand Applications

WFS reuse can be beneficial at several applications. Foundries are trying to avoid costly permitting, land filling and transportation costs. Therefore, they are desperate to find a method of utilization. For example, in Istanbul, cost permission, dumping (land filling), and transportation costs are in total as much as 12\$/m<sup>3</sup>. In Turkey, total amount of WFS is about 450.000 tones per year [27]. Non costly improvements such as treatment and stabilization may enable WFS suitable for new applications. Transportation costs for hauling WFS, however, generally dictate the need for a relatively close proximity between the foundry and site of utilization. WFS have been used in hot mix asphalt, ready mix concrete, precast concrete products, bricks and povers, grouts and mortars, landfill daily cover, landfill construction material so far. As shown in Table 1.2 the largest volumes of recycled WFS are currently used in construction applications such as structural fills, general fills, road and building base, and embankments [25].

**Table 1.2 : Foundry Sand Application by Volume [25].**

| Ranking | Application                  |
|---------|------------------------------|
| 1       | Embankments/Structural Fiils |
| 2       | Road base/Subbase            |
| 3       | Hot Mix Asphalt (HMA)        |
| 4       | Flowable Fills               |
| 5       | Soil/Horticultural           |
| 6       | Cement and Concrete Products |
| 7       | Traction Control             |
| 8       | Other Applications           |

### **1.3 Objectives of the Study**

The main objective of this study is to investigate applicability of stabilized waste foundry sand in highway construction where large volume of this material may be utilized.

The economical aspect of this study is to determine the potential usage of waste foundry sand in road base or sub-base instead of more expensive fill materials. Also, another economical benefit is to prevent or reduce cost for hauling, and landfilling if road construction provided that WFS is available close proximity to construction site.

## **2. LITERATURE STUDY**

A major study of laboratory test data for the geotechnical properties of WFS was published by Javed and Lovell in 1994. The results of this study give an overall idea on characteristics of WFS detailed as follows:

### **2.1 Loss on Ignition**

The organic content of WFS was measured by using the loss on ignition (LOI) test. Weight loss (percentage of initial dry weight) was calculated after heating the WFS from 110°C to 550°C in a furnace. The average value for LOI was 5.46%. The LOI values for 14 specimens ranged from 2.82% to 12.06% and had a standard deviation of 2.85% [18]. However, in this study, organic content of WFS was calculated as 6.79%. The LOI values were relatively higher for green WFS than cold box and shell-molded process sands. It was believed that this was due to the presence of combustible additives in the green sand, such as seacoal.

### **2.2 Shape and Texture of WFS**

The shape and texture of green WFS was found to be subangular to rounded and relatively rough as compared to natural sands by the means of optical microscopic study. A flow test was performed to determine the uncompacted void content. This value can be correlated to the particle shape and aggregate texture. The average uncompacted void content for WFS was 50.3%, with a range from 45.1% to 58.3% for seven specimens. For comparison, a natural sand yielded 43.7% uncompacted void content. The higher value for green WFS suggests that it has a rougher texture, which the authors conclude is due to the agglomeration of sand with binder and additives [18].

### **2.3 Clay Lumps and Friable Particles**

Javed and Lovell used an alternative procedure to the ASTM C 142 method for determining the clay lumps and friable particles in WFS. The procedure is described

by the American Foundrymen's Society (AFS) and uses material retained on the No. 12 sieve. Two types of lumps were encountered. Lumps associated with molding sand easily disintegrated in water. However, those associated with cores were hard and could not be easily broken. Green WFS had an average of 10.9% clay lumps and friable particles. However, for five of the seven specimens, the average percentage of clay lumps and friable particles was 1.7%, whereas the remaining two specimens had values of 44.3% and 23.3%. It was recommended that the harder lumps must be crushed prior to construction use [18].

For embankment fill projects, this crushing may be accomplished by field compaction equipment.

## **2.4 Compressibility of WFS**

One-dimensional compression tests were performed on 2.54 cm high, 6.35 cm diameter specimens in a dense condition. Two specimens were tested dry and two specimens were tested saturated. The saturated specimens were back pressured and soaked for 24 hr. prior to testing. Swelling was measured in accordance with ASTM D 4546 Method A, as well as pore pressure changes with time. Control tests were performed on specimens of natural sand for comparison. It was found that the generation of excess pore pressures in green WFS specimens was insignificant. The two specimens tested had low volumetric swelling percentages of 0.15% and 0.82%, with corresponding swelling pressures of 9.86 kPa and 31.02 kPa. WFS specimens are labeled G1 and G3, and natural sand specimens are labeled R1. Figure 2.1 is illustrating the test results. The test showed that the WFS was more compressible than the natural sand. In addition, saturated specimens were generally more compressible than dry specimens.

It was suggested that the higher compressibility was due to the binders and additives which surround the sand particles. These binders are relatively weak in comparison to the bulky sand grains, and therefore are more likely to crush due to stress concentrations at the particle contacts. [18].

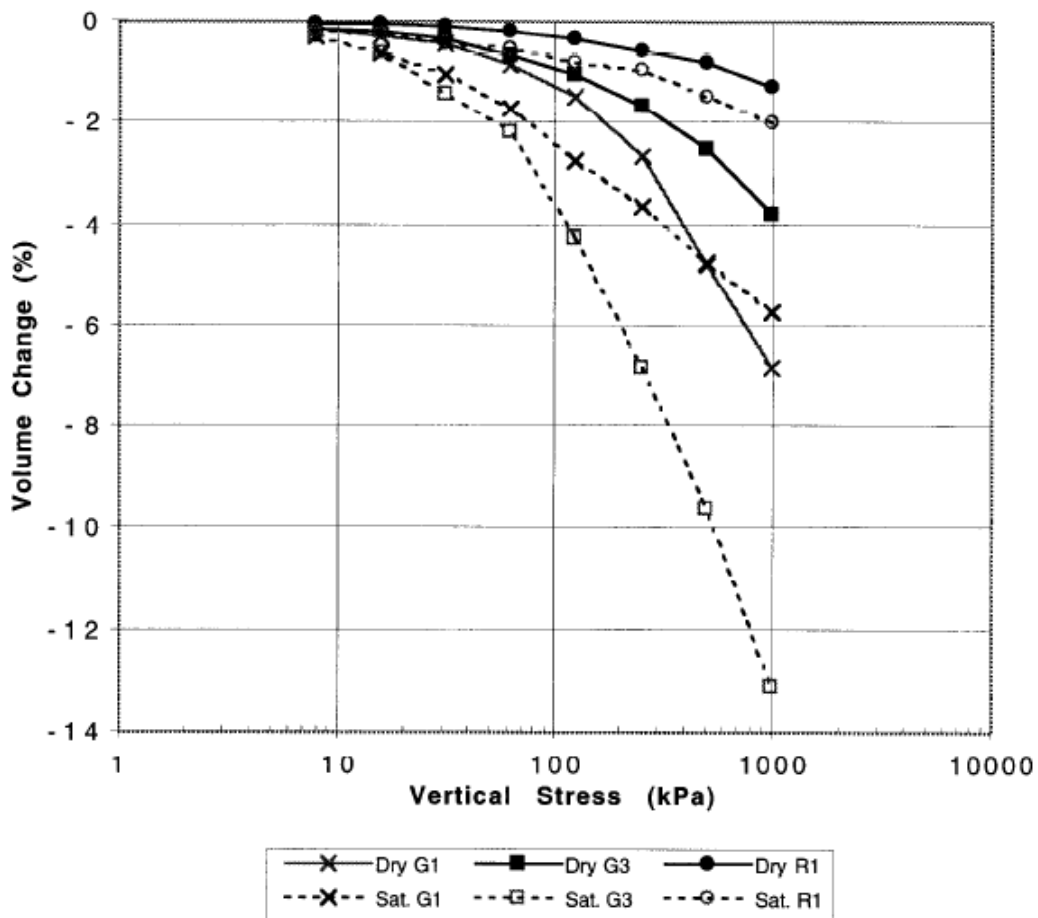


**Figure 2.1 : The Compressibility Test Results [18].**

## 2.5 Stabilization of WFS

Stabilization is improving a new or existing soil's geotechnical properties especially bearing capacity. By the means of stabilization, engineers may get acceptable performance from inferior materials as much as good, quality road materials such as crushed rock. Stabilization improves soil's plasticity, compressibility, permeability, strength, and resistance to water. History of stabilization is dated back construction of the highways just before the World War II. Before the war there was not enough time to construct perfect highways. Instead of building new roads, most countries such as England applied soil stabilization to their military roads and airports due to fact that this decision was not yielded only rapid but also economic.

Another benefit of stabilization is to get rid of or alleviate dust, generated by the operation of equipment and aircraft during dry weather or in arid climates.

Soil stabilization can be performed in two ways, namely mechanical and chemical stabilization. Chemical stabilization is addition of a chemical agent such as cement, lime, bitumen, fly ash or their combination. Before these applications the best one should be determined considering economy. In other words, previous experience is very important from an engineering point of view.

Chemical additives influence the soil in two ways;

1. Binding soil particles to each other
2. Improve water resistance

Although permeability of soil is increased, yet it does not mean that stabilized soil will be impermeable. The main goal is to prevent the soil from water as much as possible.

Indiana Department of Transportation recommends the below criteria for soil stabilization;

- a. If  $PI > 10$  and minimum clay content ( $2\mu$ )  $> 10\%$  then lime stabilization
- b. If  $PI \leq 10$  and percentage passing No. 200  $< 20\%$  then cement stabilization
- c. Lime, cement, or fly ash combination.

PI is standing for plasticity index of soil

Suggested Chemical Quantities

1. Lime or Lime By-Products: 3% to 9%
2. Cement: 3% to 10%
3. Fly ash: 10% to 25%

However, in this study only lime and cement stabilizations were performed separately for WFS. Moreover, quantities of lime and cement were 2%, 4%, 8% and 10% by weight to obtain the most economic and feasible amount of chemical additives for WFS [2].

### **2.5.1 Application methods of stabilization**

There are 3 types of application methods of soil stabilization as follows;

1. In place mixing method
2. Traveling plant method
3. Off-site mixing method

Among the methods, in place mixing method is the most preferred one.

### 2.5.1.1 In place mixing method

In this method, grader, ripper, street sprinkler, compactor, pulverizer, and spreader are frequently required. Steps for the method are listed below and some of them are shown in Figure 2.2, Figure 2.3, Figure 2.4, and Figure 2.5 [2].

- Swelling of soils by ripper
- Pulverizing of soils by pulverizer
- Spreading of additive by spreader
- Mixing of soil and additive by mixer
- Wetting of mixture by street sprinkler
- Grading of mixture by grader
- Compaction of mixture by compactors
- Curing of mixture in humidity condition



**Figure 2.2 : Swelling and Pulverizing of the Soil [2].**



**Figure 2.3 : Mixing of the Soil and Additive [2].**



**Figure 2.4 : Wetting of the Mixture [2].**



**Figure 2.5 : Compaction of the Mixture [2].**

#### **2.5.1.2 Traveling plant method**

In this method, most commonly used machine is Barber – Greene as shown in Figure 2.6. By its elevator pulverized soil is taken to mixing store. Then required water, chemical additive, and soil are mixed in the store. The new mix is spreaded and compacted [2].

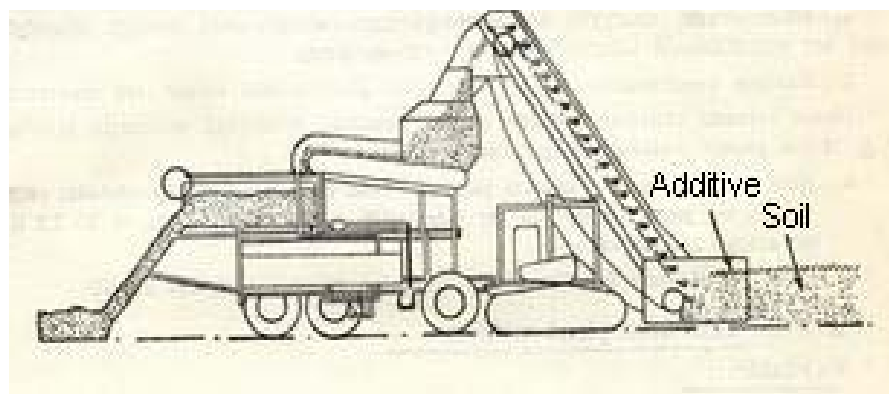


**Figure 2.6 : Barber – Greene Schematically [2].**

### **2.5.1.3 Off-site mixing method**

Off-site mixing is accomplished by using a stationary mixing plants. Similar to traveling plant method, an elevator and a mixing store are required for mixing. Once prepared, the mixture is taken to construction site by trucks [2].

Advantages and disadvantages of these applications are;

- In traveling plant and off-site mixing method it is easy to prepare an excellent uniform mixture by calculating amount of water and chemical additive whereas, it is difficult in place mixing.
- While prepared mixture is ready for compaction in place mixing method, extra cost for hauling of mixture will occur in traveling plant and off-site mixing method.

### **2.5.2 Stabilization types**

Most used stabilization types are mechanical stabilization, cement, lime, bitumen and fly-ash stabilization. Table 2.1 indicates the typical response of some important soil minerals to different stabilization methods [21].

**Table 2.1:** Response of Some Typical Minerals to Different Stabilization Methods [21].

| Typical mineral or soil component | Stabilization recommended                                             | Objective                                                                                                               |
|-----------------------------------|-----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| Organic matter                    | Mechanical stabilization                                              | Other methods are ineffective                                                                                           |
| Sands                             | Mixture with fine, non-plastic materials<br><br>Cement<br><br>Asphalt | Mechanical stability<br><br>To increase the strenght<br><br>To impart cohesion                                          |
| Silts                             | Do not respond to methods of stabilization in use                     |                                                                                                                         |
| Allophanes                        | Lime or mixtures of lime and gypsum                                   | To increase the strenght                                                                                                |
| Kaolin                            | Sand<br><br>Cement<br><br>Lime                                        | Mechanical Stability<br><br>To increase short term strength<br><br>To improve workability and impart long term strength |
| Illite                            | Cement<br><br>Lime                                                    | To increase short term strength<br><br>To improve workability and impart long term strength                             |
| Montmorillonite                   | Lime                                                                  | To improve workability and impart short term strength                                                                   |
| Chlorite                          | Cement                                                                | As yet there is no conclusive experince of the effects                                                                  |

### 2.5.2.1 Mechanical stabilization

Mechanical stabilization is accomplished by mixing or blending soils of two or more gradations to obtain a material meeting the required specification. The soil blending

may take place at the construction site, a central plant, or a borrow area. The blended material is then spread and compacted to required densities by usual practice [24].

A well-graded will be resistant to permanent deformation. This type of soil has mechanical stability and consists of sufficient fine and coarse aggregate. In general, mechanical stabilization is applied to base and sub-base layers to increase maximum dry density of material. If the gradation of a material is not suitable, then at least two or three different materials are added to adjust grading. It is essential to know index properties and other characteristics of the material before the mixing process. These are grain size distribution, Atterberg limits, resistance to freezing-thawing cycle, and Los Angeles abrasion ratio [2].

In the mechanical stabilization, amount of the maximum size of the particles in the mixture is very important, since workability of large particles are difficult and result in very rough road surfaces. An excessive amount of coarse particles makes the mixture have a tendency to segregate. On the other hand, large amount of fine materials (smaller than No: 40 Sieve) in soil makes it hard to obtain satisfactory bearing capacity and may result the road surface muddy when wet, and dusty when dry [21].

A soil having high plasticity index must be mixed with a non-plastic soil or a soil having less plasticity index. After mixing of the required amount of materials, the new mixture's liquid limit and plastic limit are measured. The new mixture is expected to be homogenous. Unless it meets the specified standards, the mixing process has to be repeat again [2].

#### **2.5.2.2 Cement stabilization**

Cement is a kind of material to modify and improve the quality of weak soils. There are various cements that have been used successfully for stabilization. However, the most common type used is ordinary Portland cement. Chemical and physical property specifications for Portland cement are explained in ASTM C 150 [3].

Definition of cement stabilization is mixing of pulverized soil, cement and water, and producing a new material that is resistant to water, thermal and frost effects as detailed previously. The first cement-stabilized road was constructed in Johnsonville. (South Carolina, USA) Despite the fact that it was constructed in 1935, it is still in use. This is evidence that cement-stabilized roads have been stable for

many years. Cement soil stabilization is not only suitable for highway construction but also appropriate various applications such as building foundations, and airports.

Soil cement, cement-improved granular-soil mix, cement-improved silt-clay mix, plastic soil cement and cement-treated soil pastes and mortars are five types of cement-stabilized soils.

Soil cement is most common used method used for load-bearing layers of roads and have adequate strength, durability and frost resistance.

Cement-improved granular-soil mix is utilized to reduce expansion or contraction, plasticity and increase load-bearing capacity. It can be used as a base layer.

Cement-improved silt-clay mix is generally used for foundation-layer improvement such as shrinkage and volume change.

While plastic soil cement is resistant to erosion, cement-treated soil pastes and mortars are utilized mainly for the injection of railways and road pavements.

Although cement is playing different roles for fine-grained soils and coarse-grained soils, its main objective is to improve geotechnical properties of soils. In cohesive soils, excellent bonds occur between soil particles due to hydration of cement. These bonds do not only prevent sliding of particles on each other but also enclose the non-bonded soil particles. Therefore, generated cellular structures make the mixture gain extra shear strength and decrease plasticity. Moreover, cement reduces clay soil's water affinity and clay's water retention capacity.

In granular soils, cement can not fill the all voids, but it creates bonds at the contact points of sand particles [16].

Physical properties of cement stabilization depend on type of soil, amount of cement, mixing process, water, compaction, and cure duration detailed as follows;

#### **a-) Type of soil**

USA Federal Highway Research Department recommends that any soils which will be stabilized with cement have to meet the following standards;

- Particle size less than 3"
- Fine particles less than 50%
- Liquid limit and plasticity index less than 40 and 18 respectively.

- Organic matter content less than 2% (tolerable up to 3% or 4%)

#### **b-) Amount of cement**

Amount of cement is determined after several tests. This amount is generally between 4% and 25%. Addition of cement greater than 25% in stabilization can not be economical. However, it is a fact that adding more cement will make soil strong and durable.

#### **c-) Mixing process**

Mixing of cement and soil has to be performed uniformly, choosing a method of mixing explained previously.

#### **d-) Water**

Water content in cement soil stabilization effects mainly compaction. Compaction should be performed at optimum water content of untreated (original) soil or higher than it.

Another important point is contents of water. Water having much more salt and organic material can damage to cement stabilization. According to previous studies, sweet and drinkable water is generally suitable, whereas mineral waters or water grades including more than 300mg/lit  $\text{SO}_3$  should not be used for cement stabilization

#### **e-) Compaction**

Since the bonds between particles occur very rapidly due to hydration of cement, compaction process should be performed immediately after mixing. Moreover, compaction should be done carefully. Otherwise, cement stabilized soil will not have predetermined geotechnical features in spite of excellent mixture.

#### **f-) Cure duration**

Curing begins immediately after compaction and detailed as follows;

Moisture and heat conditions are the significant considerations in cement stabilization process. Both of them should be monitored at least for 28-day until the material gains the strength.

According to previous researches, regarding heat curing, the following findings were stressed;

- When temperature is over 25 °C, and in case of rising, strength of cement stabilized soils will increase.

- Temperature should not be below 0
- To get same strength, more cement is required in cold weather as compared with hot weather.

Briefly speaking, curing of cement stabilized soils is similar to curing of concrete.

The following aspects are significant in cement stabilization of highways and monitored carefully during the process [11,16].

### **1. Plasticity and volume change**

By treating plastic soil with cement, its plasticity index reduces whereas its strength increases. Addition of cement increases plastic limit and decreases the liquid limit. However, according to previous studies, if the liquid limit of the unstabilized soil is greater than 40%, then addition of cement exerts decreasing effect of the limit, whereas if liquid limit is less than 40%, then an increasing effect of the limit is obtained.

Plasticity of cement stabilized soil depends on type of soil, type of cement, amount of cement in mix, and cure duration.

Addition of cement influences both shrinkage and swelling features. Therefore, volume change will occur in cement stabilized soils. It should be noted that volume change is different for cohesive soils and non cohesive soils.

In cohesive soils, as cement is filling voids between particles and decreases their movement ability, shrinkage of soil will decrease.

On the other hand, cement addition to non cohesive soils which are not sensitive to volume change, the decreasing of volume change of the mix will be higher due to shrinkage during the cement hydration [22,23].

### **2. Compactibility**

The most important factors are the optimum moisture content (OMC) and the maximum dry unit weight ( $\rho_{dmax}$ ) for compaction of cement stabilized soil. According to previous researches, cement addition has different effects on  $\rho_{dmax}$  and OMC [16].

Cement addition causes unimportant changes on OMC value. In Figure 2.7 difference between the Proctor curves of untreated soil and cement stabilized soil is given.

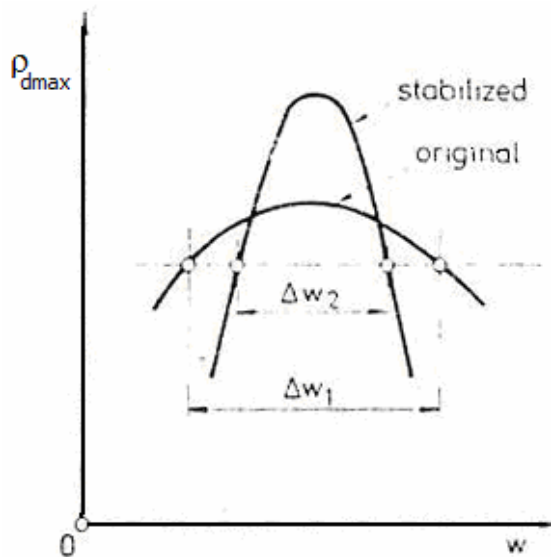


**Figure 2.7 :** Difference between the Proctor Curves of Untreated Soil and Soil Cement [16].

### 3. Strength

In cement stabilization, particle size of soils is significant on strength. Coarse sands and gravels are difficult to stabilize with cement; however they seldom require stabilization because their performances are usually satisfactory. Furthermore, they may suffer from serious cracking problems if treated with cement.

Another point for strength of cement – treated soil is regarding flexibility. Based on experience an unconfined compressive strength exceeding about  $55 \text{ kg/cm}^2$  is not suggested for soil – cement mixtures. Higher strength makes pavement layers rigid and susceptible to crackings [22].

### 4. Permeability

Pavement layers have to be impermeable against water. Otherwise, pumping action will be seen in road bases and road sub bases. Pumping action is water movement due to dynamic effect of traffic namely axial loadings of vehicles. By the pumping action, breakdowns in cement bonds will occur, thereby strength decrease is unavoidable. Therefore, cement stabilized soils have to be resistant to water permeability [16].

### 5. Frost resistance

Soils stabilized with cement are expected to have frost resistance in case of freezing–thawing cycle [19].

### **2.5.2.3 Lime stabilization**

Lime is an excellent material for stabilization of soils. Besides, lime is the cheapest choice for soil stabilization in Turkey. There are two types of lime, namely hydrated and quick lime. Properties of hydrated lime are described in ASTM Standard Specifications C 207. [3,8].

Lime is suitable for almost all fine-grained soils, but the best improvement is obtained in clays of moderate to high plasticity. National Lime Associations of Virginia explained that pozzolanic reaction produced stable calcium silicate hydrates and calcium aluminate hydrates as the calcium from the lime reacts with the aluminates and silicates solubilized from the clay.

During lime-soil stabilization the following chemical and physical reactions occur. [8].

#### **Chemical Reactions**

Three steps are mostly seen during chemical reactions of lime-soil stabilization. They are ion exchange, cementation, and carbonation [5,8].

##### **a-) Ion exchange**

Ion exchange occurs especially in soils containing more clay where plasticity of soil is decreased. Since soil becomes loose in the first place, this reaction occurs rapidly and it is generally completed in a few days [5,8].

##### **b-) Cementation**

Cementation is defined as reaction of Calcium (existing in lime) with Aluminium and Silicon minerals (existing in soil). This reaction results in Calcium Aluminate (CA) and Calcium Silicate ( $\text{CaO} \cdot \text{SiO}_2$ ). These compositions are similar to compositions occurred in cement hydration that is the reason why this reaction is called Cementation.

Cementation due to minerals in soil such as Aluminium and Silicon are called as Pozzolona. Quality of cementation depends on amount and type of Pozzolanas. If there are no adequate Pozzolonas for cementation, it is necessary to add artificial Pozzolanas such as Fly Ash. More time is required for cementation in lime-soil mix as compared with cement-soil mix. Additionally, moisture and density of mix will influence the cementation during compaction [5,8].

### **c-) Carbonation**

Carbonation is defined as reaction of  $\text{CO}_2$  in the air with  $\text{Ca(OH)}_2$  resulting in  $\text{CaCO}_3$ . In other words, it is absorption of  $\text{CO}_2$ . In case of carbonation, cementation and pozzolanic reaction will not perform as well as lime-soil mix can not increase its strength.

To prevent carbonation, lime has to be in hydrated form or be kept away from  $\text{CO}_2$  before soil stabilization [5,8].

### **Physical Reactions**

Physical reactions of lime-soil stabilization are classified into five main groups detailed as follows:

#### **a-) Flocculation**

Definition of flocculation is enlarging of grains by the adding lime to soils especially containing more clay. Through the flocculation, enlarged grains protect their size for years even they get wet. Therefore, soils containing clay can become convenient for highway construction.

Extent of flocculation depends on type of soil, amount and type of lime, and cure duration. An experimental study by General Directorate of Highways in Turkey proved that increasing of cure duration and lime presence had reduced the flocculation [5,8].

#### **b-) Reducing of plasticity**

In highway construction, soils having low plasticity index are preferred. Sometimes plasticity index of soils can be higher than standard limit.

There are two ways to reduce plasticity index of soils. One way is addition of a soil having lower plasticity index. The other and appropriate way is to add lime. By this way, not only plasticity index of soil will decrease, but also bearing capacity and resistance against freeze will increase.

Lime influences both liquid limit ( $\omega_l$ ) and plastic limit ( $\omega_p$ ). While liquid limit gets decreased, plastic limit gets increased. Therefore plasticity index ( $I_p$ ) of soil will reduce due to difference between liquid limit and plastic limit.

Plasticity index of lime-soil mix depends on type of soil and lime, amount of lime and cure duration. Generally, reduction of plasticity index is completed in 2-3 days and the type of hydrated lime accelerates this reaction [5,8].

### **c-) Change of volume**

Addition of lime to clay soils results in volume change. Lime makes shrinkage limit higher and shrinking ratio lower. In brief, volume of lime-soil mixture will reduce.

Experiment by Lund and Ramsey showed that volume of lime-soil had rapidly decreased in a few hours. Moreover, they proved that 3% lime by weight was adequate for maximum volume change and they specified that generally addition more lime than 3% would not affect volume change [5,8].

### **d-) Increasing of durability**

Durability is the ability of a material to remain unchanged against environmental conditions such as heat, moisture or air. Lime can increase the durability of soils. It is significant that lime differs from other stabilizing agents. Each soil has optimum lime content. In case of higher or lower lime presence than optimum, lime-soil mix can not obtain maximum durability and strength. Addition of more lime than optimum content will increase durability and strength of soil. Additionally, speed of increase in strength for cement stabilization is higher than lime stabilization. These features are discrimination for lime and cement stabilization [5,8].

### **e-) Increasing of resistance to freeze-thawing and water**

Materials being used in highway construction such as road base, sub-base have to be resistant for freeze-thawing and wetting-drying. Otherwise, deformation, undulation, and swelling will occur in road base and sub-base due to precipitation especially in winter and autumn. Additionally, bearing capacity of pavement will reduce.

Resistance of lime-soil mix against freeze and water depends on amount of lime, cure duration, compaction, type of lime and soil.

Previous studies proved that at least 5% lime by weight was adequate. Secondly, application of lime-soil mix has to be in warm weather because temperature is an important factor for curing of lime-soil mix. [5,8,16].

### **Evaluation of lime stabilization**

In brief, important aspects of lime stabilization are given as follows;

1. Lime modifies clay soils and improves their geotechnical properties. Therefore, soils containing clay can be convenient for highway construction due to reduction of volume and plasticity index.
2. Cementation makes clay soils have more strength.
3. Lime stabilization is the cheapest application for most soils.

4. Sometimes fly ashes can be added to lime-soil mix in case insufficiency of Pozzolanas
5. Generally, amount of lime for stabilization is not higher than 10% by weight.
6. Effect of moisture is very important for lime stabilization.
7. Lime-soil stabilization has to be compacted at required compaction energy.
8. Strength of lime-soil mix gets increased gradually over along period of time.
9. Lime stabilization has to be performed in warm weather.

#### **2.5.2.4 Bitumen stabilization**

Bituminous stabilization is considered as a process by which a controlled amount of bituminous material is thoroughly mixed with an existing soil or aggregate material to create a stable base and sub-base or wearing surface. For the first time, cutback asphalt and bitumen were utilized for soil stabilization in South Carolina in 1925. Bitumen-stabilized pavement was applied to 4800-kilometer highway in California, in 1929. Bitumen makes the mixture increase its cohesion, load-bearing capacity, and resistant against water. In other words, there are two main purposes of bituminous stabilization aspects of highway construction;

1- ) to provide a binder for the soil

2- ) to make the soil to increase its resistant against water and weather conditions.

Despite of the fact that the bitumen-soil mixture is supposed to have a maximum stability, sometimes this implement is not only expensive but also inconvenient for some soils. Especially, a soil having more fine particles and high plasticity index is not suitable for the bituminous stabilization as bitumen makes the plasticity index higher.

Bituminous stabilization is generally performed by using asphalt cement, cutback asphalt, or asphalt emulsions. The type of bitumen to be utilized is dependent on the type of soil to be stabilized, method of construction, and weather conditions. Additionally, according to United States Army Corps of Engineering Standards the recommended soil gradations for sub grade materials and base or sub-base course materials are given in Table 2.2 and Table 2.3 respectively.

**Table 2.2 :** Recommended Gradations for Bituminous-Stabilized Sub grade Materials.

| <u>Sieve Size</u> | <u>Percent Passing</u> |
|-------------------|------------------------|
| 3 inch            | 100                    |
| No. 4             | 50-100                 |
| No. 30            | 38-100                 |
| No. 200           | 2-30                   |

**Table 2.3 :** Recommended Gradations for Bituminous-Stabilized Base and Sub-base Materials.

| <u>Sieve Size</u> | <u>1-1/2-inch Maximum</u> | <u>1-inch Maximum</u> | <u>3/4-inch Maximum</u> | <u>1/2-inch Maximum</u> |
|-------------------|---------------------------|-----------------------|-------------------------|-------------------------|
| 1-1/2-inch        | 100                       | --                    | --                      | --                      |
| 1-inch            | 84 $\pm$ 9                | 100                   | --                      | --                      |
| 3/4-inch          | 76 $\pm$ 9                | 83 $\pm$ 9            | 100                     | --                      |
| 1/2-inch          | 66 $\pm$ 9                | 73 $\pm$ 9            | 82 $\pm$ 9              | 100                     |
| 3/8-inch          | 59 $\pm$ 9                | 64 $\pm$ 9            | 72 $\pm$ 9              | 83 $\pm$ 9              |
| No. 4             | 45 $\pm$ 9                | 48 $\pm$ 9            | 54 $\pm$ 9              | 62 $\pm$ 9              |
| No. 8             | 35 $\pm$ 9                | 37 $\pm$ 9            | 41 $\pm$ 9              | 47 $\pm$ 9              |
| No. 16            | 27 $\pm$ 9                | 28 $\pm$ 9            | 32 $\pm$ 9              | 36 $\pm$ 9              |
| No. 30            | 20 $\pm$ 9                | 21 $\pm$ 9            | 24 $\pm$ 9              | 28 $\pm$ 9              |
| No. 50            | 14 $\pm$ 7                | 16 $\pm$ 7            | 17 $\pm$ 7              | 20 $\pm$ 7              |
| No. 100           | 9 $\pm$ 5                 | 11 $\pm$ 5            | 12 $\pm$ 5              | 14 $\pm$ 5              |
| No. 200           | 5 $\pm$ 2                 | 5 $\pm$ 2             | 5 $\pm$ 2               | 5 $\pm$ 2               |

There are two common types of bituminous stabilization that exist, namely emulsion stabilization and expanded asphalt stabilization. Emulsion stabilization is performed by injecting emulsion through a spray bar into a predetermined specified depth of reclaimed material typically within the range of 100 - 200mm. Expanded asphalt stabilization is very attractive due to its low life cycle cost, low environmental impact, and ease of construction.

Since fewer bonds occur in bitumen-stabilized soil compared with cement stabilized soil, bituminous stabilization should be applied to particularly base and sub-base layer but not to wearing surface.

Amount of bitumen for the sandy-soil to be stabilized is typically between 2 and 3 percent, while amount of bitumen for the clay-soil having high plasticity is between 6 and 8 percent. However, it is a fact that bitumen more than 4% does not provide more stable mixture.

RC (Rapid-Curing) cutback asphalt is convenient for sandy-soil, while MC (Medium-Curing) cutback asphalt is convenient for fine-soils.

One important issue about bituminous stabilization is about dissolution of cutback asphalt among soil particles. Stability of soil-water-cutback asphalt is a function of predetermined mixing process. After the mixing process, stability becomes maximum value at the end of the certain mixing period. When this period exceeds the certain mixing time, the stability of mixture will decrease [23].

#### **2.5.2.5 Fly ash stabilization**

Fly-ash can be used to improve base and sub-base or sub grades in order to stabilize backfill for decreasing lateral earth pressures and stabilizing embankments to improve slope stability. The primary reason fly ash is applied in soil stabilization applications is to improve the compressive and shearing strength of soils. The compressive strength of fly ash stabilized soils depends on in-place soil properties, delay time, moisture content at time of compaction, and fly-ash addition ratio. [25].

##### **a-) In-place soil properties**

The plasticity of soils treated with fly ash is influenced by the types of clay minerals present in the soil and their adsorbed water. Soils containing more than 10 percent sulfates have been prone to swell excessively in some applications. Also, organic soils are difficult to stabilize using fly ash. [25].

##### **b-) Moisture content**

The moisture content of the fly ash stabilized soil mixture has a big impact on the strength. The maximum strength realized in soil-fly ash mixtures is generally obtained at moisture contents below optimum moisture content for density. For silt and clay soils the optimum moisture content for strength generally changes from four to eight percent below optimum for maximum density. For granular soils the

optimum moisture content for maximum strength is generally one to three percent below optimum moisture for density. As a result, it is important that moisture content be controlled during construction. Moisture content is mainly measured by a nuclear density measurement device. [25].

**c-) Delay time**

Delay time is considered as the elapsed time measured between the fly ash first comes into contact with water and final compaction of the soil, fly ash and water mixture. Delay time is very important because of the rapid nature tricalcium aluminate ( $C_3A$ ) reaction occurring when fly ash is mixed with water. Compressive strength mostly depends on delay time. Maximum strength in fly-ash stabilized soil is obtained at no delay. Generally, a-one-hour compaction delay is specified for construction purposes [25].

**d-) Fly ash addition ratio**

The amount of fly-ash must be determined by laboratory mix design testing. It depends on the nature of the soil, the characteristics of the fly ash and strength desired. Typical fly ash addition rates change from 8 percent to 16 percent based on dry weight of soil. In general the higher the addition rate the higher the realized compressive strength.

### 3. INDEX PROPERTIES OF WFS

Twenty buckets of WFS (400kg) were obtained from ATACELIK Corporation (located in Istanbul, Turkey) in June 2007. As mentioned in previous sections all laboratory testings are carried out using Steel WFS (green WFS). The laboratory testing program was conducted on WFS specimens stabilized with cement and lime to determine their suitability as highway base and subbase materials. Before the main experiments some geotechnical features of WFS are obtained. Subsequently, the mixtures were compacted in the laboratory at optimum moisture content and specific compactive efforts then subjected to ultrasonic pulse velocity test (UT), unconfined compressive strength (UCS) test, and California bearing ratio (CBR) test.

#### 3.1 Grain Size Distribution

The aims of particle size analysis are to find relative proportions of each size range and classification of soils. Particle size and distribution are important factors in determination of a soil's engineering features. As information obtained from grain size analysis may be used to predict soil water movement yet, hydraulic conductivity test is often used. Moreover, the data obtained from grain size distribution curves may be used to determine suitability of a soil for road construction. Particle size will also influence contaminant migration. Particle size distribution of coarse material is determined by sieve analysis and hydrometer analysis is carried out for grading of a soil finer than No : 200 Sieve. Particles passing through No : 200 sieve refers to fine material and particles remaining on No : 200 Sieve refers to coarse material. Percentage of fine and coarse particles in a soil can be measured from Equation 3.1 and Equation 3.2

$$F = \frac{M_f}{M} * 100 \quad (3.1)$$

F is percentage of fine particles,  $M_f$  is mass of particles passing No : 200 Sieve, and M is initial mass of the soil.

$$C = \frac{M_c}{M} * 100 \quad (3.2)$$

C is percentage of coarse particles and  $M_c$  is Mass of particles remaining on No : 200 Sieve.

According to ASTM D 422 Particle Size Analysis of Soils Standards, the grain size distribution of WFS was calculated and given in Table 3.1 [3]. The grain size distribution of WFS is used for classification as well as it is beneficial for determination of appropriate compaction technique in-situ.

**Table 3.1 : Grain Size Distribution of WFS.**

| <b>Grain Size Distribution of WFS</b> |                        |             |               |
|---------------------------------------|------------------------|-------------|---------------|
| Sieve Number                          | Diameter of Sieves(mm) | Passing (%) | Remaining (%) |
| 3/4"                                  | 19.100                 | 100.0       | 0.0           |
| 3/8"                                  | 9.520                  | 100.0       | 0.0           |
| 4                                     | 4.760                  | 100.0       | 0.0           |
| 10                                    | 2.000                  | 99.5        | 0.5           |
| 20                                    | 0.840                  | 99.2        | 0.8           |
| 40                                    | 0.420                  | 90.6        | 9.4           |
| 70                                    | 0.210                  | 31.5        | 68.5          |
| 100                                   | 0.149                  | 20.6        | 79.4          |
| 200                                   | 0.074                  | 12.8        | 87.2          |
| 230                                   | 0.064                  | 8.9         | 91.1          |
| 325                                   | 0.045                  | 8.6         | 91.4          |
| 450                                   | 0.033                  | 7.8         | 92.2          |
| 500                                   | 0.024                  | 7.6         | 92.4          |

According to Table 3.1 percentage of coarse particles for type of WFS is equal to 87% and percentage of fines (passing No : 200 sieve) is equal to %13 (F = 13 % and C = 87%). Then the curve of grain size distribution of WFS is shown in Figure 3.1.

Furthermore, according to AASHTO's soil classification, WFS may be considered as A-2-4 soil type [1].

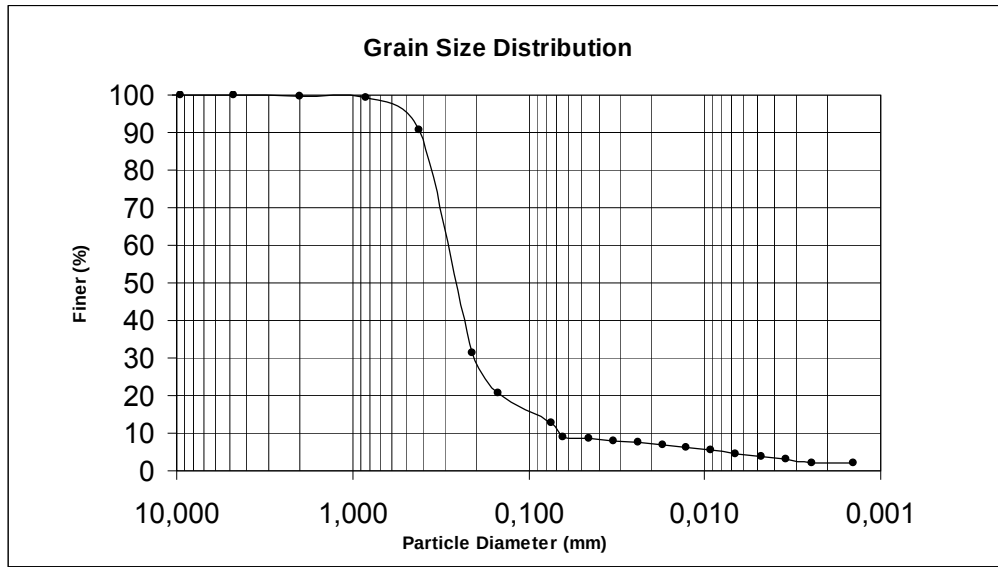


**Figure 3.1 :** The Curve of Grain Size Distribution for WFS.

### 3.2 Solid Density of WFS

Solid density ( $\rho_s$ ) of any soil is the ratio of particles' mass to particles' volume and it can be calculated as follows in Equation 3.3.

$$\rho_s = \frac{M_s}{V_s} \quad (3.3)$$

where,  $M_s$  = mass of a given volume of soil particles, and  $V_s$  = the given volume of soil particles.

The density of WFS was calculated as 2.56 This result was obtained from three specimens ranging from 2.46 to 2.62 ( $\rho_1 = 2.62$   $\rho_2 = 2.60$  and  $\rho_3 = 2.46$ ). Then average solid density was obtained 2.56 according to Equation 3.4.

$$\rho_{average} = \frac{\rho_1 + \rho_2 + \rho_3}{3} \quad (3.4)$$

### 3.3 Specific Gravity of WFS

Specific gravity of a soil is used to calculate the phase relationships of soils or the relative volumes of solids to water and air in a given volume of soil. Specific gravity ( $G_s$ ) of any soil can be calculated from the Equation 3.5

$$G_s = \frac{\rho}{\rho_w} \quad (3.5)$$

where,  $\rho$  = density of a given soil, and  $\rho_w$  = density of water ( equal to 1 gr/cm<sup>3</sup> at 4°C).

Since specific gravity is the ratio of the density of the soil to the density of water it is a dimensionless parameter. The specific gravity of WFS was calculated as 2.56 according to ASTM D 854 Specific Gravity of Soils Standards [3].

### 3.4 Atterberg Limits of WFS

The main goals of "Atterberg test" are to find out an estimate of a soil's consistency at various water contents. Atterberg limits are classified into three groups; liquid limit ( $\omega_l$ ), plastic limit ( $\omega_p$ ), and shrinkage limit ( $\omega_s$ ) which are used extensively in the classification of cohesive soil. Figure 3.2 is showing the relationship among these states. After determination of liquid and plastic limit, plasticity of cohesive soil is obtained from plasticity index ( $I_p$ ) which is  $\omega_l - \omega_p$

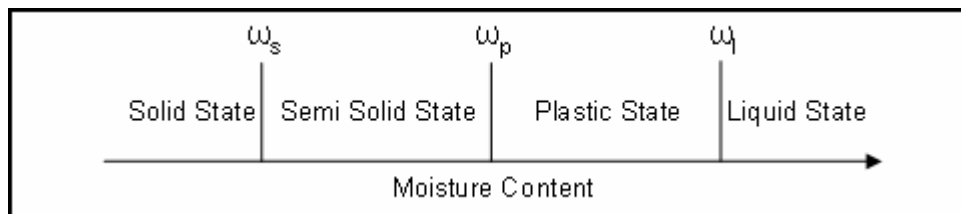


**Figure 3.2 : States of a Soil.**

Cohesive soil is fine grained soil including clayey silt, sandy clay, silty clay and organic clay. Additionally, cohesive soil is hard to break up when dry and exhibits significant cohesion that is caused by capillary stresses, or the surface tension of moisture in soils. States of cohesive soil vary according to moisture content [6].

Cohesionless soil considered as gravel, sand and nonplastic silts has no important cohesion and plastic behaviour when it is submerged. Atterberg limits of this type of soil can not be determined.

### 3.4.1 Liquid limit

Liquid limit ( $\omega_l$ ) is defined as the minimum moisture content at which soil changes from the liquid state to the plastic state. In other words, at liquid limit, soil will flow upon loading of a very small shearing force. It is mainly used to determine physical properties of a given soil. There are two current methods to calculate the liquid limit, namely the Cone Penetrometer Method and Casagrande Method. The Cone Penetrometer Method is applied when the results are more easily reproducible and it is easier to perform. Casagrande Method as shown in Figure 3.3 is an old test which has been used as dynamic method and thus reduces reproducibility between operators. However, in this study Casagrande Method was used to calculate liquid limit of WFS.



**Figure 3.3 : Casagrande Method [19].**

Liquid limit is calculated by drawing a semi-logarithmic graph. The graph shows the relationship between the moisture content ( $w$ ) and the corresponding number of drops ( $N$ ). Liquid limit is obtained from the moisture content corresponding to the intersection of the line with the 25 drop abscissa [19].

### 3.4.2 Plastic limit

The Plastic limit ( $\omega_p$ ) is defined as minimum moisture content of a soil at which it becomes too dry to be plastic. Namely, it is the moisture content, considered as a percentage of the mass of the oven-dried soil, at the boundary between the plastic and semi-solid states. The plastic behavior can depend on the clay content.

The plastic limit is the moisture content at which a 3 mm diameter thread of a soil-water paste shears when rolled on a glass plate with the tip of fingers, and the test is repeated three or four times to get an average value as shown in Figure 3.4 [19].



**Figure 3.4 : Measuring of Plastic Limit [19].**

#### **3.4.3 Shrinkage limit**

The shrinkage limit ( $\omega_s$ ) is the moisture content at which the soil changes its state from solid to semi-solid. In other words, minimum moisture content at which a soil can be completely saturated at this dry volume is defined as the shrinkage limit. It is important for highway construction due to volume change aspect. Below the shrinkage limit, any moisture content change will not result in a volume change of the soil. Above the shrinkage limit, any moisture content change will result in accompanying volume change.

Shrinkage limit of a given soil is determined according to ASTM D 4943 Standard Test Method for Shrinkage Factors of Soils by the Wax Method [19].

#### **3.4.4 Plasticity index**

The Plasticity Index ( $I_p$ ) is defined as the numerical difference between the liquid limit and the plastic limit for a given soil and indicates the magnitude of the range of moisture content over which the soil remains plastic. It is used to predetermine the amount of swelling and shrinkage. Equation 3.6 is showing the calculation of plasticity index is below.

$$I_p = \omega_l - \omega_p \quad (3.6)$$

According to US Department of Transportation Federal Highway Administration, WFS is generally nonplastic without fines. For WFS with 6 to 10% clay, liquid limit ( $\omega_l$ ) greater than 20 and a plastic index ( $I_p$ ) greater than 2 are typical. Truly, it was confirmed that WFS was nonplastic according to ASTM D 4318, Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils. [3,19,25].

### **3.5 Permeability of WFS**

Permeability is defined as a measure of the ability of a soil to transmit water. Water generally flows through soils owing to gravity augmented in some cases by capillary tension. This flow occurs in two ways. The first one takes place when flow lines do not intercept each other excluding the microscopic effect of molecular interchange, thus the flow is said to be laminar. The second one takes place when the lines intersect, then flow is believed to be turbulent. In case of low velocity, the flow is laminar, but if the velocity increases beyond a certain limit, it turns to be turbulent. In returning to laminar flow, it has been observed that the transition occurs at a lower speed than the one that was reached when the laminar flow became turbulent. This illustrates that an interval in the velocity at which the flow can either be laminar or turbulent.

Reynolds discovered that in all fluids there is a certain velocity below which for a certain channel diameter and a given temperature, flow is always laminar. This velocity is known as the critical flow velocity. Likewise, there is also a velocity above which the flow is always turbulent.

The initial theory on flow through soils is belonged to Darcy. His experimental device is shown in Figure 3.5.

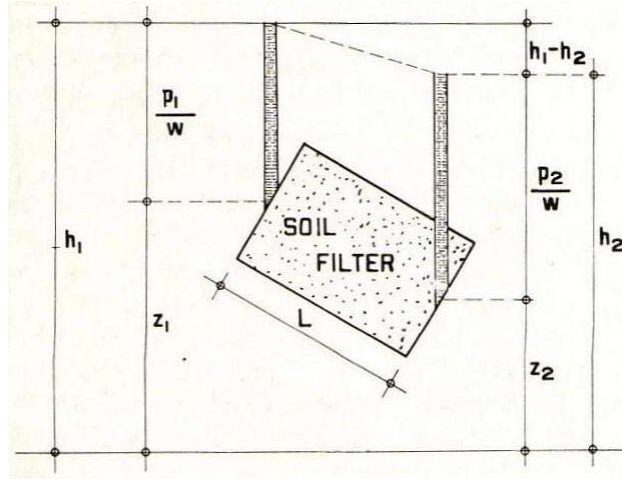


**Figure 3.5 :** Experimental Device for Permeability Coefficient by Darcy [22].

According to his experimental work, Darcy found out that for lower speeds, the flow (discharge) through the soil is explained by Equation 3.7

$$Q = k \cdot i \cdot A \quad (3.7)$$

where;  $A$  is the cross-section area of soil through which the water seeps,  $k$  is the coefficient of permeability, and  $i$  is the gradient or head loss over a given flow distance, given by Equation 3.8

$$i = \frac{(h_1 - h_2)}{L} \quad (3.8)$$

Moreover, flow of any fluid is measured by Equation 3.9

$$Q = A \cdot v \quad (3.9)$$

where;  $v$  is flow velocity. Since  $A \cdot v = k \cdot i \cdot A$  from Equation 3.7 and Equation 3.9, a new formula is obtained and shown in Equation 3.10

$$v = k \cdot i \quad (3.10)$$

Permeability coefficient  $k$  is defined as the velocity at which a quantity of water passes through a soil when submitted to a unit hydraulic gradient. By this way,  $k$  has same unit of velocity whereas  $i$  is dimensionless. It is apparent that value of  $k$  depends on the physical properties of soil and fluid.

However, the velocity  $v$  does not refer to real velocity of water flowing through the soil filter. This refers to the water discharge velocity, related to a certain area  $A$  of the soil, not the whole cross-sectional area,  $A_v$ , through which the water flows. An approach can be obtained from the real velocity. It is indicated that flow is only possible through the voids. If a corresponding seepage velocity ( $v_1$ ), namely real velocity is defined, then the flow continuity gives as shown in Equation 3.11

$$\begin{aligned}
 A_v * v_1 &= A * v \\
 \text{then;} \\
 v_1 &= \frac{A * v}{A_v}
 \end{aligned}
 \tag{3.11}$$

If a unit thickness is considered and the definition of void ratio is taken into account as shown in Equation 3.12 then;

$$\begin{aligned}
 e &= \frac{A_v}{(A - A_v)} \\
 \text{then;} \\
 \frac{1}{e} &= \frac{A}{A_v - 1} \\
 \text{and,} \\
 \frac{A}{A_v} &= \frac{(1 + e)}{e}
 \end{aligned}
 \tag{3.12}$$

is obtained.

By this relationship, the seepage velocity can be expressed in terms of the flow velocity, as shown in Equation 3.13

$$v_1 = \frac{1+e}{e} * v
 \tag{3.13}$$

Darcy's Law was derived experimentally, thus its applicability can go beyond the specific conditions under which the initial experiments were carried out. Darcy's experiments involved groundwater flow using a great variety of soil types and hydraulic gradients, thus, his experimental results applicable to majority of real conditions. In other words, Darcy's Law is valid for groundwater flow of soils finer than medium sands, for almost any hydraulic gradient.

Soil permeability is associated with the type of the material. Table 3.2 is showing the permeability of some soils.

**Table 3.2 : Permeability Values of Some Soils [22].**

| Type of Soil                       | Permeability (cm/s)    |
|------------------------------------|------------------------|
| Clean Gravels                      | 100                    |
| Clean Sands                        | $10^{-2} \sim 10^{-3}$ |
| Fine Sands                         | $10^{-4}$              |
| Silts and moraine                  | $10^{-5} \sim 10^{-6}$ |
| Clays                              | $10^{-5}$              |
| Homogeneous montmorillonitic clays | $10^{-8} \sim 10^{-9}$ |

Generally, having a permeability under  $10^{-3}$  cm/s, a soil can not be considered suitable as a drainage material and having a permeability below  $10^{-7}$  cm/s, a soil can be considered as an impervious material.

No reliable relationship has been founded between the permeability coefficient and the grain size distribution of soils. However, for fine sands, Hazen proposed a relationship as shown in Equation 3.14.

$$R = C * D_{10}^2 \quad (3.14)$$

where  $D_{10}$  is the effective diameter of the soil (10% by weight of the soil is smaller than this diameter), expressed in cm. The value of the constant C varies between 41 and 146 in Hazen's tests and a value of 120 is usually mentioned as an accepted average for using the formula.

The mineral composition of clays has impact on soil permeability due to the absorption layers that form around, and adhere very strongly to, the mineral crystal, hence hindering ground-water flow.

Generally, the permeability of a soil is affected by the following characteristics;

- Void ratio
- Particle size
- Mineralogical and physico – chemical composition

- Soil structure
- Degree of saturation
- Temperature of the water

Permeability is influenced by the structure of the soil. In very fine soils, it is crucial to know whether the structure is flocculent or oriented, because when oriented there are higher permeabilities parallel to the aligned faces of the particles, and marked anisotropy in the permeability. These conditions are observed particularly in compacted soils, in which the structure obtained is flocculent or dispersed, depending on the compaction procedures employed.

Saturation is important for permeability since saturation less than 100% permeability will be low. Additionally, cracks and fissures increase permeability greatly by orders of magnitude [22].

In this study, permeability of WFS was obtained by a falling-head permeameter. According to the results, permeability of WFS was obtained as  $1.44 \times 10^{-6}$

### **3.6 Compaction of WFS**

Compaction is a geotechnical application that improves the properties of soils by the means of mechanical energy. This application can be performed on an existing soil as well as on built structures such as embankments and road bases.

The main goals of compaction are to increase shear strength, stiffness and density of soils. Besides, as bearing capacity of soils is increased, potential settlement and frost heave of soils are decreased by compaction.

There are several factors affecting the compaction of soils. These are nature and type of soil, grading, plasticity, water content, site conditions, layer thickness and type of compactive effort. Actually, the vital factors are water content of soil and the amount of compactive energy during compaction. In other words, the most important issue before implementation of most tests is to find out the relationship between optimum moisture content (OMC) and maximum dry density ( $\rho_{d_{max}}$ ) of WFS at a specified compactive effort. This specified compactive effort is the amount of mechanical energy that is applied to WFS.

There are two types compaction tests are used in practice. One of which is the Standard Proctor Test and another is the Modified Proctor Test developed by R.R Proctor in 1993.

Proctor methods are described based on the standards as follows;

ASTM D 698 – Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400ft – lbs/ft<sup>3</sup> (600 KN-m/m<sup>3</sup> )) [3].

In the Standard Proctor Test, the soil is compacted by a 2.49 kg (5.5 lb) hammer falling a distance of 30.5 cm (one foot) into a soil filled mold. The mold is filled with three equal layers of soil, and each layer is subjected to 25 drops of the hammer.

ASTM D 1557 – Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000ft – lbs/ft<sup>3</sup> (2700 KN-m/m<sup>3</sup> )) [3].

The Modified Proctor Test is similiar to the Standard Proctor Test except a 4.54 kg (10 lb) hammer falling a distance of 45.72 cm (18 inches), and uses five equal layers of soil instead of three.

There are two types of compaction molds used for testing as shown in Figure 3.6. The smaller type, namely standard Proctor mold is 10.16cm (4 inches) in diameter and has a volume of about 944 cm<sup>3</sup> (1/30 ft<sup>3</sup>), and the larger type, namely modified Proctor mold is 15.24 cm (6 inches) in diameter and has a volume of about 2123 cm<sup>3</sup> (1/13.333 ft<sup>3</sup>). If the larger mold is used each soil layer must receive 56 blows instead of 25. In this study, first type of molds was used to prepare specimens for UT and UCS tests. Second type was used to prepare specimens for CBR test.



**Figure 3.6 : Compaction Molds [4].**

Before preparing samples in laboratory, the maximum dry density ( $\rho_{d_{max}}$ ) and the optimum moisture content (OMC) of the material are required. OMC is the moisture content that results in the  $\rho_{d_{max}}$  for a specified compactive effort. OMC is extremely

important geotechnical feature of any soil. Because compacting at any water contents higher than OMC results in a relatively dispersed soil structure which is weaker, less permeable, more ductile, softer, more susceptible to shrinking and less susceptible to swelling than any soil compacted dry of optimum to the same density. Likewise, the soil compacted lower than the OMC typically results in an aggregated into small lumps soil structure that has the opposite features of the soil compacted wet of the OMC to the same density [4].

### **3.6.1 Determination of optimum water content (OMC) of WFS**

In this study, after pulverizing WFS and sieving through the No : 4 Sieve the weight of WFS and the weight of WFS and the compaction mold with its base (without the collar) were noted. Then, water was added, and amount of water added to initial WFS were measured. After the mixing, compaction process was performed according to ASTM D 1557 standard. Weight of the compacted WFS and the mold with base were measured. Samples were taken from the top and bottom of the compacted WFS, and the water content was determined by drying out the material in an oven at 105°C. Next, the WFS specimen was placed in a large tray and was broken up in order to add more water to increase water content. Figure 3.7, Figure 3.8, and Figure 3.9 are illustrating the compaction steps.



**Figure 3.7 : Compaction Step – I [4].**

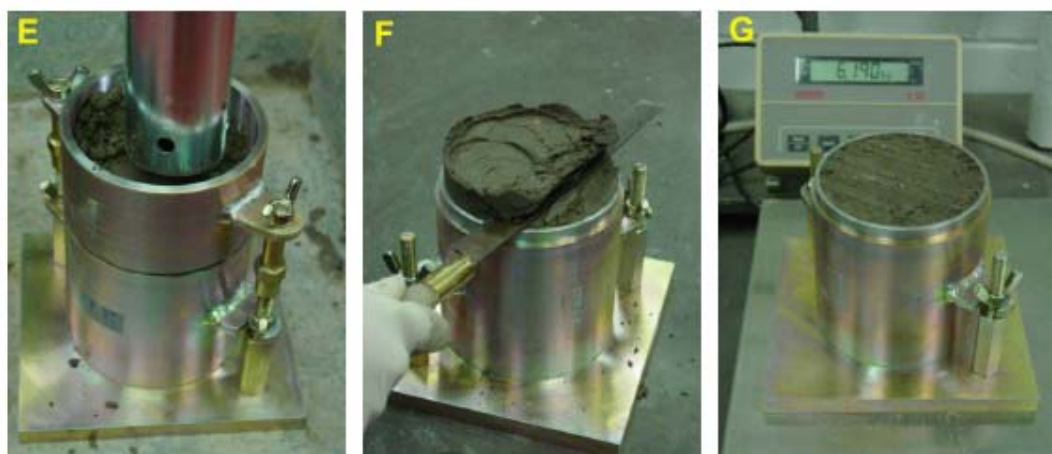


**Figure 3.8 : Compaction Step – II [4].**



**Figure 3.9 : Compaction Step – III [4].**

Approximately, 2% more water was added at each step up to at least 5 different moisture contents were obtained.

Basic principle of compaction can be formulated as follows in Equation 3.15, Equation 3.16, and Equation 3.17.

$$\rho = \frac{M}{V} \quad (3.15)$$

where;  $\rho$  is bulk density of soil,  $M$  is mass of a given volume of soil, and  $V$  is the given volume of soil.

$$w = \frac{100 * M_w}{V} \quad (3.16)$$

where;  $w$  is moisture content (percent),  $M_w$  is mass of water in the given volume of soil.

$$\rho_d = \frac{M_s}{V} = \frac{100 * \rho}{(100 + w)} \quad (3.17)$$

where;  $\rho_d$  is dry density of soil and  $M_s$  is mass of solid particles in the given volume of soil [6,19].

In this study, OMC of WFS is determined 15% and maximum dry unit weight is found 1,75gr/cm<sup>3</sup> and the relationship between OMC and  $\rho_d$  is shown in Figure 3.10.

$$(w_{opt}=15\% ; \rho_{dmax} = 1,75 \text{ gr/cm}^3)$$

Besides, optimum moisture content (OMC) and maximum dry density ( $\rho_{dmax}$ ) of WFS was determined after cement and lime stabilization. This was necessary

because adding lime or cement might change the soil's OMC and  $\rho_{dmax}$ . But, the difference was negligible for OMC but not  $\rho_{dmax}$ .

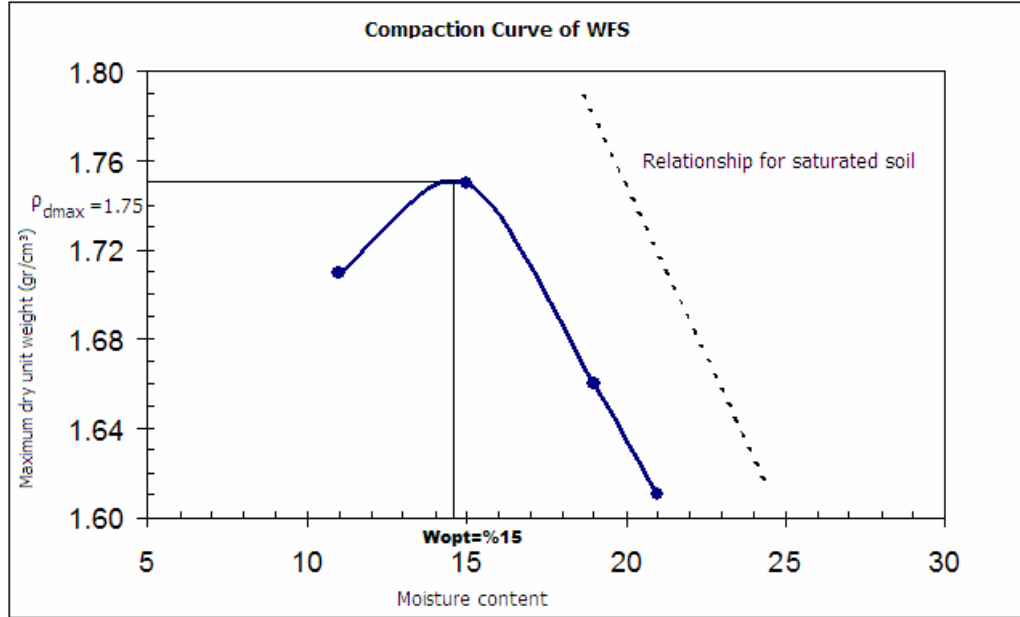


**Figure 3.10 :** The Relationship between OMC and  $\rho_{dmax}$

### 3.7 Labelling of WFS Samples

As mentioned in previous sections two main materials (cement and lime) were amended for stabilization of WFS. Basically, cure duration and amount of cement or lime were two important issues in this study.

The specimens subjected to UCS, CBR and ultrasonic tests had been categorized in two groups. One of them was including specimens stabilized with cement and another was including specimens stabilized with lime. Hereafter, labelling for Group I is C-WFS and labelling for Group II is L-WFS. Moreover there will be used a sub-labelling methodology explaining weight percentage of lime or cement, the cure duration, and range of specimen. Both Groups I and II had five main sub-groups in accordance with cure duration. They were main sub-groups that had been cured 7-day, 14-day, 28-day, 3-month and 6-month in humidity room. Secondly, these five main sub-groups were considered having four subsets. The specimens having 7-day, 14-day, 28-day, 3-month and 6-month cure duration also had 2%, 4%, 8% and 10% cement or lime presence by weight. As shown in Table 3.3 Group I and II had 80 specimens individually.

**Table 3.3 : Labelling of Samples.**

| Group I (C-WFS)                                 |                  |                    | Group II (L-WFS)                                |                |                    |
|-------------------------------------------------|------------------|--------------------|-------------------------------------------------|----------------|--------------------|
| Cure Duration of Specimens                      | Amount of Cement | Range of Specimens | Cure Duration of Specimens                      | Amount of Lime | Range of Specimens |
| 7-day<br>14-day<br>28-day<br>3-month<br>6-month | 2%               | C-WFS-I            | 7-day<br>14-day<br>28-day<br>3-month<br>6-month | 2%             | L-WFS-I            |
|                                                 |                  | C-WFS-II           |                                                 |                | L-WFS-II           |
|                                                 |                  | C-WFS-III          |                                                 |                | L-WFS-III          |
|                                                 |                  | C-WFS-IV           |                                                 |                | L-WFS-IV           |
|                                                 | 4%               | C-WFS-I            |                                                 | 4%             | L-WFS-I            |
|                                                 |                  | C-WFS-II           |                                                 |                | L-WFS-II           |
|                                                 |                  | C-WFS-III          |                                                 |                | L-WFS-III          |
|                                                 |                  | C-WFS-IV           |                                                 |                | L-WFS-IV           |
|                                                 | 8%               | C-WFS-I            |                                                 | 8%             | L-WFS-I            |
|                                                 |                  | C-WFS-II           |                                                 |                | L-WFS-II           |
|                                                 |                  | C-WFS-III          |                                                 |                | L-WFS-III          |
|                                                 |                  | C-WFS-IV           |                                                 |                | L-WFS-IV           |
|                                                 | 10%              | C-WFS-I            |                                                 | 10%            | L-WFS-I            |
|                                                 |                  | C-WFS-II           |                                                 |                | L-WFS-II           |
|                                                 |                  | C-WFS-III          |                                                 |                | L-WFS-III          |
|                                                 |                  | C-WFS-IV           |                                                 |                | L-WFS-IV           |

Figure 3.11 is explaining the meaning of one sample belonged to Group I (C-WFS);

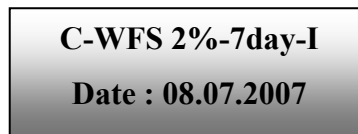


**Figure 3.11 : Group I.**

where; C is standing for cement stabilization of WFS, 2% is standing for cement presence of WFS, 7-day is standing for cure duration, I is standing for range of samples having same content, and Date is showing the date of preparation of the sample.

C-WFS 2%-7day-I states “First specimen of WFS stabilized with 2% cement by weight and was cured 7 days in humidity room.”

Likewise, Figure 3.12 is explaining the meaning of one specimen belonged to Group II (L-WFS);

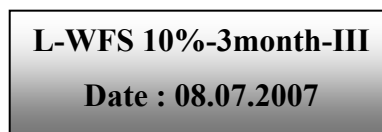


**Figure 3.12 : Group II.**

where; L is standing for lime stabilization of WFS, 10% is standing for lime presence of WFS, 3-month is standing for cure duration, III is standing for range of specimen having same content, and Date is showing the date of preparation of specimen.

L–WFS 10%-3month-III states “Third specimen of WFS stabilized with 2% lime by weight and was cured 3 months in humidity room.”

In total, 160 specimens were prepared for UT, UCS and CBR tests. 60 specimens of each group were prepared according to ASTM D 698 standards for UT and UCS tests. 20 specimens of each group were prepared according to ASTM D 1557 standards for CBR test [3]. After compaction process, specimens were removed from the mold and they were covered with plastic wrap against any moisture loss. Then they were labeled as shown in Figure 3.13 and then, taken into humidity room for curing.



**Figure 3.13 : Prepared Specimens.**

## **4. EXPERIMENTAL STUDY**

In this study, samples were subjected to following tests;

- Ultrasonic pulse velocity test (UT)
- Unconfined compressive strength (UCS) test
- California bearing ratio (CBR) test.

### **4.1 Ultrasonic Pulse Velocity Test**

The ultrasonic pulse velocity test (UT) is a measurement of the transit time of a longitudinal vibration pulse through a sample which has a known path length. The aims of (UT) are to inspect material characterization, maintenance applications and material discontinuities as well as to observe effects of stabilization. UT is suitable to apply to any material in which acoustic waves can be introduced electromagnetically. However, materials that are rough, very small, having irregular shape as well as cast iron and coarse-grained materials are not suitable for UT because of low sound transmission and high signal noise. The test is carried out by applying two transducers (transmitting and receiving) to the opposite end surfaces of the samples. A sufficient acoustical contact between the transducers and the surface of the sample is maintained by a couplant such as silicon grease. The pulse delay between the transducers is measured as the transit time and the ultrasonic pulse velocity is calculated using the length of the sample (the distance between the transducers) [17].

Generally, an UT apparatus consists of several functional units, such as pulser, transducer, and display screen. A pulser is a kind of equipment that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. Through specimens, sound waves can propagate in four ways. They are longitudinal, shear, surface and

plate ways. Longitudinal and shear waves are the two principle modes that are most commonly used in UT. In this study, longitudinal wave was propagated through the specimens. In Figure 4.1 propagation of longitudinal and shear waves are shown.

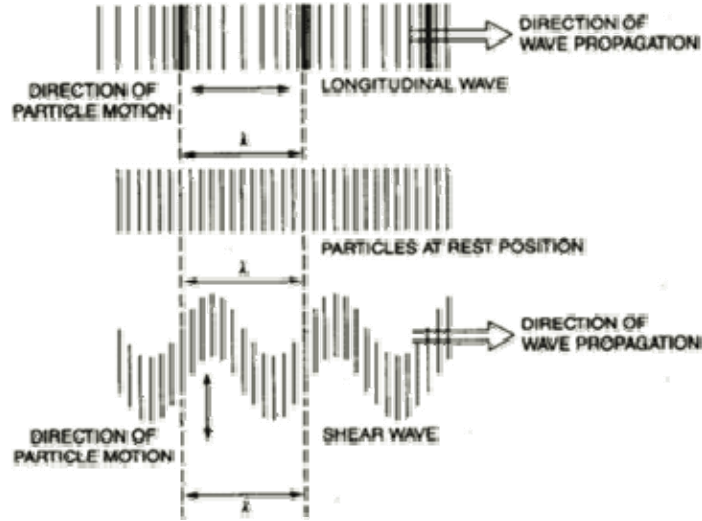


**Figure 4.1 :** Propagation of Longitudinal and Shear Waves.

Longitudinal waves are known as pressure waves since they are compressional. Despite the fact that steel and concrete are commonly evaluated using ultrasonic testing in civil engineering application, there are no established procedures and standards available for ultrasonic evaluation of stabilized soils. To obtain dynamic elasticity modulus of WFS specimens, procedures and standards were performed according to ASTM C 597 (Standard Test Method for Pulse Velocity Through Concrete). By this approach, Equation 4.1 was used to calculate dynamic elasticity modulus of WFS specimens.

$$E_d = 10^5 * V^2 * \frac{\Delta}{g} \quad (4.1)$$

where;  $E_d$  is dynamic elasticity modulus ( $\text{kg/cm}^2$ ),  $V$  is velocity ( $\text{km/sn}$ ),  $\Delta$  = density ( $\text{kg/dm}^3$ ), and  $g$  = acceleration of gravity ( $\text{m/s}^2$ ).

Details of calculation of  $E_d$  values are given in Appendix A. Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5, and Figure 4.6 are showing the relationship of  $E_d$  values between cement and lime stabilized samples cured 7-day, 14-day, 28-day, 3-month, and 6-month.

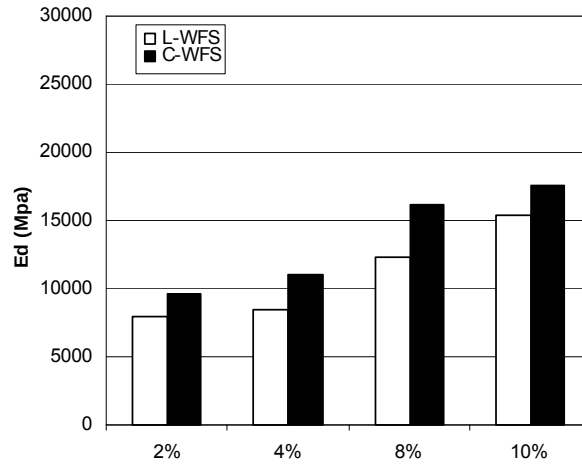


**Figure 4.2 :**  $E_d$  Values of Cement and Lime Stabilized and 7-day Cured Samples.

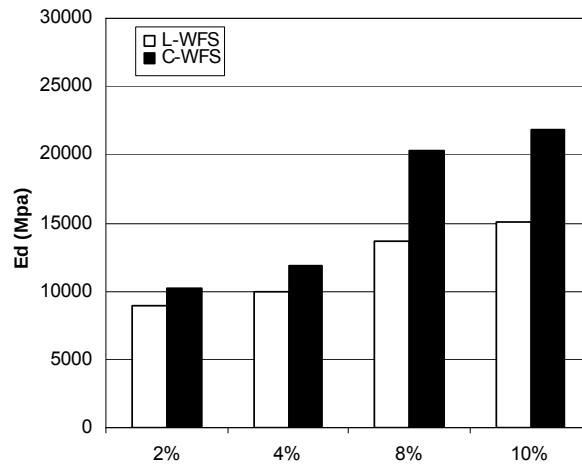


**Figure 4.3 :**  $E_d$  Values of Cement and Lime Stabilized and 14-day Cured Samples.

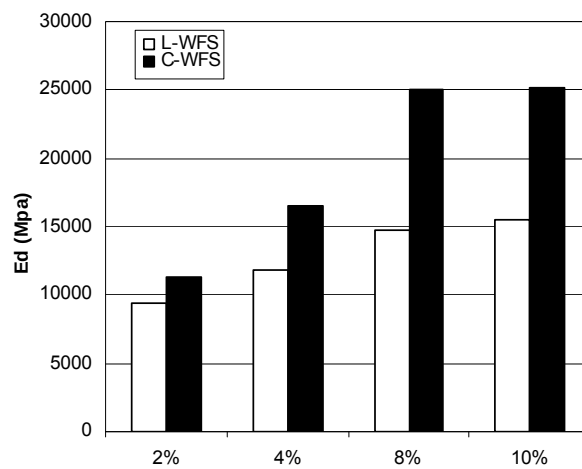


**Figure 4.4 :**  $E_d$  Values of Cement and Lime Stabilized and 28-day Cured Samples.

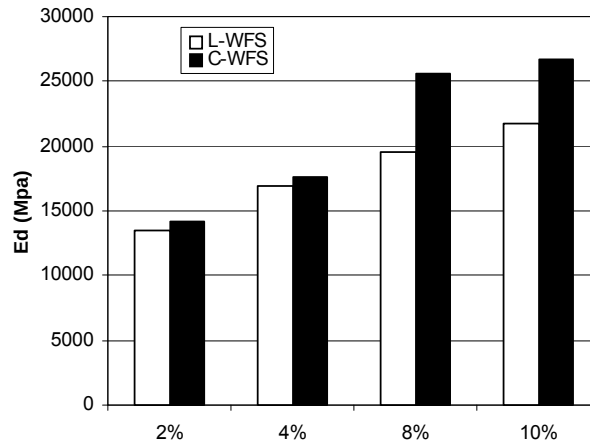


**Figure 4.5 :**  $E_d$  Values of Cement and Lime Stabilized and 3-month Cured Samples.

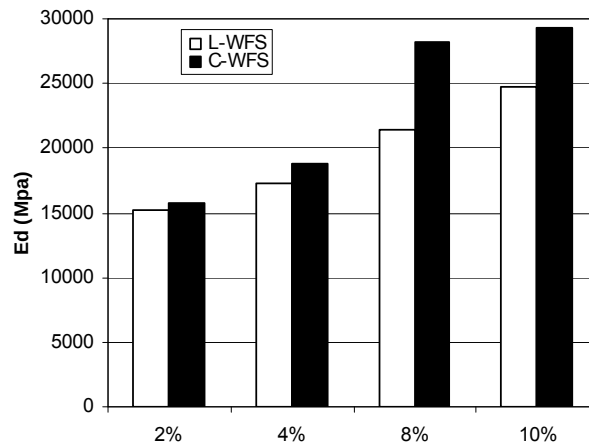


**Figure 4.6 :**  $E_d$  Values of Cement and Lime Stabilized and 6-month Cured Samples.

## 4.2 Unconfined Compressive Strength Test

The strength gain over time is one of the most important parameter associated with performance of a stabilized road base and sub-base over time. Unconfined compressive strength (UCS) test is one of the laboratory test to determine the strength ( $q_u$ ) of the soils, stabilized materials and concrete. In other words, it is a widespread measure used to determine the relative response of the materials to the parameter mentioned previously. Also the test is very useful to obtain the shear strength parameters of cohesive (fine-grained) soils, but it is not suitable to cohesionless or coarse grained soils.

UCS test is applied in accordance with the procedures given in ASTM D 1633 (Compressive Strength of Molded Soil-Cement Cylinders) and ASTM D 5102 (Unconfined Compressive Strength of Compacted Soil-Lime Mixtures) [3]. The test involves the loading cylindrical samples to failure in simple, without lateral confinement. For each type of samples, 3 to 5 UCS tests are recommended for statistical significance of the results. In this study, 3 samples were prepared for UT and UCS test. Samples stabilized with cement or lime having agent content were 2%, 4%, 8%, and 10% by weight. The samples were tested after 7-day, 14-day, 28-day, 3-month, and 6-month curing as detailed previously.

During UCS test INSTRON 5500R model as shown in Figure 4.7 was used. Details of UCS plots are given in Appendix B.



**Figure 4.7 :** Instron 5500R.

ASTM standard recommends a correction factor that is implemented to the UCS value obtained from testing if the specimen's length to diameter is greater or less than 2. Because the specimens in this study were prepared according to ASTM D 1557 Standard, this correction factor also was applied to test results rather than

trimming the specimens into preferred dimensions (7.11cmX14.22cm). The height and diameter of standard compaction mold are 11.64cm and 10.16cm respectively.

Since surfaces of the specimens were not smooth, both surfaces of each samples were capped before applying the UCS test. By this way, loading to specimens would be uniform during test. Besides, capping was required for rough surfaces in order to transmit ultrasound during the ultrasonic pulse velocity test.

Figure 4.8, Figure 4.9, Figure 4.10, Figure 4.11, and Figure 4.12 are showing the relationship of  $q_u$  between cement and lime stabilized samples and cured 7-day, 14-day, 28-day, 3-month, and 6-month.

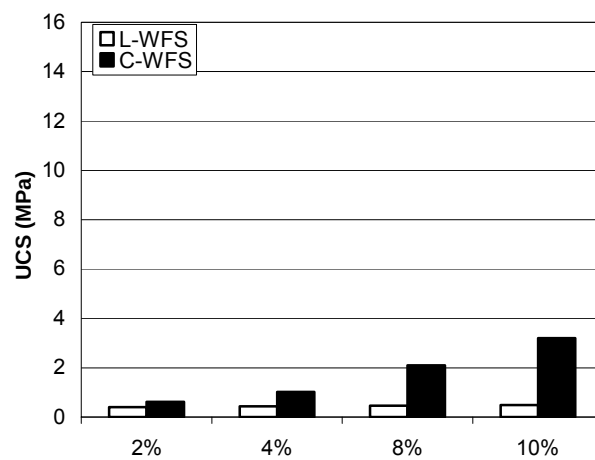


**Figure 4.8 :** UCS Values of Specimens Cured 7-day.

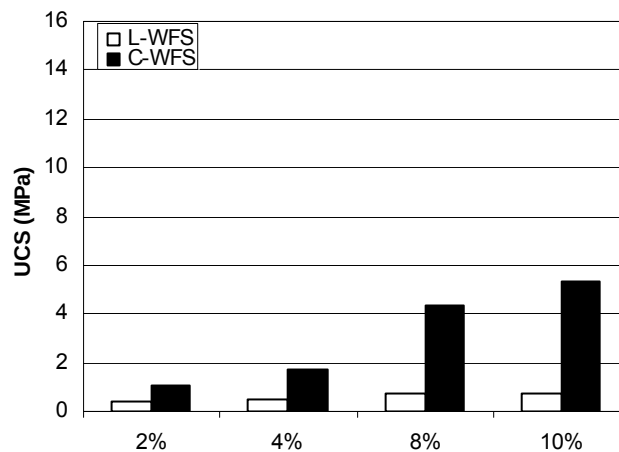


**Figure 4.9 :** UCS Values of Specimens Cured 14-day.

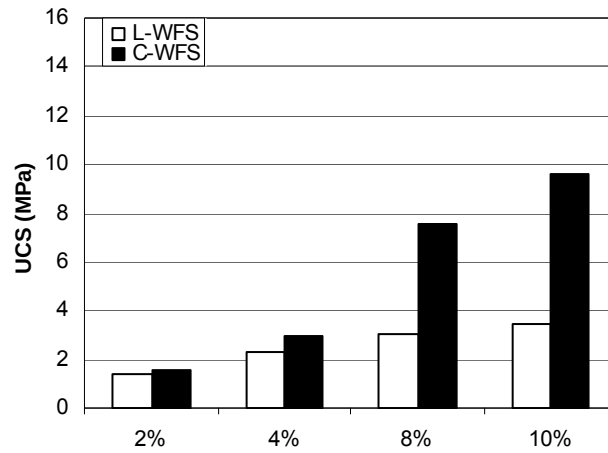


**Figure 4.10 : UCS Values of Specimens Cured 28-day.**

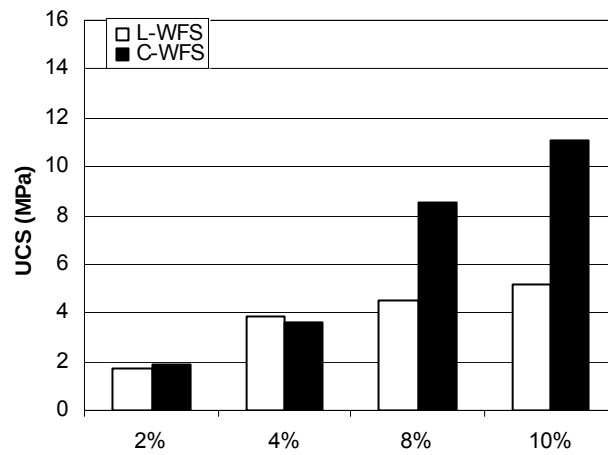


**Figure 4.11 : UCS Values of Specimens Cured 3-month.**

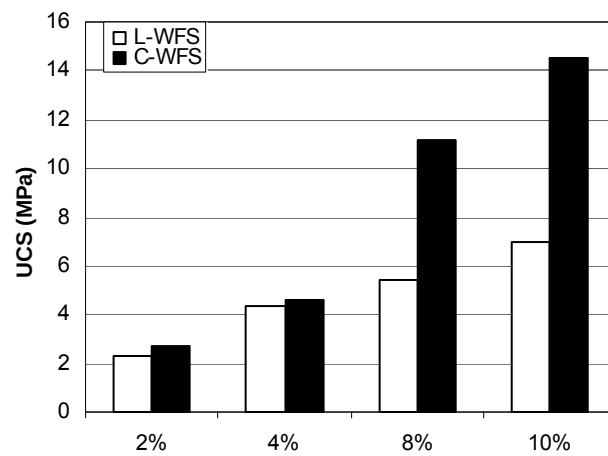


**Figure 4.12 : UCS Values of Specimens Cured 6-month.**

## 4.2.1 Elasticity Modulus (E) of WFS samples

### 4.2.1.1 Definition of strain

When a specimen is being exposed to an increasing force as shown in Figure 4.13, a change in length between two points, as A and B on the specimen is observed. This initial distance between the two points is called a gage distance.

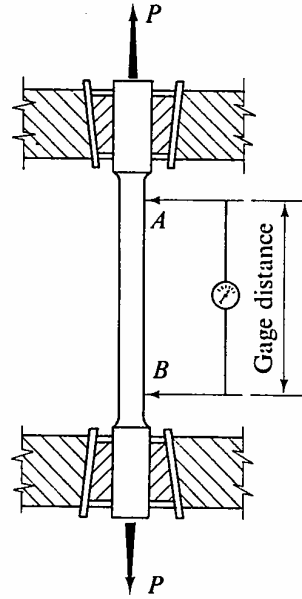


**Figure 4.13 : Loading Force.**

As the load is increased, a larger gage distance, namely a larger deformation is observed. If  $\Delta$  is the total change in a given original gage length  $L$ , the change per unit of length ( $\epsilon$ ) is calculated as follows in Equation 4.2.

$$\epsilon = \frac{\Delta}{L} \quad (4.2)$$

This change per unit of length is defined as strain. It is a dimensionless quantity. If the strain is known, the total deformation of an axially loaded sample is  $\epsilon \cdot L$  [22].

### 4.2.1.2 Stress – strain diagram

Stress – strain diagrams establish a relationship between applied stress and resulting strain. For pragmatic reasons, it is assumed independent of the size of the specimen or its gage length. For stress – strain diagrams, it is customary to use the ordinate

scale for stresses and the abscissa for strains. Stresses are generally measured on the basis of the original area of a specimen.

Shape of stress – strain diagram differs considerably for different materials. Even for the same material it differs, depending on the temperature at which the test was conducted, the speed of the test and several other variables. In this study, the speed of the loading was set 50mm/min (deformation ratio) for all specimens. For each type of samples, three same specimens were prepared.

Despite of the fact that each material has its unique curve, two types of diagrams are common. One type can be recognized for ductile materials as shown in Figure 4.14. The other type is represented for brittle materials as shown in Figure 4.15.

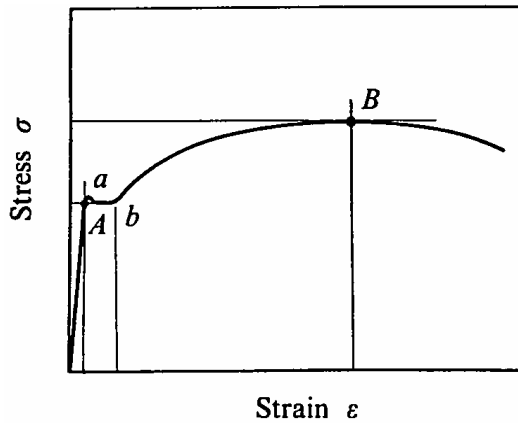


**Figure 4.14 : Ductile Materials.**

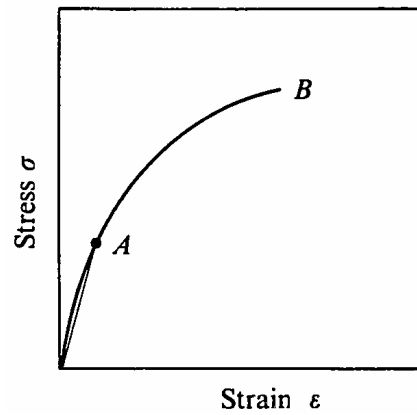


**Figure 4.15 : Brittle Materials.**

Materials capable of withstanding large strains are referred to as ductile materials. The opposite applies to brittle materials [20,22].

#### **4.2.1.3 Hooke's law**

It is a fact that one feature of stress – strain diagrams is applicable with sufficient accuracy to nearly all materials. It is known that for a certain distance from the origin the experimental values of stress strain lie essentially on a straight line. This rule holds true almost except reservations for glass. It is true for ductile materials up to point A in Figure 4.14. On the other hand, the straight part of the curve hardly exists in concrete, annealed copper, or cast iron. Nevertheless, for all practical purposes, up to some such point as A (also in Figure 4.15) the relationship between stress and strain may be said to be linear for all materials. This idealization concept is known as Hooke's Law. The law can be expressed by the Equation 4.3.

$$\sigma = E * \varepsilon$$

or;

$$E = \frac{\sigma}{\varepsilon} \quad (4.3)$$

where;  $\sigma$  is stress and  $\varepsilon$  is strain.

In other words, that stress is proportional to strain and the constant of proportionality is E. This constant E is called elastic modulus, modulus of elasticity, or Young's modulus. As  $\varepsilon$  is dimensionless, E has the units of stress in this relation. Because the stress was obtained as Mega Pascal (MPa) in this study, the E values of WFS specimens are given in MPa.

Graphically E is interpreted as the slope of a straight line from the origin to the rather vague point A on a stress – strain diagram. The stress corresponding to the latter point is termed the proportional limit of the material. Physically speaking the elastic modulus represents the stiffness of the material to an imposed stress. The value of the elastic modulus is a definite property of materials.

An elastic material is able to regain completely its original dimensions upon removal of the applied forces. Increasing stress is reached up to a point that causes permanent deformation on the material. This level of stress is called the elastic limit of the material. In practice, the elastic limit corresponds closely to the proportional limit of the material [22].

It is found that WFS specimens behave as brittle materials, in other words their diagrams are similar to diagram shown in Figure 4.15. Elastic modulus of WFS specimens will be calculated based on Veollmy Parabola method.

#### **4.2.1.4 Veollmy parabola method**

Elastic Modulus is the mathematical description of a material's tendency to be deformed elastically when a force is applied onto it. In other words, it is considered as a material's rigidity to elastic deformation [10].

In this study, E values of WFS specimens were calculated according to Veollmy's approach using stress – strain values obtained from UCS test detailed in previous section. Since there is no linear relationship between stress and deformation, the following equations were used as shown in Figure 4.16, the Equation 4.4 and Equation 4.5 are obtained.

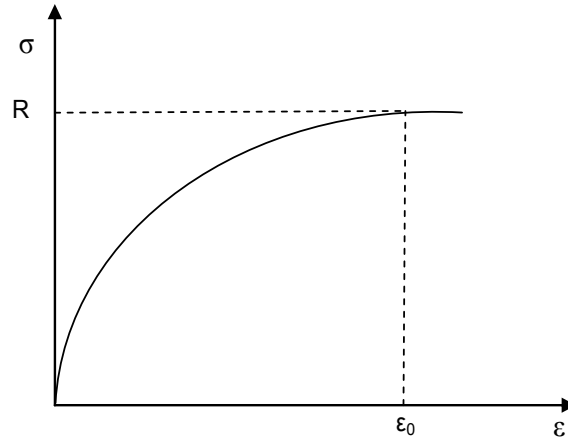


**Figure 4.16 : Veollmy Parabola.**

$$\sigma = R * \frac{\varepsilon}{\varepsilon_0} * \left( 2 - \frac{\varepsilon}{\varepsilon_0} \right) \quad (4.4)$$

where;  $\sigma$  is stress,  $\varepsilon$  is deformation,  $\varepsilon_0$  is unit deformation at fracture point and,  $R$  is compressive strength.

$$E = \left( \frac{d\sigma}{d\varepsilon} \right)_{\varepsilon=0} = \left( \frac{2R}{\varepsilon_0} - \frac{2R * \varepsilon}{\varepsilon_0^2} \right)_{\varepsilon=0} = \frac{2R}{\varepsilon_0} \quad (4.5)$$

and,

$$\varepsilon_0 = \frac{\Delta l_{\max}}{l_0}$$

Figure 4.17, Figure 4.18, Figure 4.19, Figure 4.20, and Figure 4.21 are showing the relationship of  $E$  values between cement and lime stabilized samples and cured 7-day, 14-day, 28-day, 3-month, and 6-month.

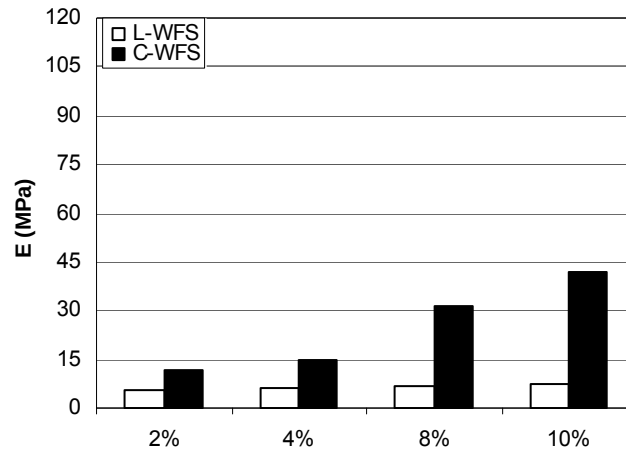


**Figure 4.17 :** Elasticity Modulus of Specimens Cured 7-day.

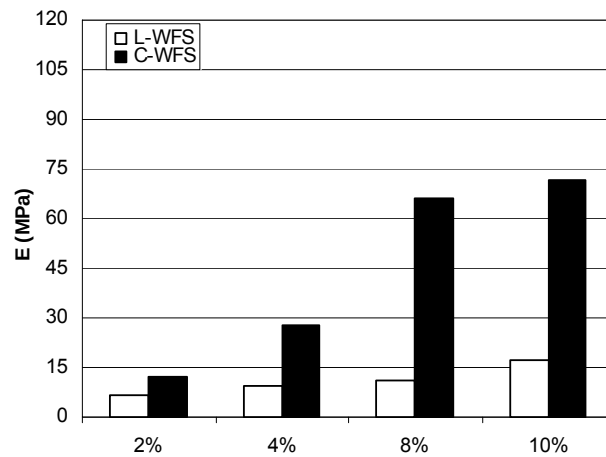


**Figure 4.18 :** Elasticity Modulus of Specimens Cured 14-day.

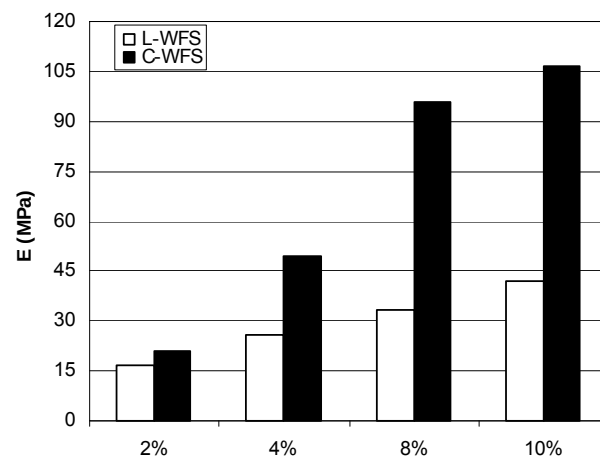


**Figure 4.19 :** Elasticity Modulus of Specimens Cured 28-day.

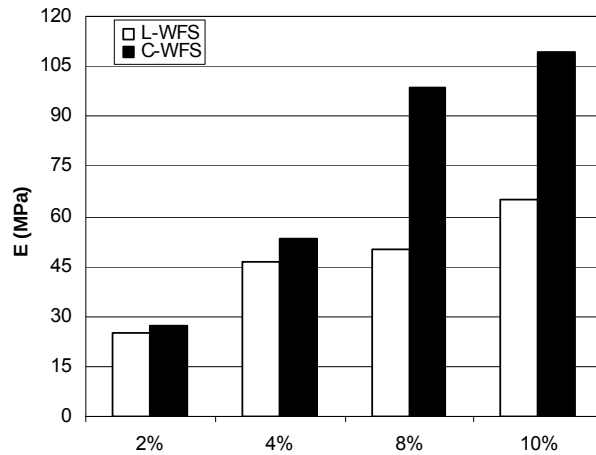


**Figure 4.20 : Elasticity Modulus of Specimens Cured 3-month.**

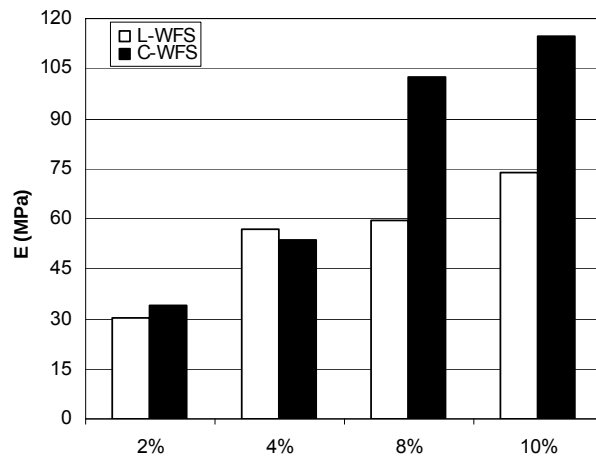


**Figure 4.21 : Elasticity Modulus of Specimens Cured 6-month.**

#### **4.2.1.5 Deflection analysis by KENLAYER computer program**

KENLAYER computer program which was written in FORTRAN 77 is used to calculate pavement analysis and design under various loadings (single or multiple wheels) [26].

In this study, after obtaining elastic modulus of stabilized WFS samples, this program was used to calculate the maximum surface deflection of a three – layer system under a set of dual – tandem tires. It was considered that each tire had a contact radius of 95.6mm (3.76 inch) and a contact pressure of 700 kPa (101 psi). Layer 1 (asphaltic concrete) has an elastic modulus of 2800 MPa (406106 psi) and a Poisson ratio of 0.4 and a thickness of 10 cm (3.93 inch). Layer 2 (consisting of

various stabilized WFS samples) as a base layer has various thicknesses of 15 cm (5.90 inch), 20 cm (7.87 inch), 25 cm (9.84 inch), 30 cm (11.81 inch) and has various elastic modulus (changing according to percentage of agent and type of agent and cure duration) and a Poisson ratio of 0.20. Layer 3 is considered as sub grade and having elastic modulus 20 MPa (2900 psi), 50 MPa (7251 psi), 100 MPa (14503 psi), and 150 MPa (21755 psi) and having Poisson ratio of 0.45 and 0.35 respectively as shown in Figure 4.22.

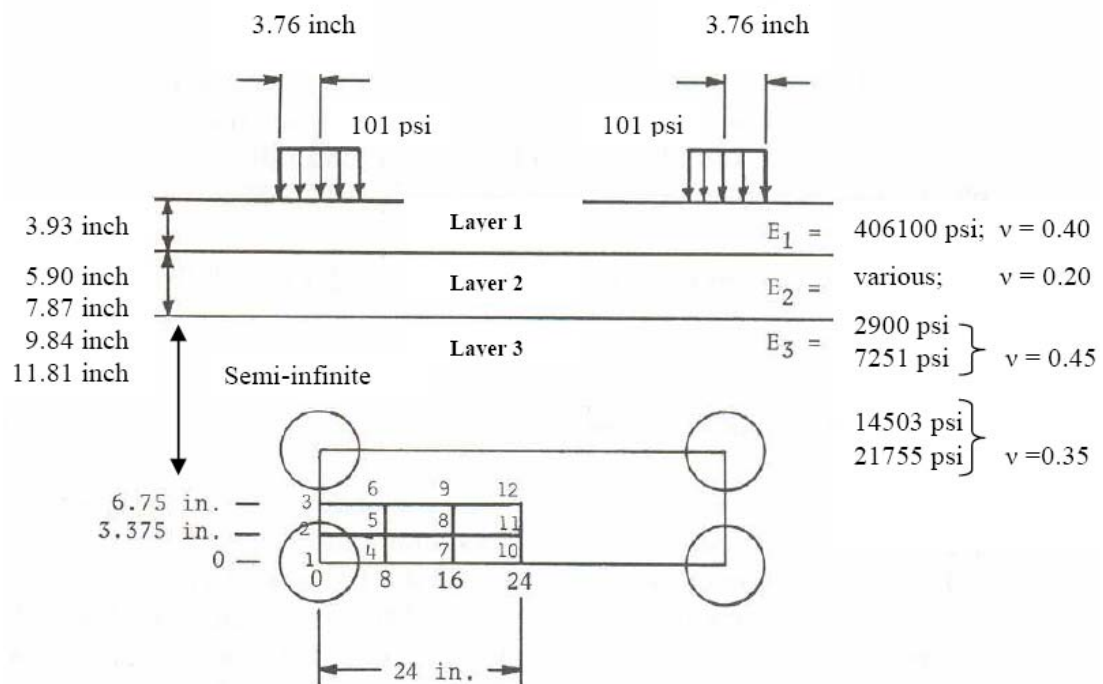


**Figure 4.22 : Deflection Analysis.**

The results obtained by KENLAYER showed that the maximum surface deflection occurs at point 3 and they are given in Appendix C.

### 4.3 California Bearing Ratio Test

California Bearing Ratio Test was initially developed by the California Division of Highways. Although it is an empirical method, however widely used all around the world because of its simplicity. The California Bearing Ratio (CBR) is basically a penetration test, in which a piston having an area of  $19.4 \text{ cm}^2$  is forced to penetrate a sample of soil (or pavement material) at a rate of  $0.127 \text{ cm/min}$ . CBR of the soil is determined as the ratio (expressed as a percentage) between the force that is

necessary to penetrate 0,25cm and the force obtained from a reference material (crushed rock) used originally in California.

It should be noted that if the CBR value at 0,25cm penetration is higher than the CBR value obtained at 0,50cm penetration, then the test is stopped and the CBR value for the material tested is adopted at 0,25cm penetration or vice versa. In this study, since CBR value at 0,50cm penetration was higher than the CBR value at 0,25cm penetration.

Generally speaking, CBR testing of clays gives higher CBR values at 0,25cm penetration. Although WFS is containing bentonite ( a type of clay), CBR values at 0,50cm penetration were greater than CBR values at 0,25cm penetration probably due to cement and lime stabilization.

The CBR test may be carried out on either soaked or unsoaked samples. After a soaking period of 4 days, soaked specimens are supposed to be representative of the most severe conditions that might occur in pavements. However, unsoaked WFS specimens were tested in this study.

The soil specimen on which the test is conducted is confined in a mold which has a 15,2cm in diameter and a 17,8cm in height and compacted at optimum moisture content in accordance with ASTM D 1557.

As the CBR method is a kind of deformation test, then the force – penetration line is linear for small penetrations, and tends to become slightly curved downwards as penetration is increased. This line depends on the nature of the soil, its water content and compaction conditions.

As same material may have even very different stress – strain regime, depending on the circumstances in which it is loaded, a question arises whether loading conditions are representativity. Therefore, a specific stress – strain behaviour obtained in the laboratory has an engineering value only when it matches the real conditions namely in-situ conditions.

Another problem is the variability of test results, which is shown by the great differences obtained by different operators, working correctly on the same soil and using the same technique [22].

A CBR value of 100 is generally considered as an excellent pavement layer. In this study, extreme precaution was taken and all testing was carried out by same apparatus as well as one operator. The results are given in Figure 4.23, Figure 4.24, Figure 4.25, Figure 4.26, and Figure 4.27.

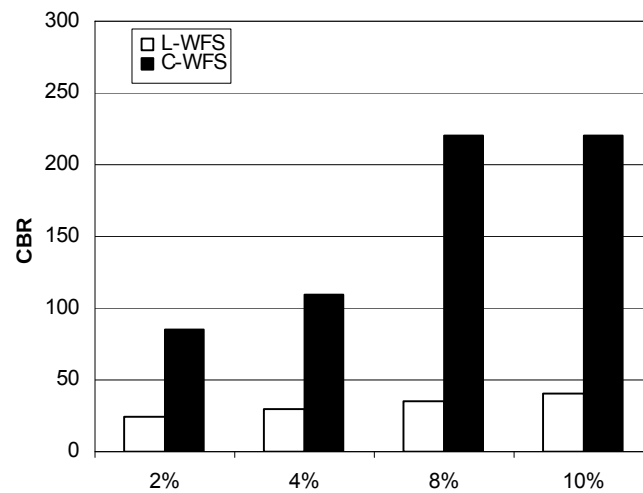


**Figure 4.23 : CBR Values of Samples Cured 7-day.**

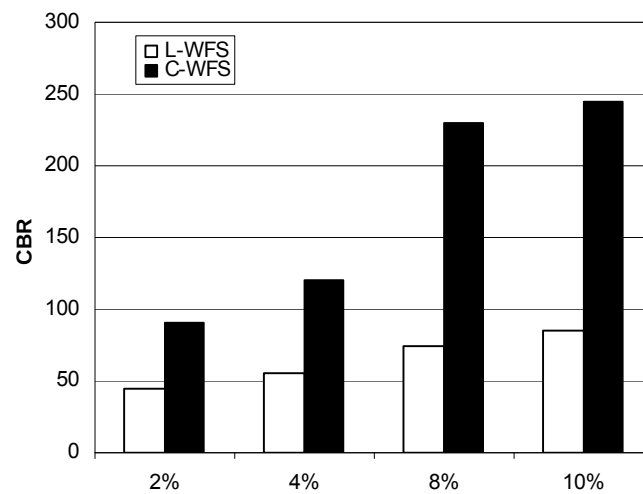


**Figure 4.24 : CBR Values of Samples Cured 14-day.**

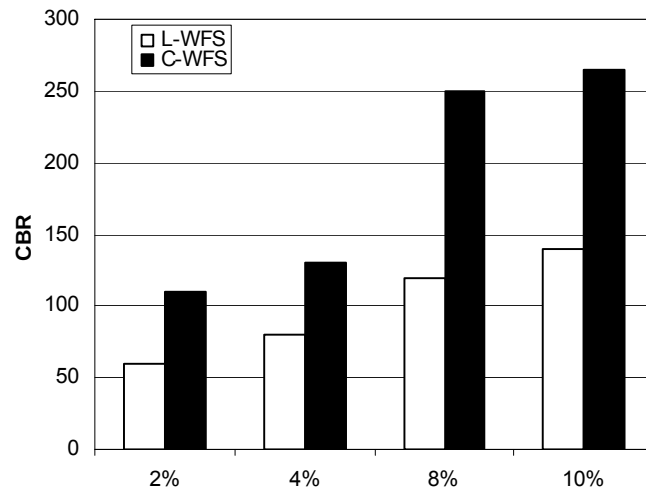


**Figure 4.25 : CBR Values of Samples Cured 28-day.**

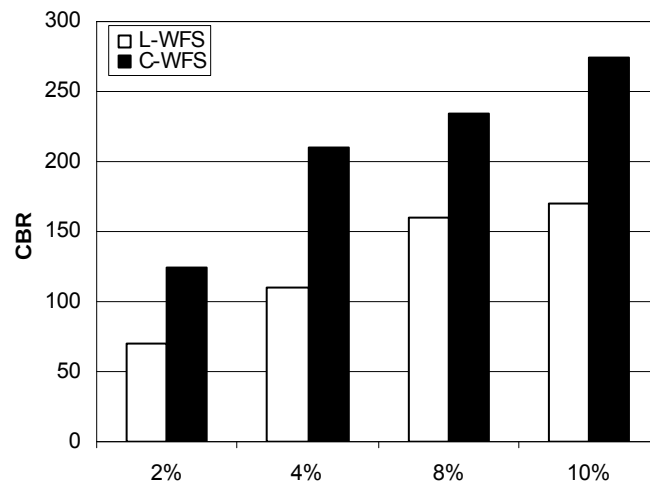


**Figure 4.26 : CBR Values of Samples Cured 3-month.**

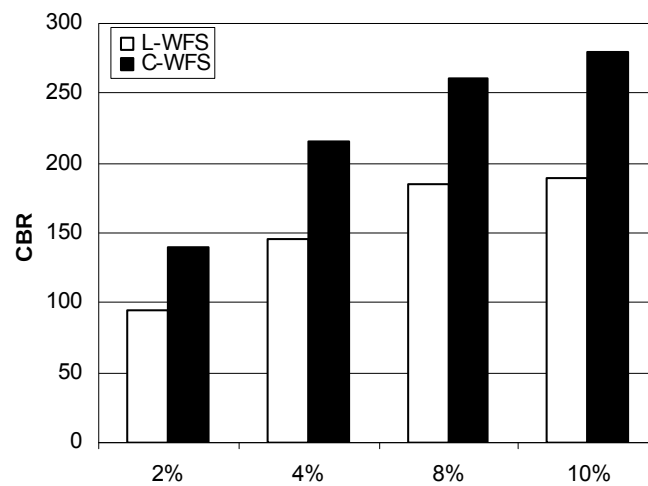


**Figure 4.27 : CBR Values of Samples Cured 6-month.**

## 5. CONCLUSION

Both cement and lime favourable agents in soil stabilization. According to the results, it is apparent that cement is superior to lime as stabilization agent. However, cost of cement stabilization is quite expensive than lime stabilization in Turkey. According to KGM's (General Directorate of Highways in Turkey) 2008 unit price, cost of cement (containing the hauling cost up to distance of 20 Km) is equal to 160\$/ton, whereas cost of hydrated lime (containing the hauling cost up to distance of 20 Km) is equal to 85\$/ton. Therefore, lime stabilization is considered as favourable application aspect of budget. However, according to the results, the unconfined compressive strength of lime stabilized samples is relatively similar and low at 7-day and 14-day cured samples. For 28-day, 3-month, and 6-month cured samples the discrepancies between lime ratios become more apparent, especially 8% and 10% lime stabilized samples increased their strength, yet still relatively low. As expected, cement stabilized samples gained higher strength than lime-stabilized samples in the first 7 days and continued to increase its trend until 6 months. Besides, the ratio of strength gain between 8% and 10% cement and lime stabilized samples are significant especially at 3 and 6 months.

$E_d$  and CBR values are in accord with the UCS values explained above. Particularly, regardless of agent type, amount and cure duration stabilized WFS showed excellent CBR results. 8% and 10% cement stabilized samples having more than doubled the strength that reference crushed rock. Based on the CBR results, it may be said that stabilized WFS could be considered as a quality pavement material.

Although the test results of cement stabilization are superior to lime stabilization, cement stabilized samples; particularly at higher cement ratios might be fragile. This would cause premature cracks in pavement layer and may be reflected to upper layers. Therefore, this drawback of cement stabilization should carefully be investigated and it is beyond the scope of this study. In addition, it is essential that before utilization of WFS as highway material, its possible hazardous effects should be taken into account aspects of humanity and environment.

In conclusion, this study aimed to assess the suitability of WFS as a road material and basic mechanical tests were performed. From the results obtained, WFS is a promising road material provided that further investigations will be carried out utilizing advanced geotechnical testing to establish the most appropriate cement and lime contents.

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## **APPENDIXES**

### **APPENDIX A : Calculation of Dynamic Elasticity Modulus ( $E_d$ ) of WFS Samples**

**Table A.1 :  $E_d$  Values of Cement Stabilized and 7-day Cured Samples.**

| <b>Group I (C-WFS)</b>   |                  |                  |                           |                        |                                 |                                         |
|--------------------------|------------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Cement | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 7-day                    | 2%               | C-WFS-I          | 12,8                      | 69,9                   | 9351                            | 9673,8                                  |
|                          |                  | C-WFS-II         | 12,7                      | 69,4                   | 9339                            |                                         |
|                          |                  | C-WFS-III        | 12,8                      | 66,5                   | 10332                           |                                         |
|                          | 4%               | C-WFS-I          | 12,9                      | 65,2                   | 10916                           | 11077,3                                 |
|                          |                  | C-WFS-II         | 12,7                      | 62,9                   | 11369                           |                                         |
|                          |                  | C-WFS-III        | 12,7                      | 64,1                   | 10947                           |                                         |
|                          | 8%               | C-WFS-I          | 12,6                      | 52,3                   | 16186                           | 16098,2                                 |
|                          |                  | C-WFS-II         | 12,7                      | 54,5                   | 15143                           |                                         |
|                          |                  | C-WFS-III        | 12,9                      | 52,3                   | 16966                           |                                         |
|                          | 10%              | C-WFS-I          | 12,8                      | 52,5                   | 16577                           | 17504,7                                 |
|                          |                  | C-WFS-II         | 12,8                      | 49,5                   | 18647                           |                                         |
|                          |                  | C-WFS-III        | 12,5                      | 50,2                   | 17291                           |                                         |

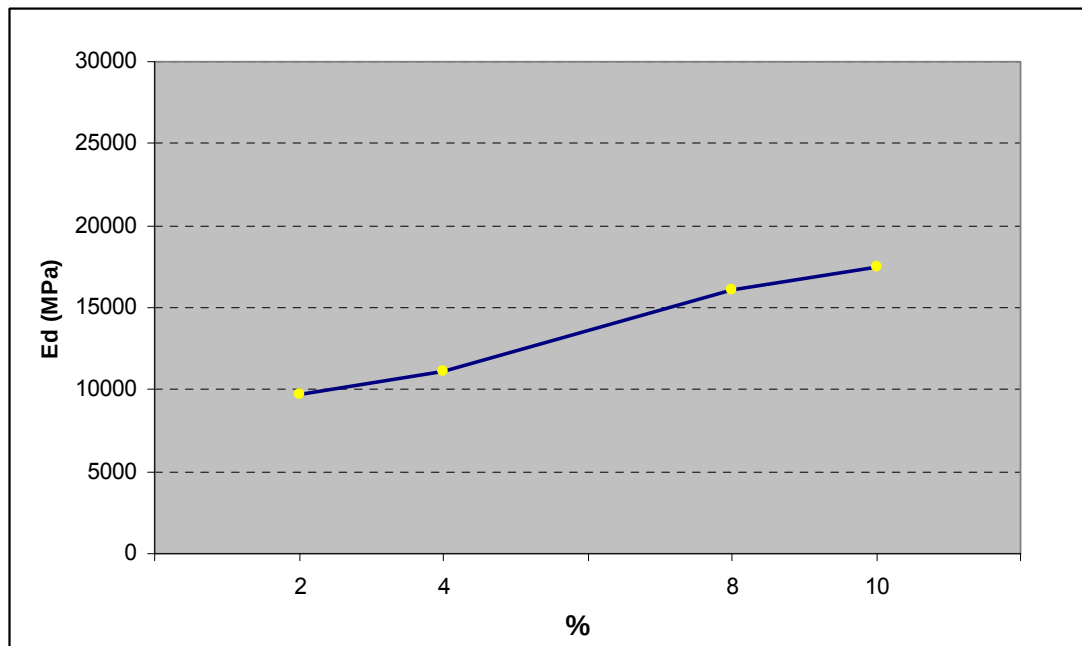


**Figure A.1 :  $E_d$  Values of Cement Stabilized and 7-day Cured Samples.**

**Table A.2 :**  $E_d$  Values of Lime Stabilized and 7-day Cured Samples.

| Group II (L-WFS)         |                |                  |                           |                        |                                 |                                         |
|--------------------------|----------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Lime | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 7-day                    | 2%             | L-WFS-I          | 12,3                      | 76,2                   | 7266                            | 7984                                    |
|                          |                | L-WFS-II         | 12,8                      | 75,6                   | 7994                            |                                         |
|                          |                | L-WFS-III        | 12,8                      | 72,5                   | 8692                            |                                         |
|                          | 4%             | L-WFS-I          | 12,7                      | 76,0                   | 7787                            | 8470                                    |
|                          |                | L-WFS-II         | 13,0                      | 74,2                   | 8560                            |                                         |
|                          |                | L-WFS-III        | 12,8                      | 71,0                   | 9064                            |                                         |
|                          | 8%             | L-WFS-I          | 12,8                      | 61,2                   | 12199                           | 12296                                   |
|                          |                | L-WFS-II         | 12,8                      | 60,8                   | 12360                           |                                         |
|                          |                | L-WFS-III        | 12,7                      | 60,4                   | 12329                           |                                         |
|                          | 10%            | L-WFS-I          | 12,8                      | 56,0                   | 14569                           | 15345                                   |
|                          |                | L-WFS-II         | 12,6                      | 53,4                   | 15526                           |                                         |
|                          |                | L-WFS-III        | 12,6                      | 52,7                   | 15941                           |                                         |

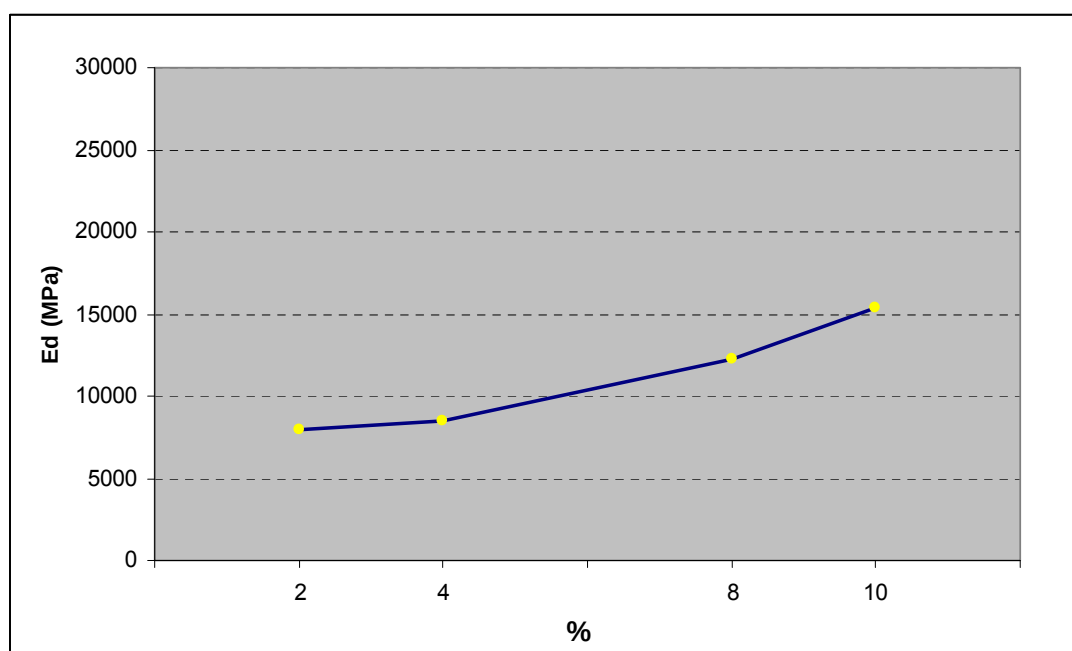


**Figure A.2 :**  $E_d$  Values of Lime Stabilized and 7-day Cured Samples.

**Table A.3 :**  $E_d$  Values of Cement Stabilized and 14-day Cured Samples.

| Group I (C-WFS)          |                  |                  |                           |                        |                                 |                                         |
|--------------------------|------------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Cement | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 14-day                   | 2%               | C-WFS-I          | 12,5                      | 65,1                   | 10281                           | 10212                                   |
|                          |                  | C-WFS-II         | 12,8                      | 68,6                   | 9709                            |                                         |
|                          |                  | C-WFS-III        | 12,7                      | 65,0                   | 10646                           |                                         |
|                          | 4%               | C-WFS-I          | 12,7                      | 62,4                   | 11551                           | 11910                                   |
|                          |                  | C-WFS-II         | 13,0                      | 61,0                   | 12666                           |                                         |
|                          |                  | C-WFS-III        | 12,8                      | 63,0                   | 11512                           |                                         |
|                          | 8%               | C-WFS-I          | 13,0                      | 48,0                   | 20455                           | 20327                                   |
|                          |                  | C-WFS-II         | 12,7                      | 47,1                   | 20275                           |                                         |
|                          |                  | C-WFS-III        | 12,8                      | 47,5                   | 20250                           |                                         |
|                          | 10%              | C-WFS-I          | 12,7                      | 46,7                   | 20624                           | 21848                                   |
|                          |                  | C-WFS-II         | 12,6                      | 44,4                   | 22458                           |                                         |
|                          |                  | C-WFS-III        | 12,8                      | 45,1                   | 22463                           |                                         |

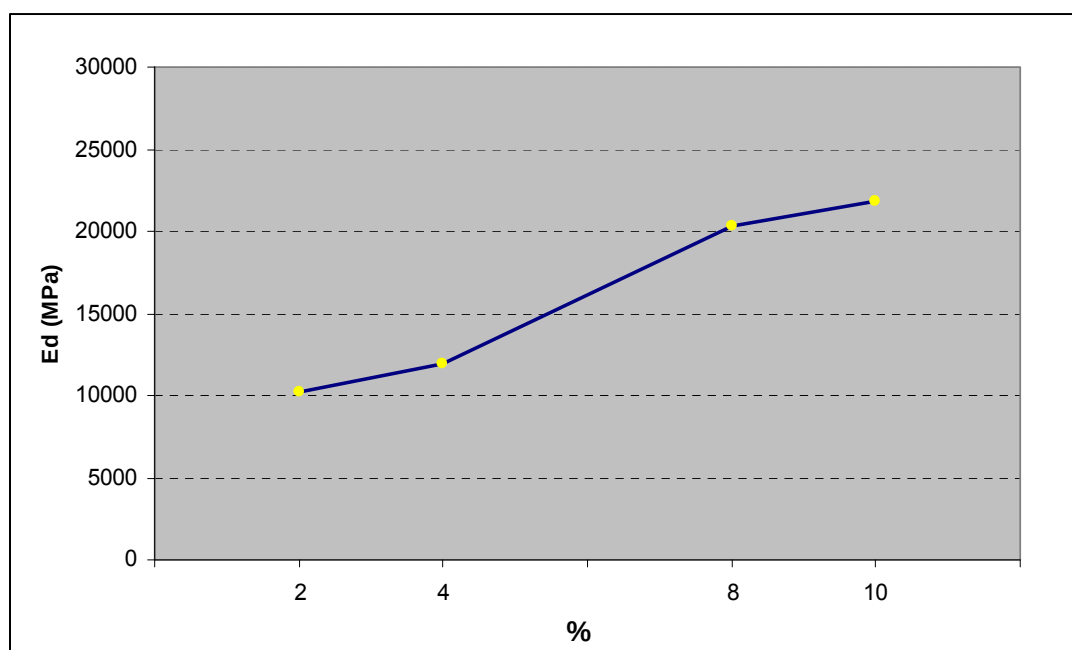


**Figure A.3 :**  $E_d$  Values of Cement Stabilized and 14-day Cured Samples.

**Table A.4 :**  $E_d$  Values of Lime Stabilized and 14-day Cured Samples.

| Group II (L-WFS)         |                |                  |                           |                        |                                 |                                         |
|--------------------------|----------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Lime | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 14-day                   | 2%             | L-WFS-I          | 12,8                      | 70,9                   | 9089                            | 8912                                    |
|                          |                | L-WFS-II         | 12,7                      | 73,0                   | 8440                            |                                         |
|                          |                | L-WFS-III        | 13,1                      | 72,1                   | 9206                            |                                         |
|                          | 4%             | L-WFS-I          | 13,2                      | 70,1                   | 9888                            | 9905                                    |
|                          |                | L-WFS-II         | 13,0                      | 68,7                   | 9986                            |                                         |
|                          |                | L-WFS-III        | 13,0                      | 69,2                   | 9842                            |                                         |
|                          | 8%             | L-WFS-I          | 13,0                      | 60,2                   | 13004                           | 13658                                   |
|                          |                | L-WFS-II         | 12,9                      | 57,8                   | 13891                           |                                         |
|                          |                | L-WFS-III        | 13,1                      | 58,3                   | 14080                           |                                         |
|                          | 10%            | L-WFS-I          | 12,8                      | 55,0                   | 15104                           | 15016                                   |
|                          |                | L-WFS-II         | 12,8                      | 55,5                   | 14833                           |                                         |
|                          |                | L-WFS-III        | 12,5                      | 53,7                   | 15110                           |                                         |

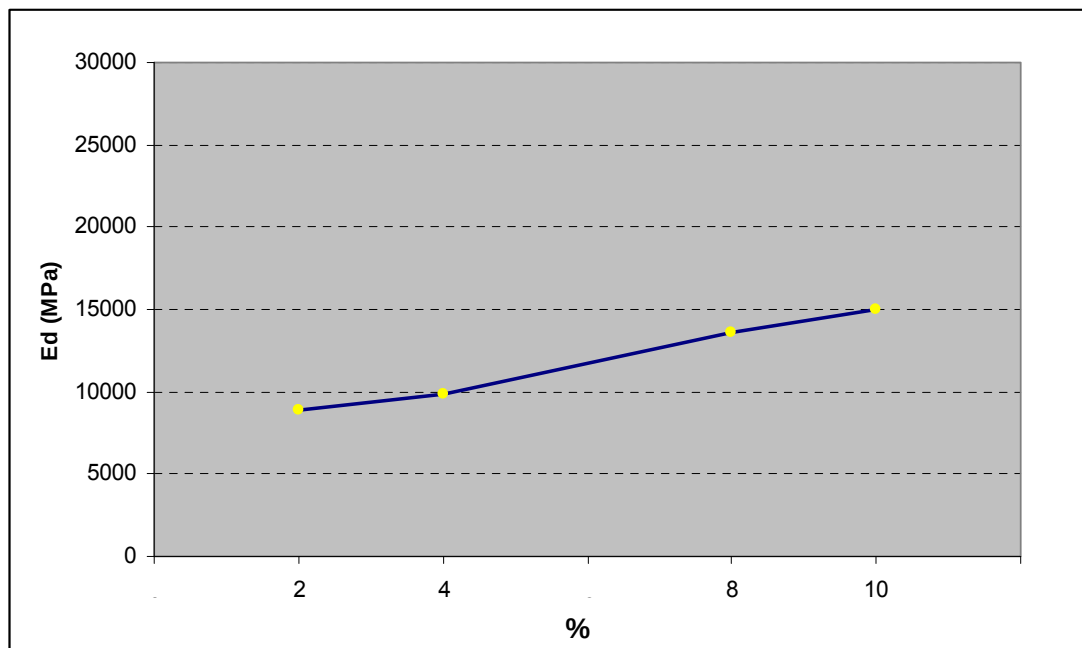


**Figure A.4 :**  $E_d$  Values of Lime Stabilized and 14-day Cured Samples.

**Table A.5 :**  $E_d$  Values of Cement Stabilized and 28-day Cured Samples.

| Group I (C-WFS)          |                  |                  |                           |                        |                                 |                                         |
|--------------------------|------------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Cement | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 28-day                   | 2%               | C-WFS-I          | 13,2                      | 65,1                   | 11465                           | 11264                                   |
|                          |                  | C-WFS-II         | 13,0                      | 68,1                   | 10162                           |                                         |
|                          |                  | C-WFS-III        | 13,2                      | 63,2                   | 12165                           |                                         |
|                          | 4%               | C-WFS-I          | 13,0                      | 53,7                   | 16343                           | 16553                                   |
|                          |                  | C-WFS-II         | 13,2                      | 52,7                   | 17495                           |                                         |
|                          |                  | C-WFS-III        | 13,1                      | 55,0                   | 15820                           |                                         |
|                          | 8%               | C-WFS-I          | 13,2                      | 44,1                   | 24984                           | 25085                                   |
|                          |                  | C-WFS-II         | 13,2                      | 44,2                   | 24871                           |                                         |
|                          |                  | C-WFS-III        | 13,4                      | 44,4                   | 25400                           |                                         |
|                          | 10%              | C-WFS-I          | 12,6                      | 43,8                   | 23078                           | 25166                                   |
|                          |                  | C-WFS-II         | 12,6                      | 41,0                   | 26337                           |                                         |
|                          |                  | C-WFS-III        | 12,6                      | 41,2                   | 26082                           |                                         |

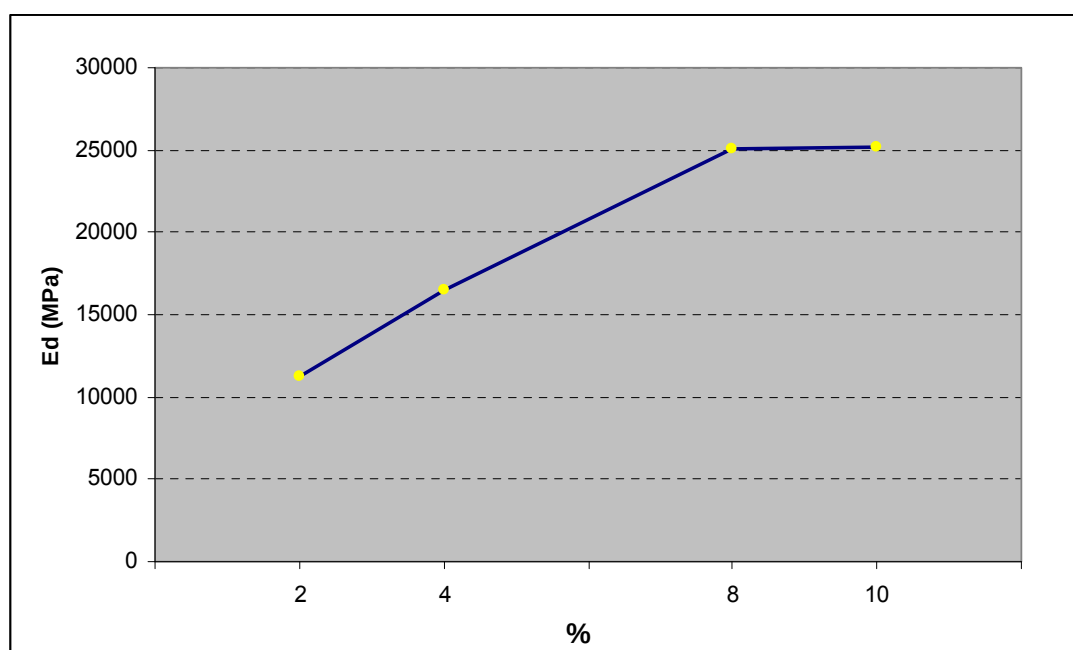


**Figure A.5 :**  $E_d$  Values of Cement Stabilized and 28-day Cured Samples.

**Table A.6 :  $E_d$  Values of Lime Stabilized and 28-day Cured Samples.**

| Group II (L-WFS)         |                |                  |                           |                        |                                 |                                         |
|--------------------------|----------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Lime | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 28-day                   | 2%             | L-WFS-I          | 13,2                      | 72,0                   | 9373                            | 9393                                    |
|                          |                | L-WFS-II         | 13,0                      | 71,7                   | 9167                            |                                         |
|                          |                | L-WFS-III        | 13,2                      | 71,0                   | 9639                            |                                         |
|                          | 4%             | L-WFS-I          | 13,0                      | 65,5                   | 10985                           | 11789                                   |
|                          |                | L-WFS-II         | 13,2                      | 63,6                   | 12012                           |                                         |
|                          |                | L-WFS-III        | 13,1                      | 62,2                   | 12370                           |                                         |
|                          | 8%             | L-WFS-I          | 13,2                      | 58,8                   | 14054                           | 14687                                   |
|                          |                | L-WFS-II         | 13,2                      | 54,4                   | 16419                           |                                         |
|                          |                | L-WFS-III        | 13,2                      | 59,8                   | 13588                           |                                         |
|                          | 10%            | L-WFS-I          | 13,2                      | 56,0                   | 15494                           | 15496                                   |
|                          |                | L-WFS-II         | 13,2                      | 55,6                   | 15718                           |                                         |
|                          |                | L-WFS-III        | 13,2                      | 56,4                   | 15275                           |                                         |

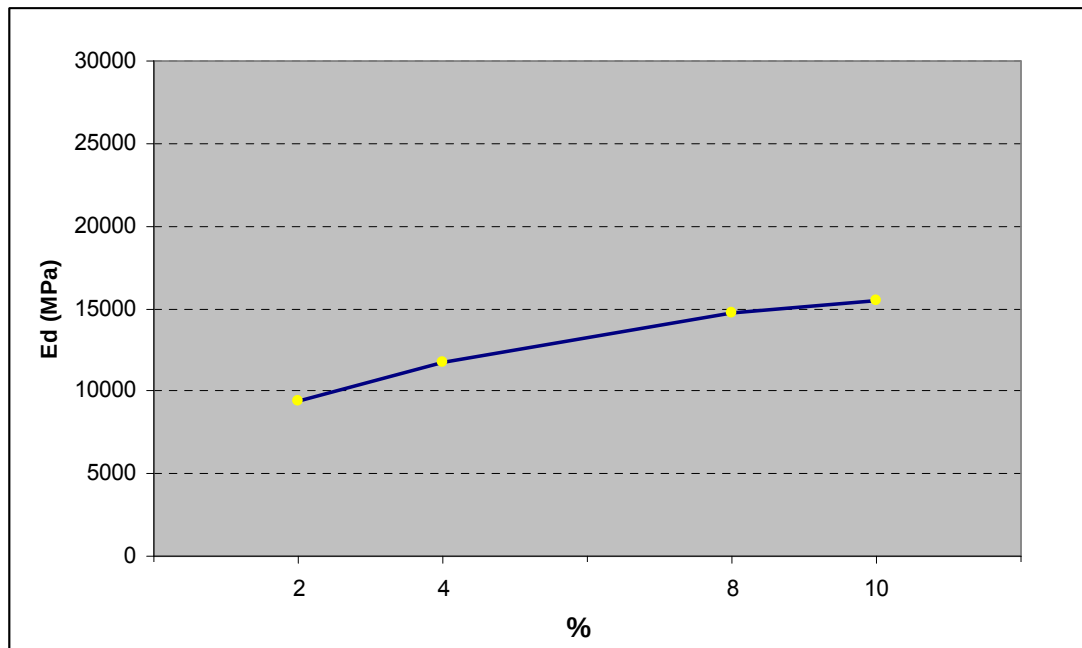


**Figure A.6 :  $E_d$  Values of Lime Stabilized and 28-day Cured Samples.**

**Table A.7 :  $E_d$  Values of Cement Stabilized and 3-month Cured Samples.**

| Group I (C-WFS)          |                  |                  |                           |                        |                                 |                                         |
|--------------------------|------------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Cement | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 3-month                  | 2%               | C-WFS-I          | 12,6                      | 53,0                   | 15761                           | 14185                                   |
|                          |                  | C-WFS-II         | 11,4                      | 55,0                   | 11981                           |                                         |
|                          |                  | C-WFS-III        | 12,1                      | 52,5                   | 14813                           |                                         |
|                          | 4%               | C-WFS-I          | 12,8                      | 49,0                   | 19029                           | 17652                                   |
|                          |                  | C-WFS-II         | 12,8                      | 51,4                   | 17294                           |                                         |
|                          |                  | C-WFS-III        | 12,7                      | 52,0                   | 16634                           |                                         |
|                          | 8%               | C-WFS-I          | 12,5                      | 41,0                   | 25921                           | 25653                                   |
|                          |                  | C-WFS-II         | 12,6                      | 43,4                   | 23505                           |                                         |
|                          |                  | C-WFS-III        | 12,6                      | 40,1                   | 27533                           |                                         |
|                          | 10%              | C-WFS-I          | 12,9                      | 41,5                   | 26945                           | 26763                                   |
|                          |                  | C-WFS-II         | 12,7                      | 41,1                   | 26627                           |                                         |
|                          |                  | C-WFS-III        | 13,0                      | 42,0                   | 26717                           |                                         |

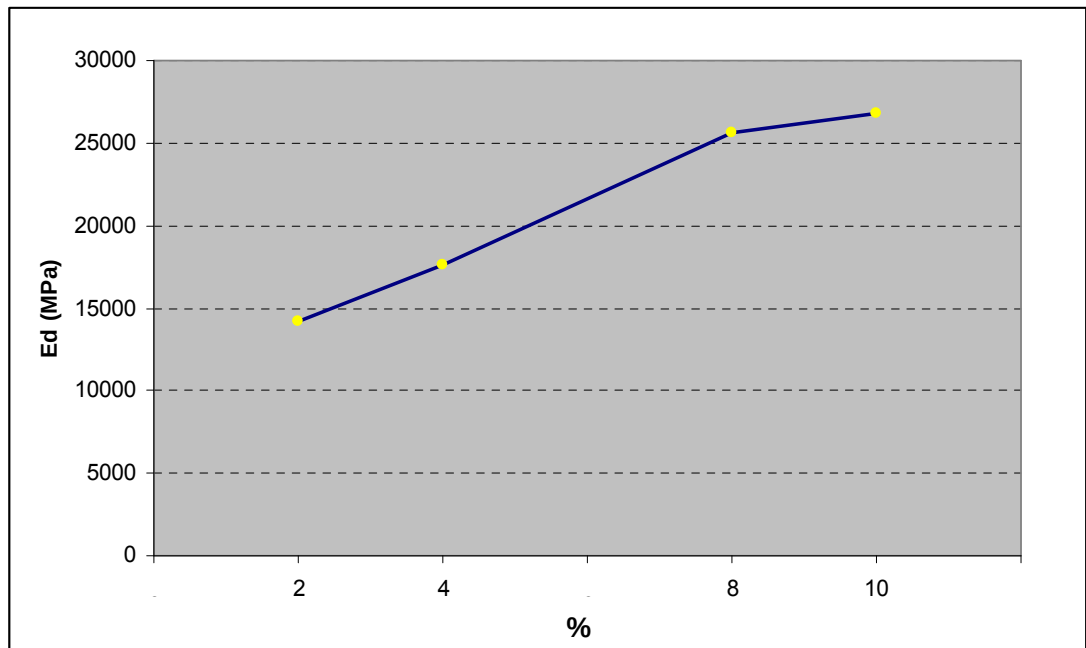


**Figure A.7 :  $E_d$  Values of Cement Stabilized and 3-month Cured Samples.**

**Table A.8 :  $E_d$  Values of Lime Stabilized and 3-month Cured Samples.**

| Group II (L-WFS)         |                |                  |                           |                        |                                 |                                         |
|--------------------------|----------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Lime | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 3-month                  | 2%             | L-WFS-I          | 12,4                      | 57,8                   | 12835                           | 13467                                   |
|                          |                | L-WFS-II         | 12,6                      | 58,4                   | 12981                           |                                         |
|                          |                | L-WFS-III        | 11,0                      | 48,1                   | 14585                           |                                         |
|                          | 4%             | L-WFS-I          | 12,6                      | 50,0                   | 17709                           | 16874                                   |
|                          |                | L-WFS-II         | 12,6                      | 53,0                   | 15761                           |                                         |
|                          |                | L-WFS-III        | 12,4                      | 50,0                   | 17151                           |                                         |
|                          | 8%             | L-WFS-I          | 12,5                      | 45,7                   | 20863                           | 19594                                   |
|                          |                | L-WFS-II         | 12,5                      | 47,4                   | 19394                           |                                         |
|                          |                | L-WFS-III        | 12,5                      | 48,5                   | 18524                           |                                         |
|                          | 10%            | L-WFS-I          | 12,9                      | 45,7                   | 22220                           | 21742                                   |
|                          |                | L-WFS-II         | 12,9                      | 47,2                   | 20830                           |                                         |
|                          |                | L-WFS-III        | 13,0                      | 46,1                   | 22176                           |                                         |

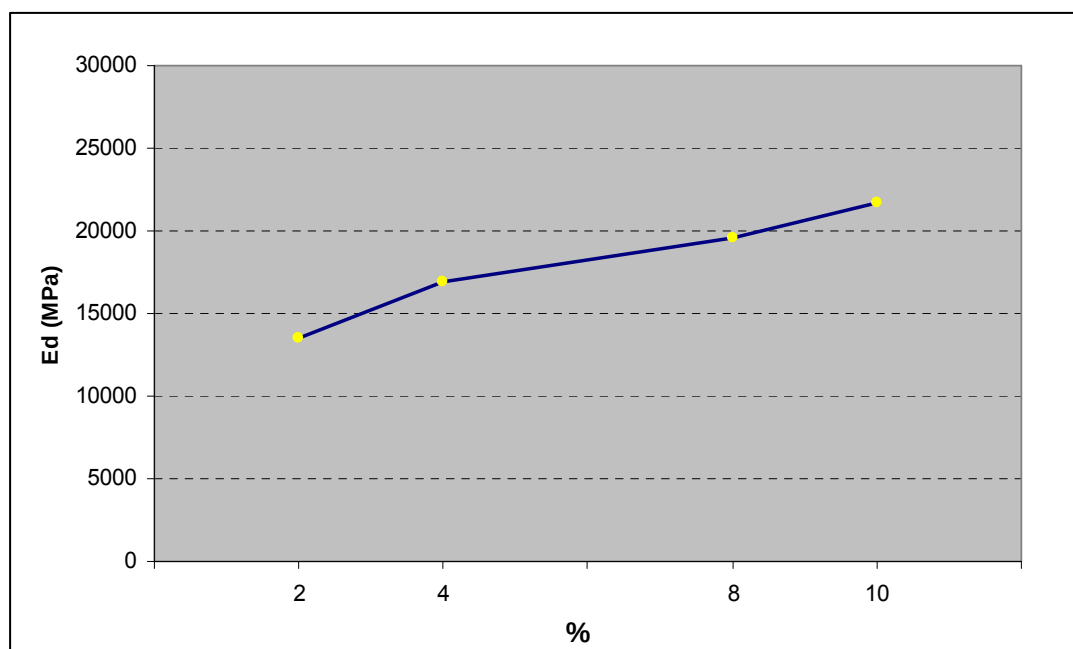


**Figure A.8 :  $E_d$  Values of Lime Stabilized and 3-month Cured Samples.**

**Table A.9 :  $E_d$  Values of Cement Stabilized and 6-month Cured Samples.**

| Group I (C-WFS)          |                  |                  |                           |                        |                                 |                                         |
|--------------------------|------------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Cement | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 6-month                  | 2%               | C-WFS-I          | 12,0                      | 52,3                   | 14681                           | 15810                                   |
|                          |                  | C-WFS-II         | 12,0                      | 51,2                   | 15319                           |                                         |
|                          |                  | C-WFS-III        | 12,5                      | 50,0                   | 17429                           |                                         |
|                          | 4%               | C-WFS-I          | 12,9                      | 49,0                   | 19328                           | 18818                                   |
|                          |                  | C-WFS-II         | 12,4                      | 50,0                   | 17151                           |                                         |
|                          |                  | C-WFS-III        | 12,9                      | 48,2                   | 19975                           |                                         |
|                          | 8%               | C-WFS-I          | 12,9                      | 41,0                   | 27606                           | 28138                                   |
|                          |                  | C-WFS-II         | 12,5                      | 42,2                   | 24468                           |                                         |
|                          |                  | C-WFS-III        | 12,6                      | 37,0                   | 32340                           |                                         |
|                          | 10%              | C-WFS-I          | 12,9                      | 40,1                   | 28859                           | 29320                                   |
|                          |                  | C-WFS-II         | 12,5                      | 40,2                   | 26963                           |                                         |
|                          |                  | C-WFS-III        | 12,9                      | 38,0                   | 32137                           |                                         |

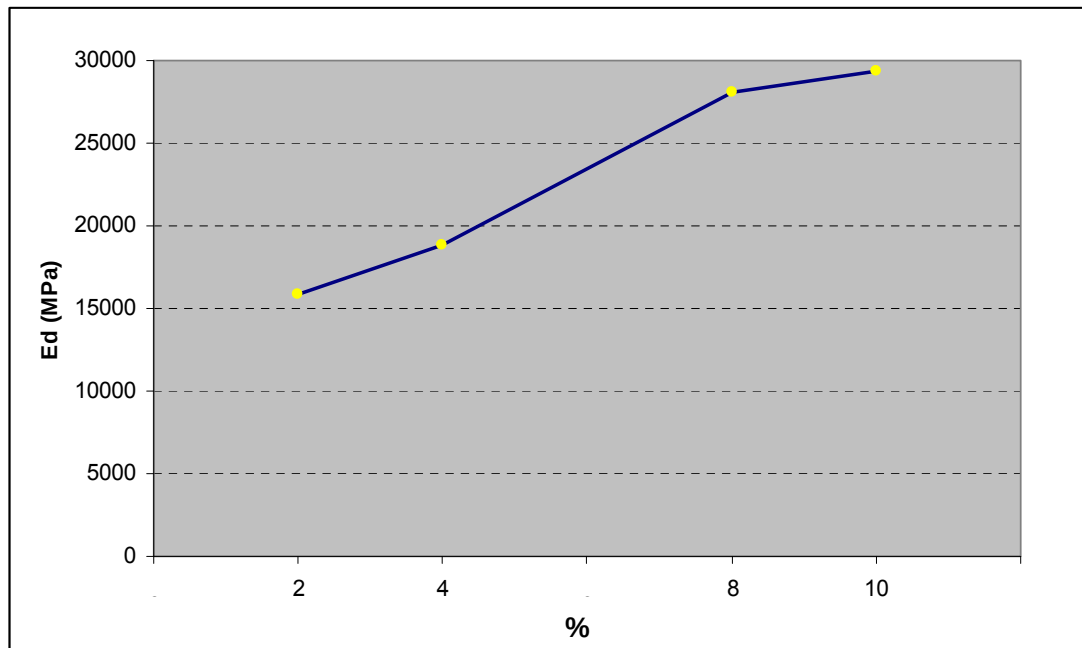


**Figure A.9 :  $E_d$  Values of Cement Stabilized and 6-month Cured Samples.**

**Table A.10 :**  $E_d$  Values of Lime Stabilized and 6-month Cured Samples.

| Group II (L-WFS)         |                |                  |                           |                        |                                 |                                         |
|--------------------------|----------------|------------------|---------------------------|------------------------|---------------------------------|-----------------------------------------|
| Cure Duration of Samples | Amount of Lime | Range of Samples | Dimension of Samples (cm) | Pulse Delay ( $\mu$ s) | Dynmaic Elasticity Modulus(MPa) | Average Dynmaic Elasticity Modulus(MPa) |
| 6-month                  | 2%             | L-WFS-I          | 12,9                      | 55,0                   | 15341                           | 15176                                   |
|                          |                | L-WFS-II         | 12,5                      | 56,7                   | 13553                           |                                         |
|                          |                | L-WFS-III        | 12,7                      | 52,0                   | 16634                           |                                         |
|                          | 4%             | L-WFS-I          | 12,9                      | 51,2                   | 17703                           | 17266                                   |
|                          |                | L-WFS-II         | 12,8                      | 50,0                   | 18276                           |                                         |
|                          |                | L-WFS-III        | 12,6                      | 52,9                   | 15821                           |                                         |
|                          | 8%             | L-WFS-I          | 12,7                      | 45,0                   | 22212                           | 21431                                   |
|                          |                | L-WFS-II         | 12,7                      | 46,2                   | 21073                           |                                         |
|                          |                | L-WFS-III        | 12,9                      | 47,0                   | 21008                           |                                         |
|                          | 10%            | L-WFS-I          | 12,8                      | 43,0                   | 24710                           | 24773                                   |
|                          |                | L-WFS-II         | 12,5                      | 42,0                   | 24701                           |                                         |
|                          |                | L-WFS-III        | 13,0                      | 43,5                   | 24906                           |                                         |

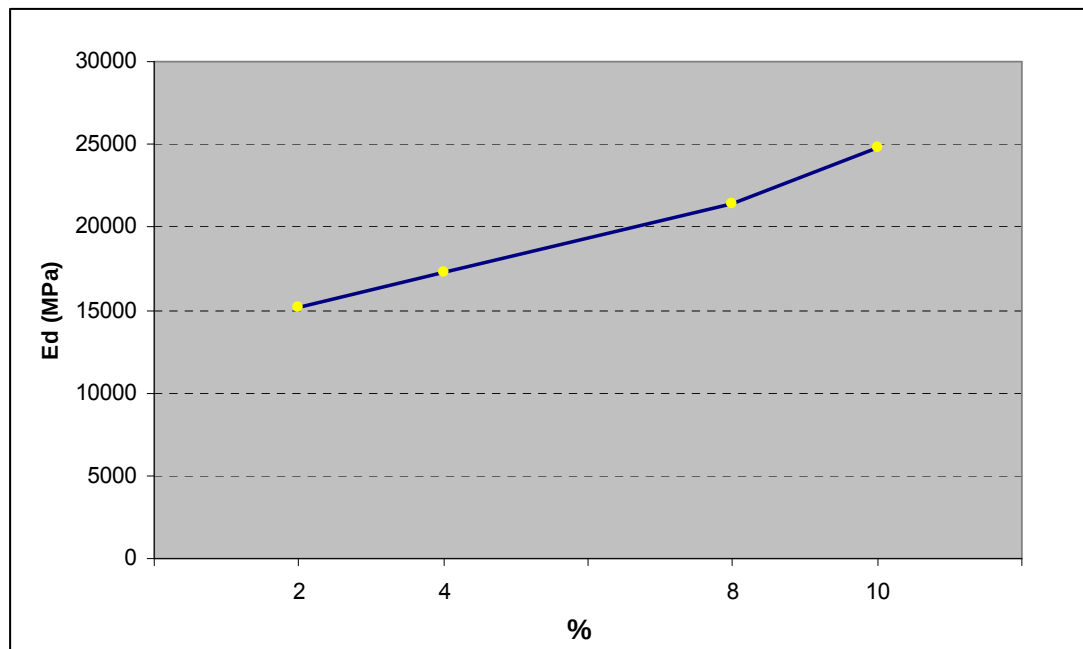


**Figure A.10 :**  $E_d$  Values of Lime Stabilized and 6-month Cured Samples.

## **APPENDIX B : Calculation of Elasticity Modulus (E) of WFS Samples**

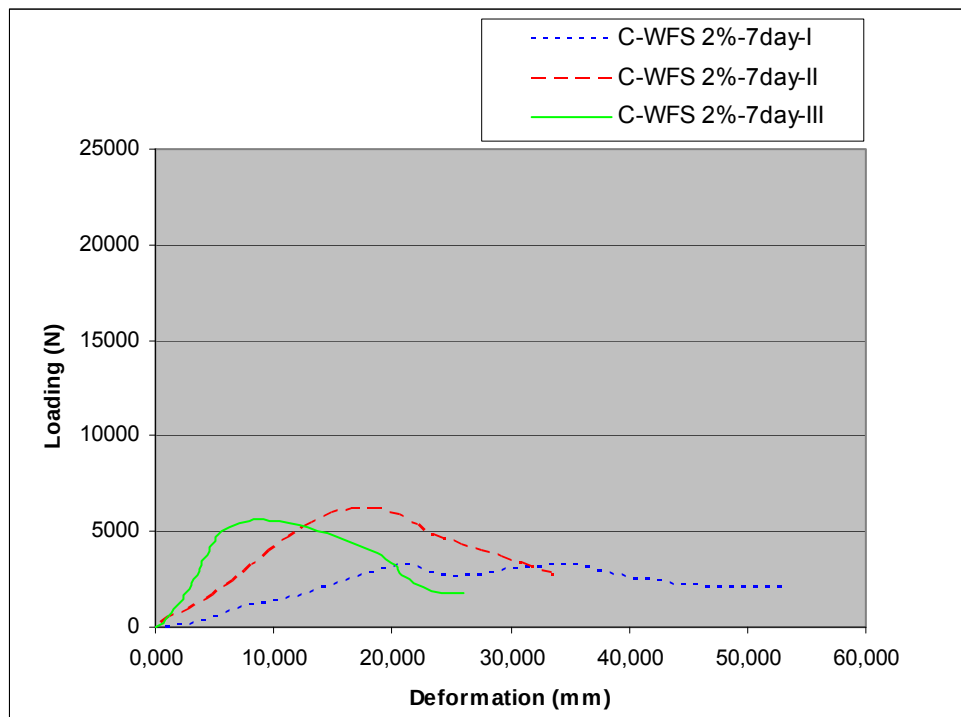


**Figure B.1 :** Loading – Deformation Diagram of C-WFS 2%-7day Samples.

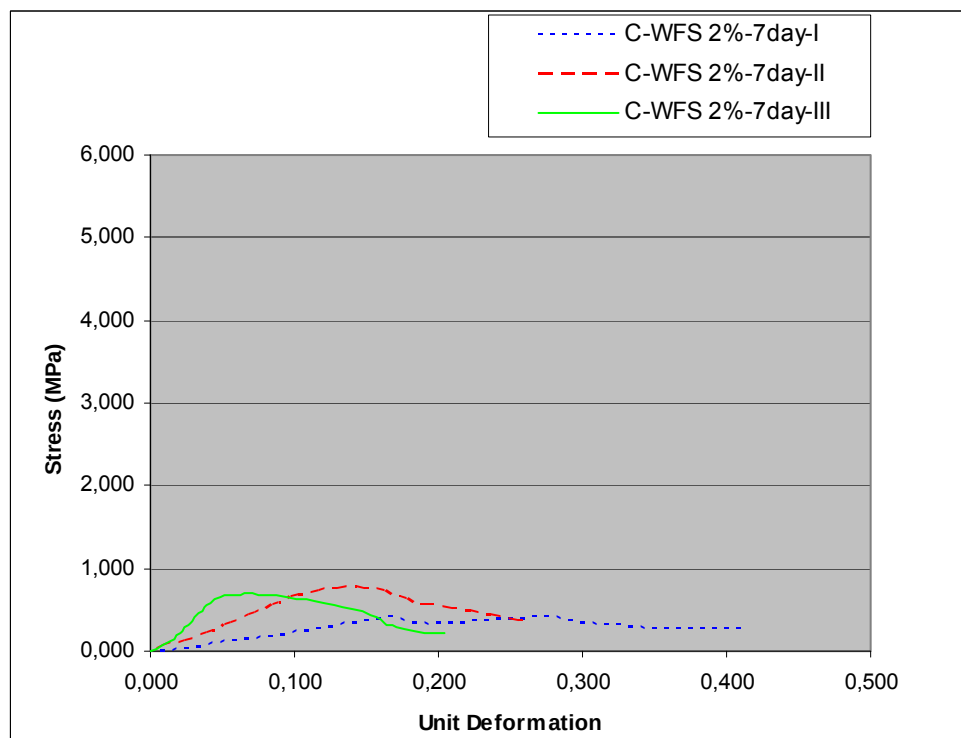


**Figure B.2 :** Stress – Unit Deformation Diagram of C-WFS 2%-7day Samples.

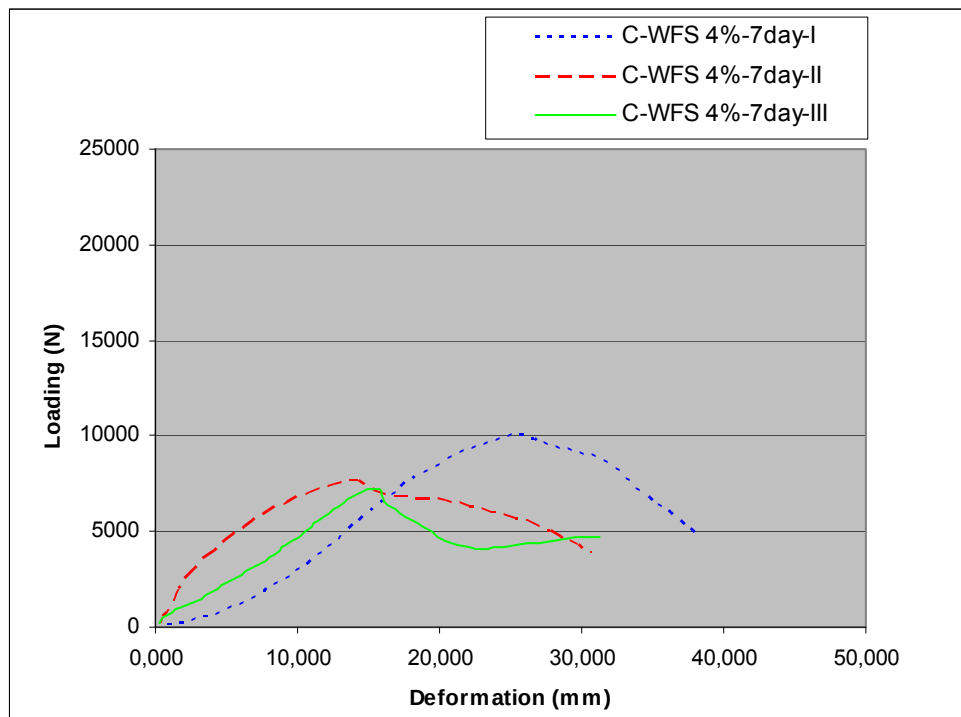


**Figure B.3 :** Loading – Deformation Diagram of C-WFS 4%-7day Samples.

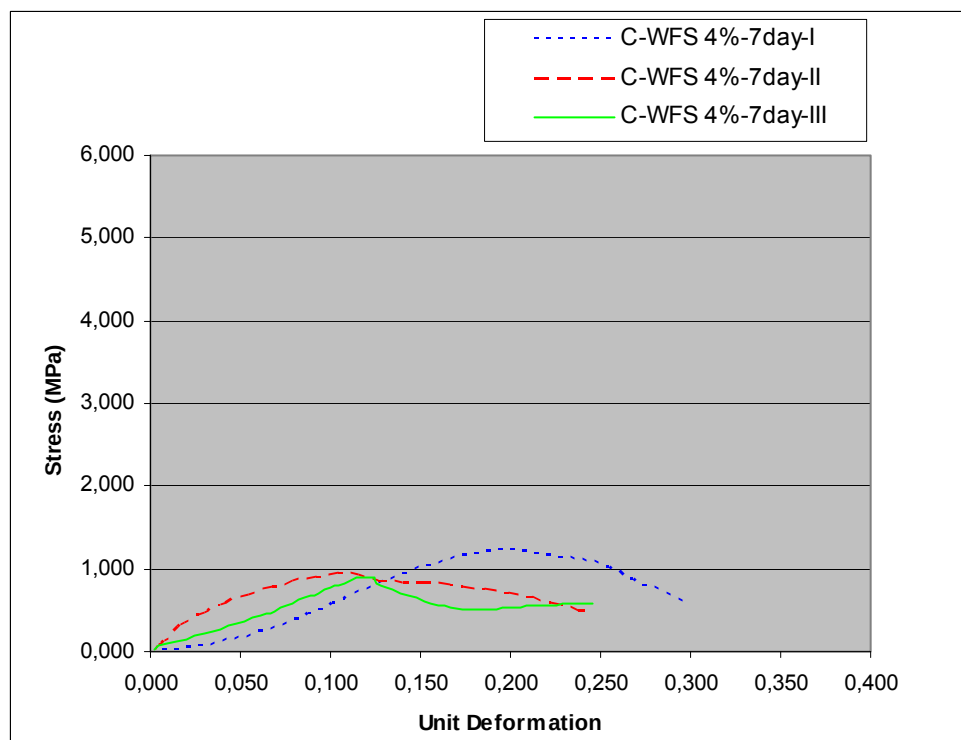


**Figure B.4 :** Stress – Unit Deformation Diagram of C-WFS 4%-7day Samples.

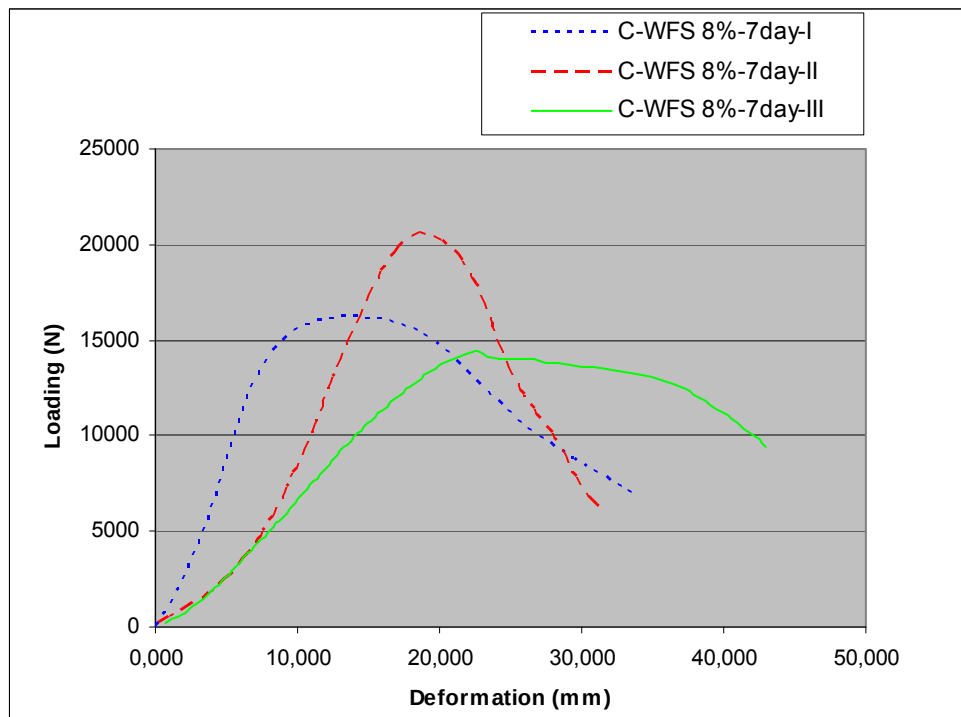


**Figure B.5 :** Loading – Deformation Diagram of C-WFS 8%-7day Samples.

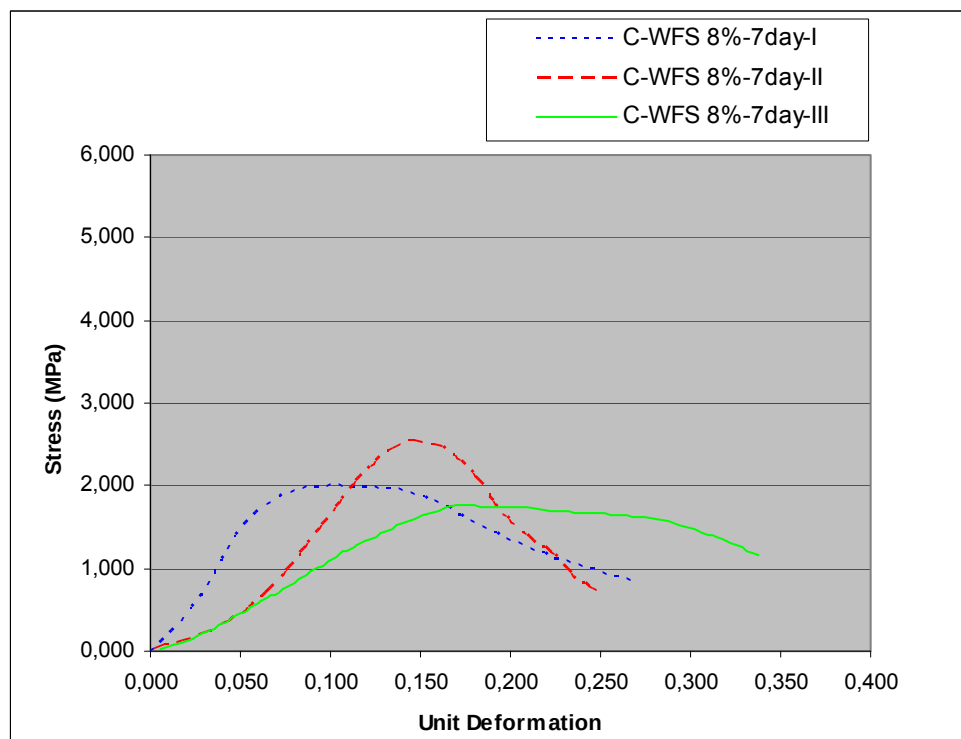


**Figure B.6 :** Stress – Unit Deformation Diagram of C-WFS 8%-7day Samples.

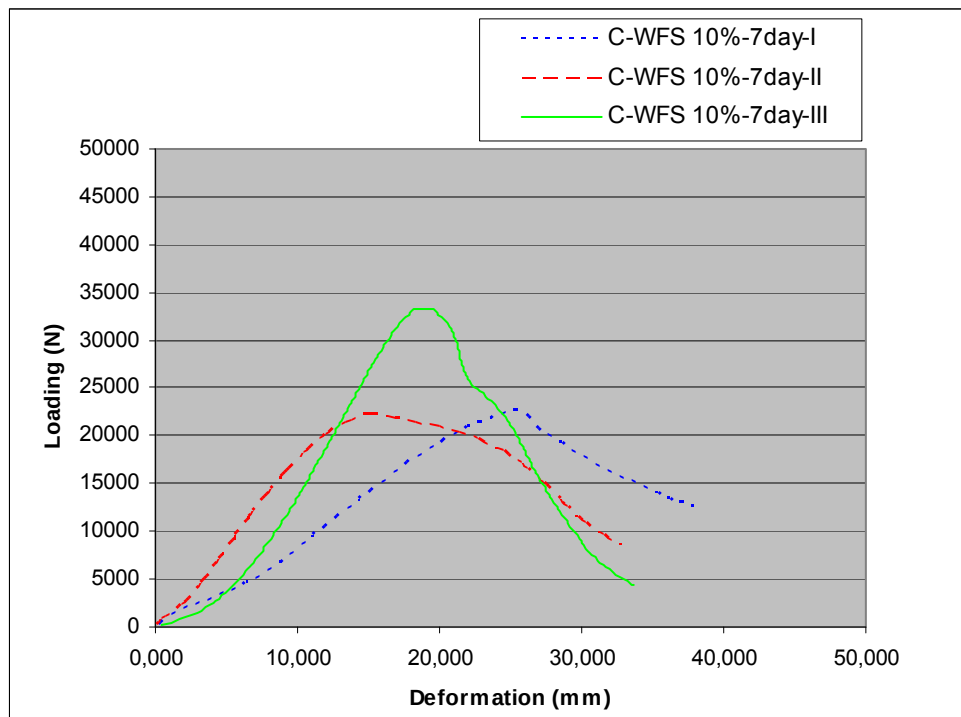


**Figure B.7 :** Loading – Deformation Diagram of C-WFS 10%-7day Samples.

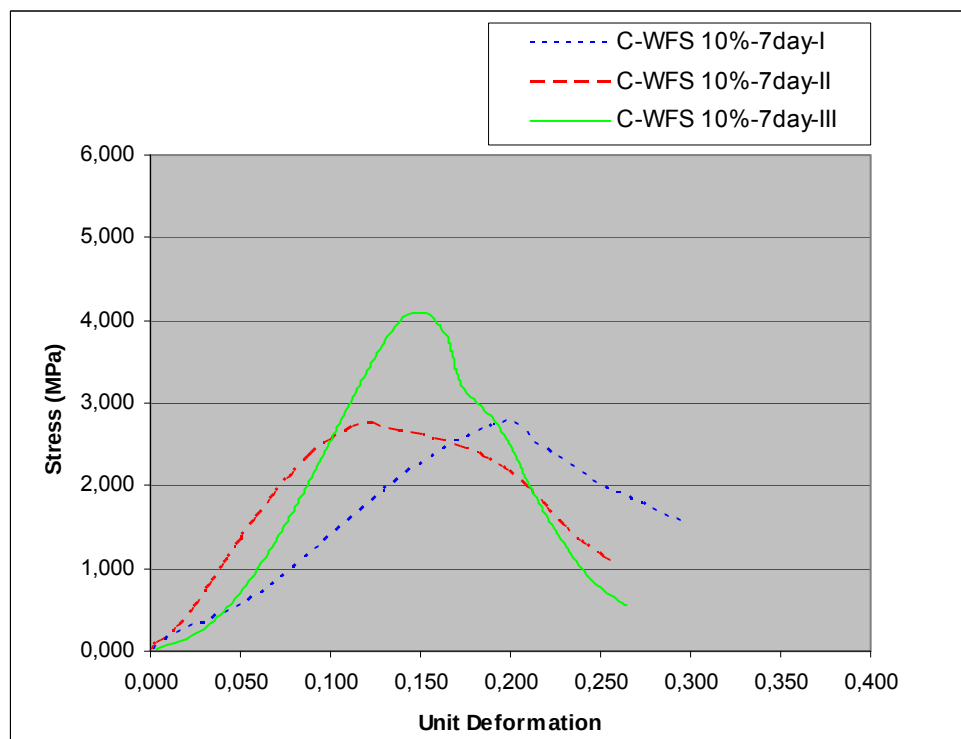


**Figure B.8 :** Stress – Unit Deformation Diagram of C-WFS 10%-7day Samples.

**Table B.1 : E Values of Cement Stabilized and 7-day Cured Samples.**

| Amount of Additives                    | Definition of Sample  | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|----------------------------------------|-----------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Cement  | C-WFS 2%-7day-I       | 34,944                           | 3261,978                      | 0,274                              | 0,402                          | 2,937                    |
|                                        | C-WFS 2%-7day-II      | 17,334                           | 6219,259                      | 0,136                              | 0,767                          | 11,281                   |
|                                        | C-WFS 2%-7day-III     | 8,753                            | 5600,687                      | 0,069                              | 0,691                          | 20,024                   |
| <b>Average Values</b>                  | <b>C-WFS 2%-7day</b>  | <b>20,344</b>                    | <b>5027,308</b>               | <b>0,160</b>                       | <b>0,620</b>                   | <b>11,414</b>            |
| WFS Samples Stabilized With 4% Cement  | C-WFS 4%-7day-I       | 25,840                           | 10077,700                     | 0,203                              | 1,243                          | 12,247                   |
|                                        | C-WFS 4%-7day-II      | 14,128                           | 7634,732                      | 0,111                              | 0,942                          | 16,968                   |
|                                        | C-WFS 4%-7day-III     | 14,929                           | 7260,624                      | 0,117                              | 0,896                          | 15,309                   |
| <b>Average Values</b>                  | <b>C-WFS 4%-7day</b>  | <b>18,299</b>                    | <b>8324,352</b>               | <b>0,144</b>                       | <b>1,027</b>                   | <b>14,841</b>            |
| WFS Samples Stabilized With 8% Cement  | C-WFS 8%-7day-I       | 13,164                           | 16198,560                     | 0,103                              | 1,998                          | 38,796                   |
|                                        | C-WFS 8%-7day-II      | 18,648                           | 20564,520                     | 0,146                              | 2,537                          | 34,747                   |
|                                        | C-WFS 8%-7day-III     | 22,523                           | 14410,110                     | 0,177                              | 1,777                          | 20,079                   |
| <b>Average Values</b>                  | <b>C-WFS 8%-7day</b>  | <b>18,112</b>                    | <b>17057,730</b>              | <b>0,142</b>                       | <b>2,104</b>                   | <b>31,208</b>            |
| WFS Samples Stabilized With 10% Cement | C-WFS 10%-7day-I      | 25,597                           | 22494,690                     | 0,202                              | 2,775                          | 27,471                   |
|                                        | C-WFS 10%-7day-II     | 15,617                           | 22271,650                     | 0,123                              | 2,747                          | 44,668                   |
|                                        | C-WFS 10%-7day-III    | 19,259                           | 33226,200                     | 0,152                              | 4,098                          | 53,925                   |
| <b>Average Values</b>                  | <b>C-WFS 10%-7day</b> | <b>20,158</b>                    | <b>25997,513</b>              | <b>0,159</b>                       | <b>3,207</b>                   | <b>42,022</b>            |

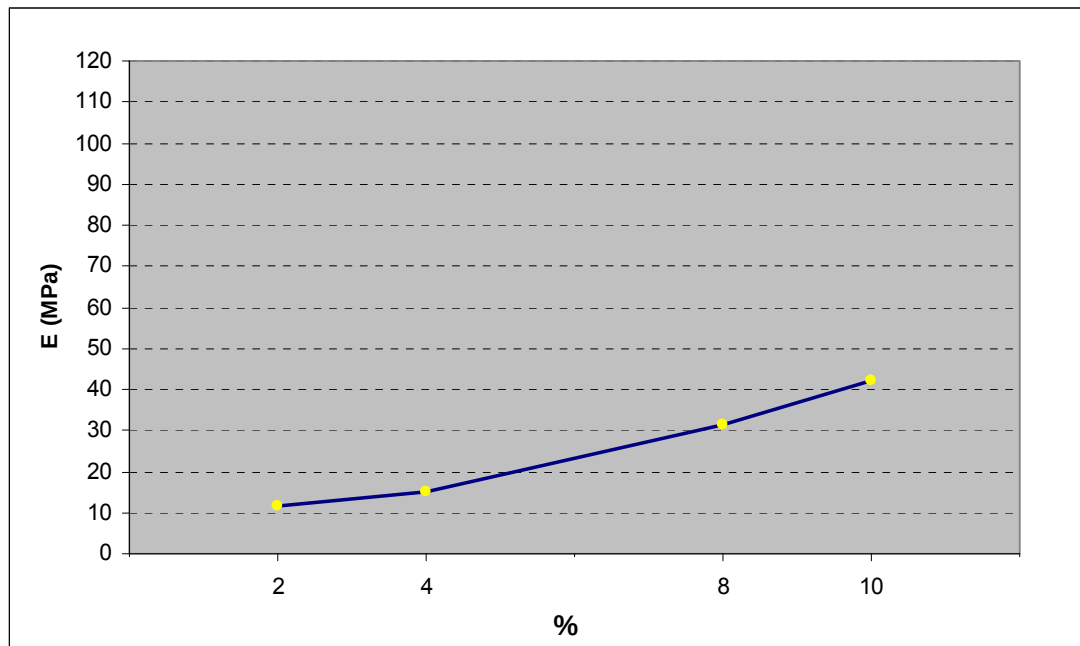


**Figure B.9 : E Values of Cement Stabilized and 7-day Cured Samples.**

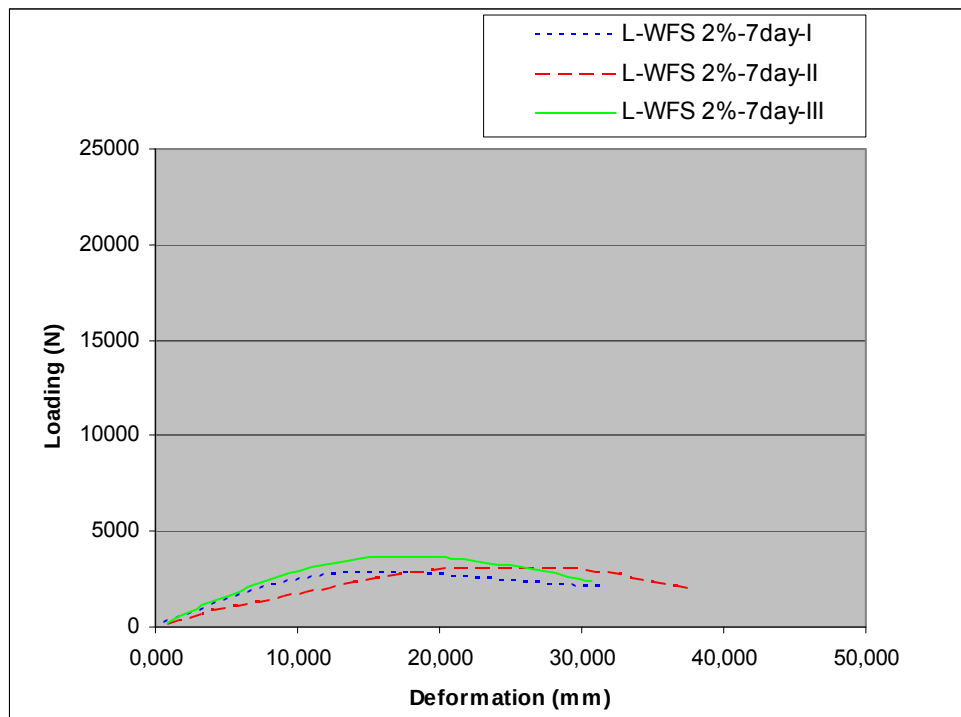


**Figure B.10 :** Loading – Deformation Diagram of L-WFS 2%-7day Samples.

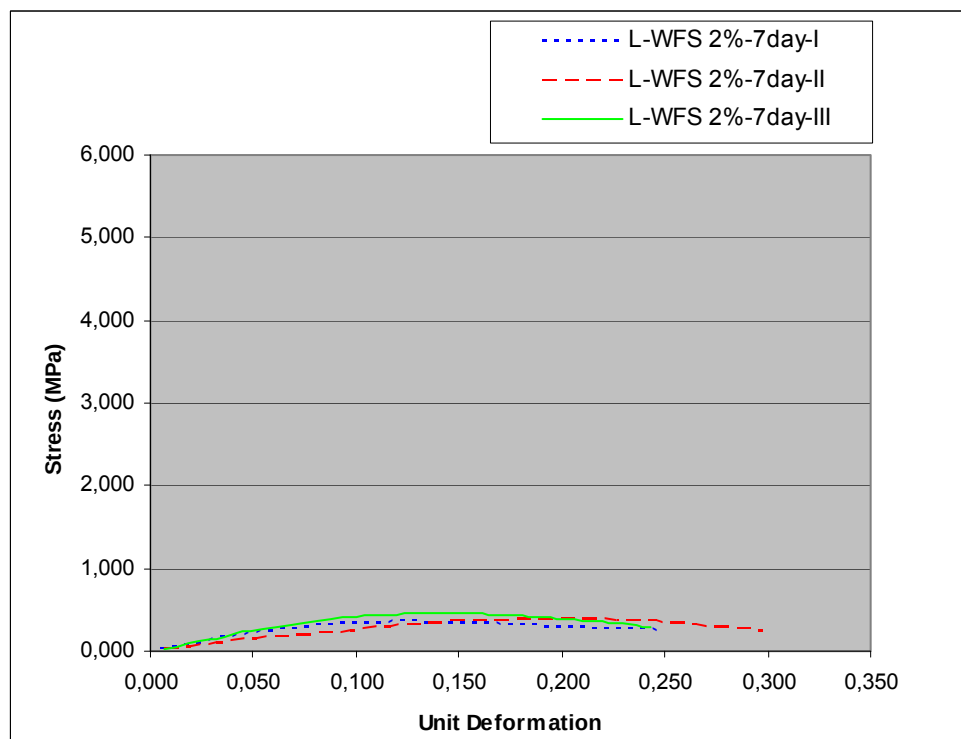


**Figure B.11 :** Stress – Unit Deformation Diagram of L-WFS 2%-7day Samples.

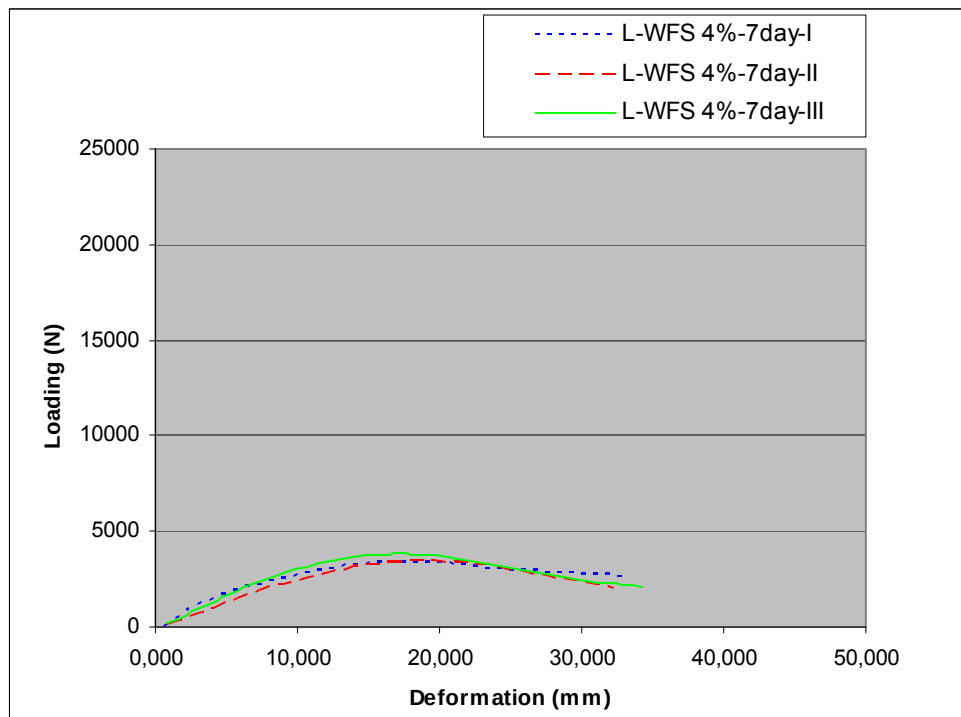


**Figure B.12 :** Loading – Deformation Diagram of L-WFS 4%-7day Samples.

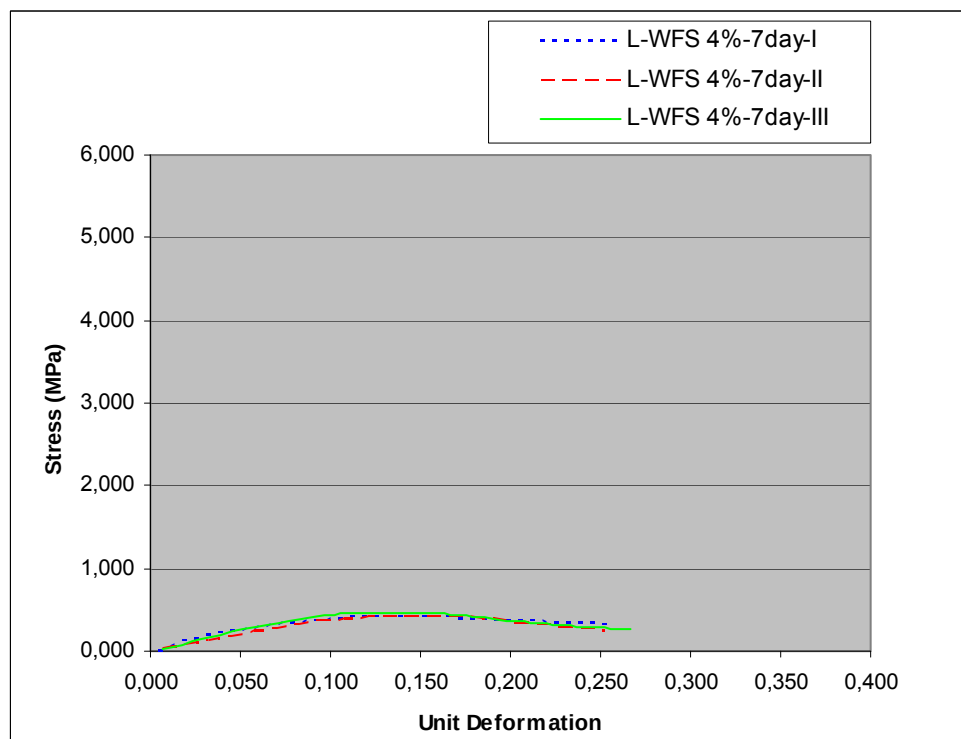


**Figure B.13 :** Stress – Unit Deformation Diagram of L-WFS 4%-7day Samples.

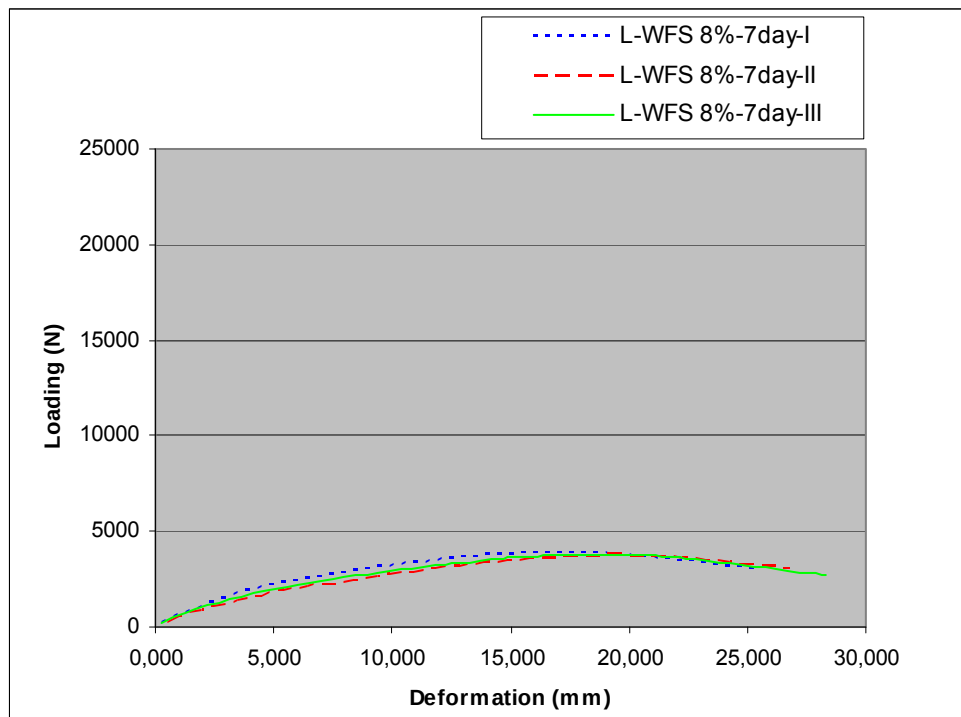


**Figure B.14 :** Loading – Deformation Diagram of L-WFS 8%-7day Samples.

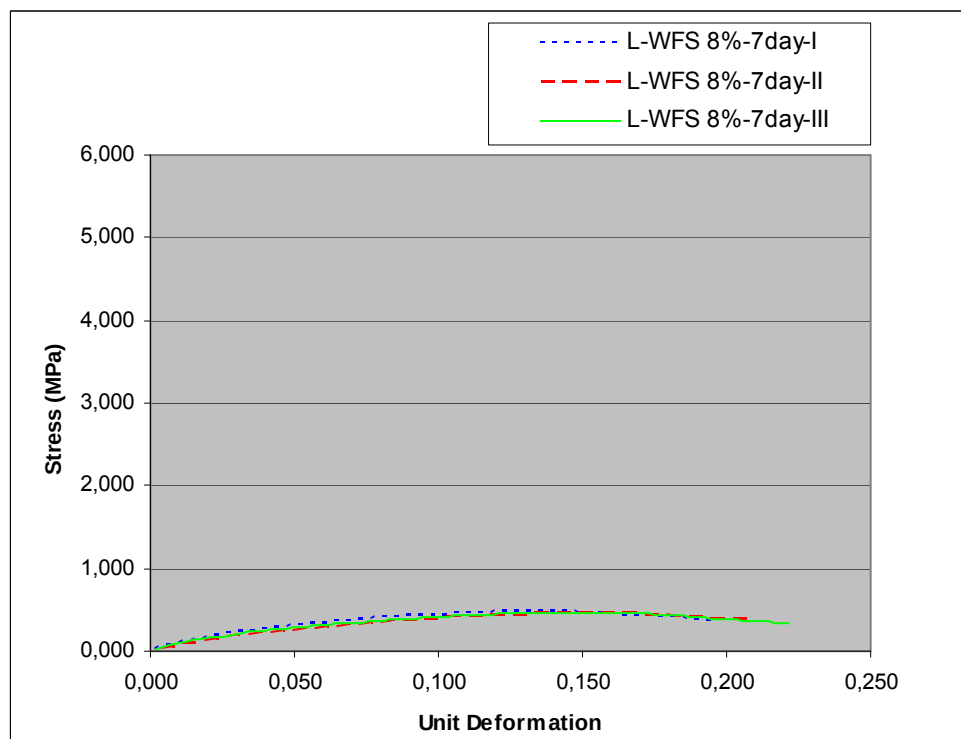


**Figure B.15 :** Stress – Unit Deformation Diagram of L-WFS 8%-7day Samples.

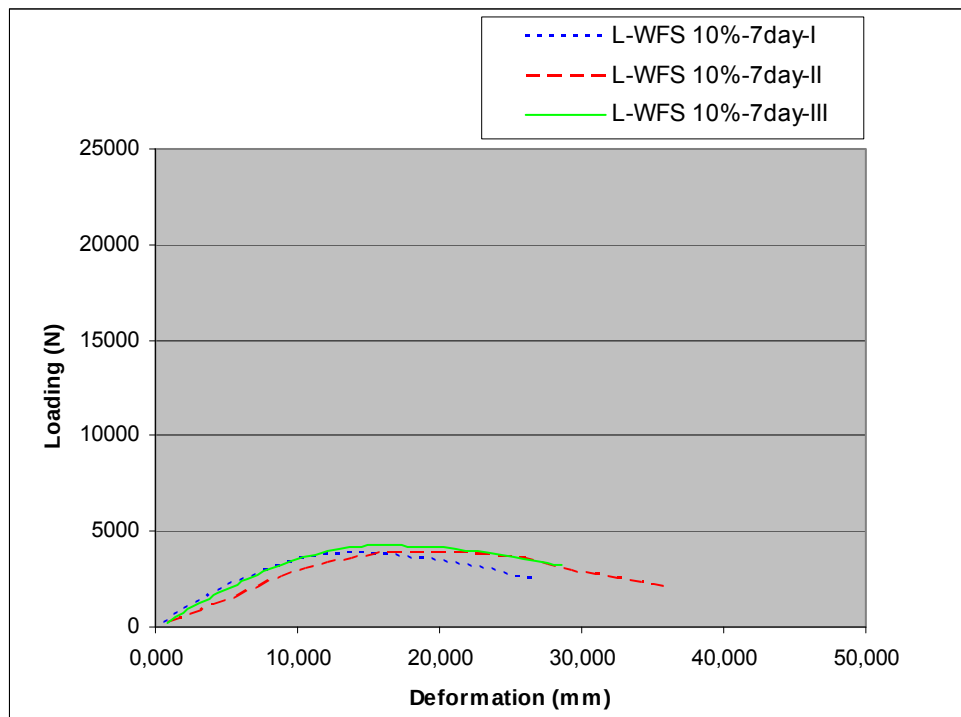


**Figure B.16 :** Loading – Deformation Diagram of L-WFS 10%-7day Samples.

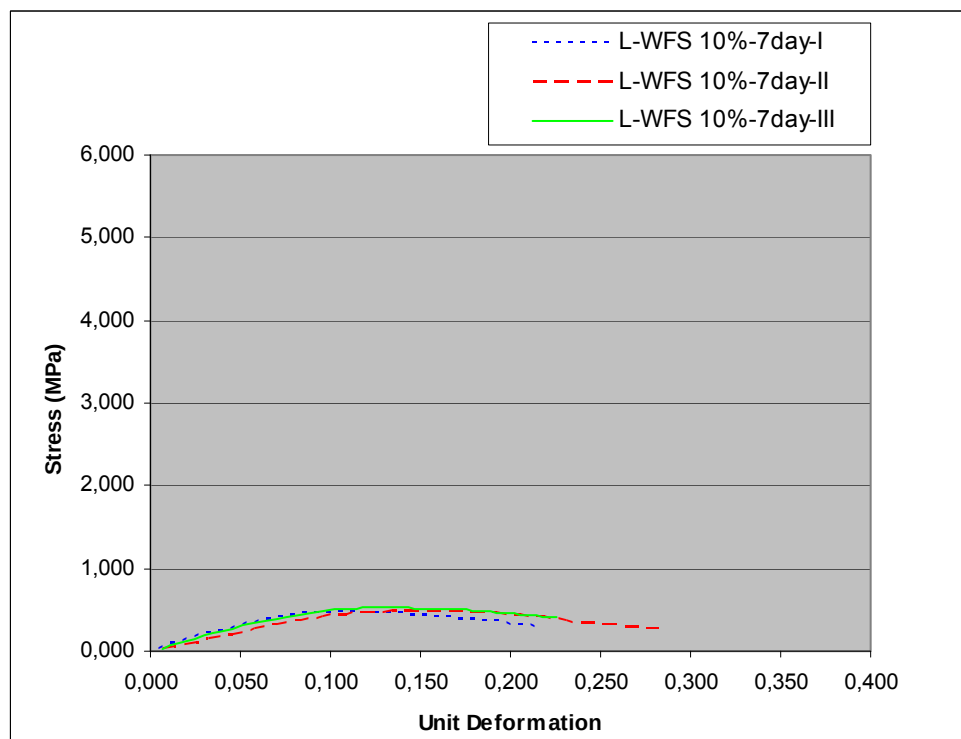


**Figure B.17 :** Stress – Unit Deformation Diagram of L-WFS 10%-7day Samples.

**Table B.2 : E Values of Lime Stabilized and 7-day Cured Samples.**

| Amount of Additives                  | Definition of Sample  | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|--------------------------------------|-----------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Lime  | L-WFS 2%-7day-I       | 15,283                           | 2853,371                      | 0,121                              | 0,352                          | 5,817                    |
|                                      | L-WFS 2%-7day-II      | 26,133                           | 3064,876                      | 0,207                              | 0,378                          | 3,653                    |
|                                      | L-WFS 2%-7day-III     | 17,539                           | 3712,704                      | 0,139                              | 0,458                          | 6,589                    |
| <b>Average Values</b>                | <b>L-WFS 2%-7day</b>  | <b>19,652</b>                    | <b>3210,317</b>               | <b>0,156</b>                       | <b>0,396</b>                   | <b>5,353</b>             |
| WFS Samples Stabilized With 4% Lime  | L-WFS 4%-7day-I       | 17,914                           | 3384,862                      | 0,140                              | 0,418                          | 5,964                    |
|                                      | L-WFS 4%-7day-II      | 18,783                           | 3411,180                      | 0,146                              | 0,421                          | 5,764                    |
|                                      | L-WFS 4%-7day-III     | 17,232                           | 3821,334                      | 0,134                              | 0,471                          | 7,035                    |
| <b>Average Values</b>                | <b>L-WFS 4%-7day</b>  | <b>17,976</b>                    | <b>3539,125</b>               | <b>0,140</b>                       | <b>0,437</b>                   | <b>6,254</b>             |
| WFS Samples Stabilized With 8% Lime  | L-WFS 8%-7day-I       | 17,509                           | 3907,211                      | 0,135                              | 0,482                          | 7,140                    |
|                                      | L-WFS 8%-7day-II      | 19,782                           | 3715,913                      | 0,153                              | 0,458                          | 5,991                    |
|                                      | L-WFS 8%-7day-III     | 18,531                           | 3812,248                      | 0,145                              | 0,470                          | 6,486                    |
| <b>Average Values</b>                | <b>C-WFS 8%-7day</b>  | <b>18,607</b>                    | <b>3811,791</b>               | <b>0,144</b>                       | <b>0,470</b>                   | <b>6,539</b>             |
| WFS Samples Stabilized With 10% Lime | L-WFS 10%-7day-I      | 14,329                           | 3831,382                      | 0,113                              | 0,473                          | 8,364                    |
|                                      | L-WFS 10%-7day-II     | 18,685                           | 3897,370                      | 0,148                              | 0,481                          | 6,496                    |
|                                      | L-WFS 10%-7day-III    | 16,160                           | 4243,230                      | 0,128                              | 0,523                          | 8,178                    |
| <b>Average Values</b>                | <b>L-WFS 10%-7day</b> | <b>16,391</b>                    | <b>3990,66</b>                | <b>0,130</b>                       | <b>0,492</b>                   | <b>7,679</b>             |

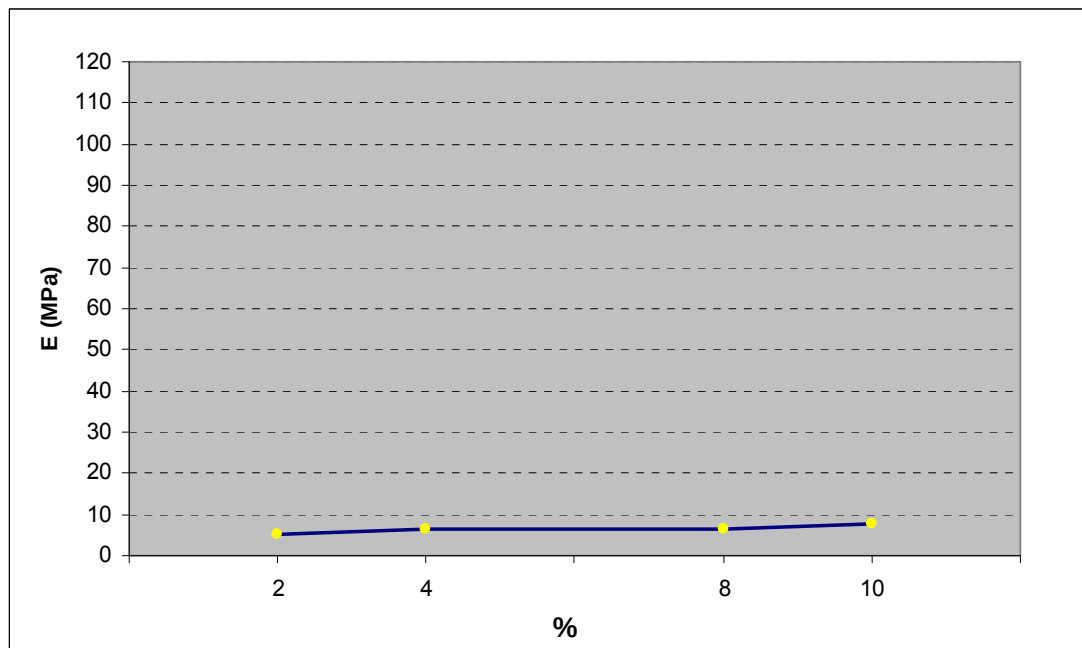


**Figure B.18 : E Values of Lime Stabilized and 7-day Cured Samples.**

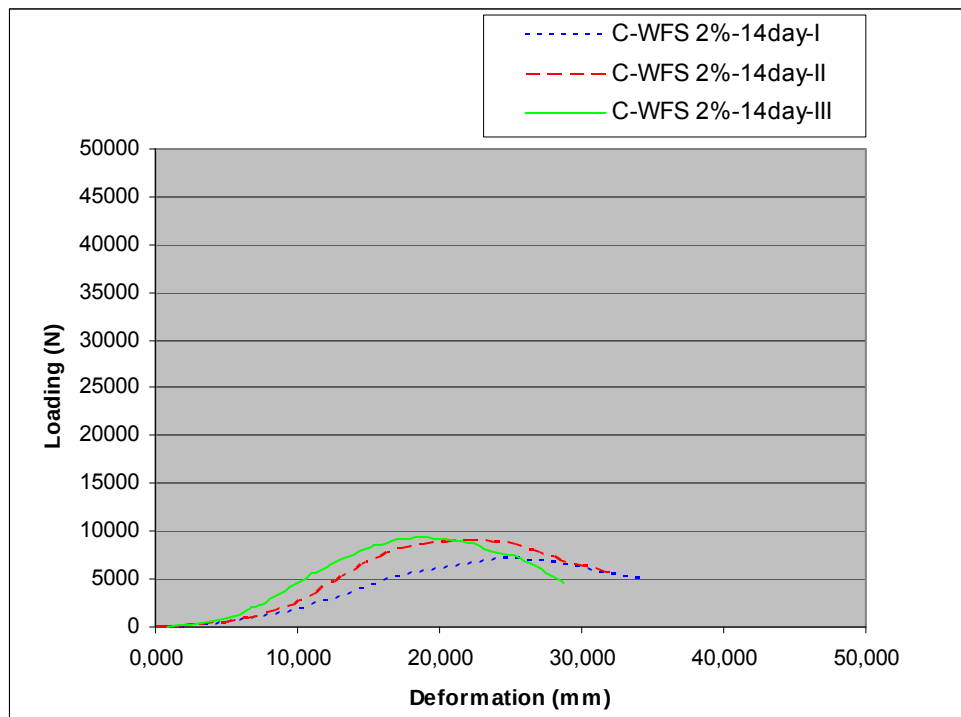


**Figure B.19 :** Loading – Deformation Diagram of C-WFS 2%-14day Samples.

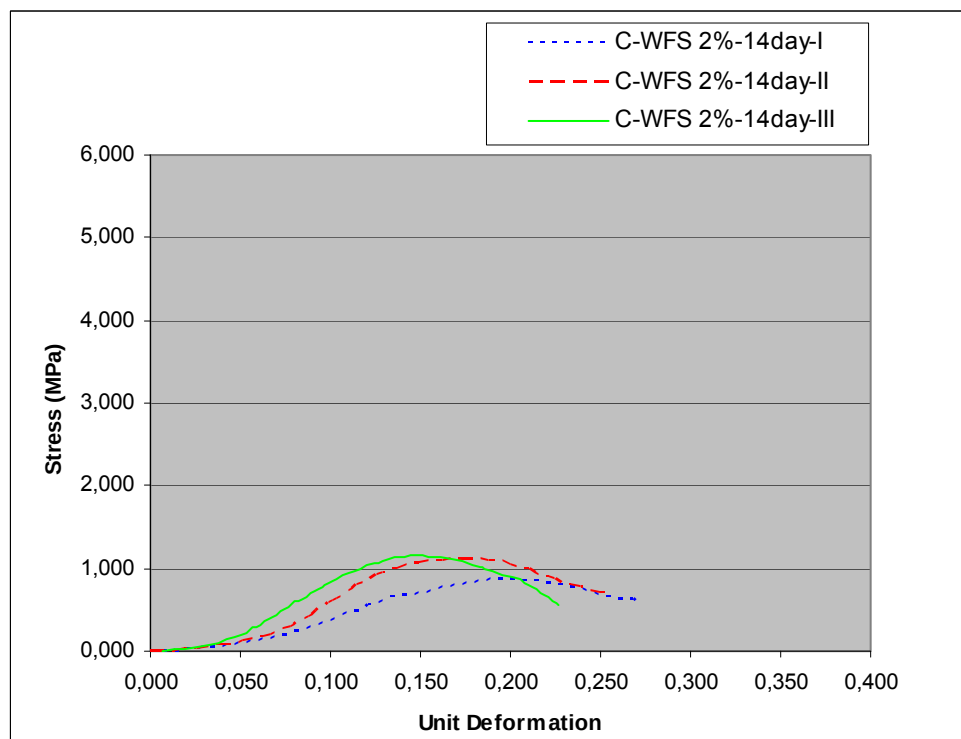


**Figure B.20 :** Stress – Unit Deformation Diagram of C-WFS 2%-14day Samples.

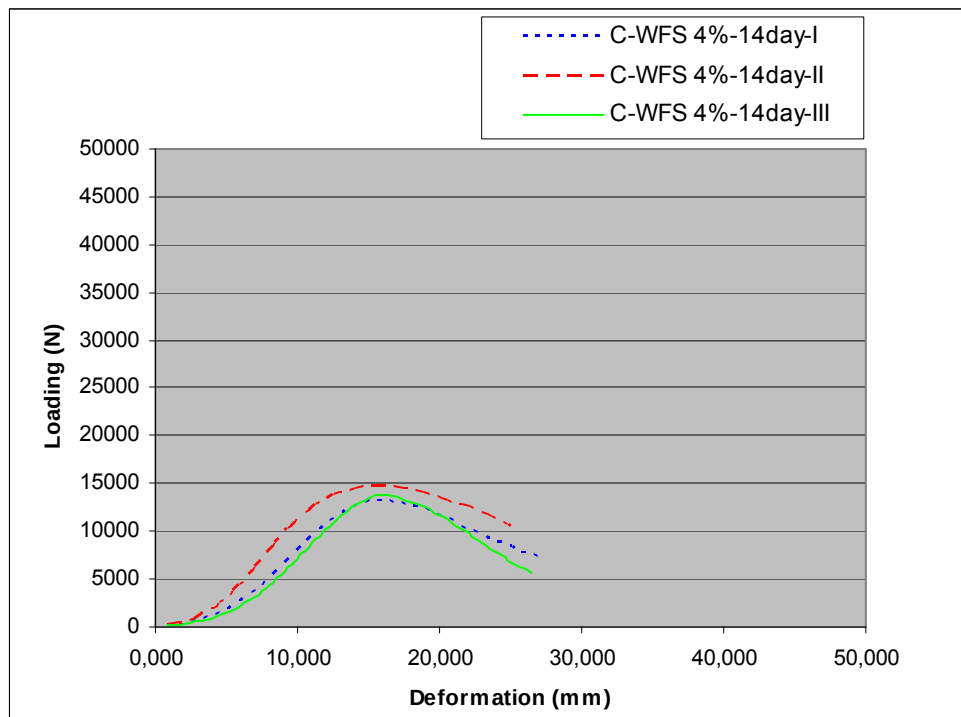


**Figure B.21 :** Loading – Deformation Diagram of C-WFS 4%-14day Samples.

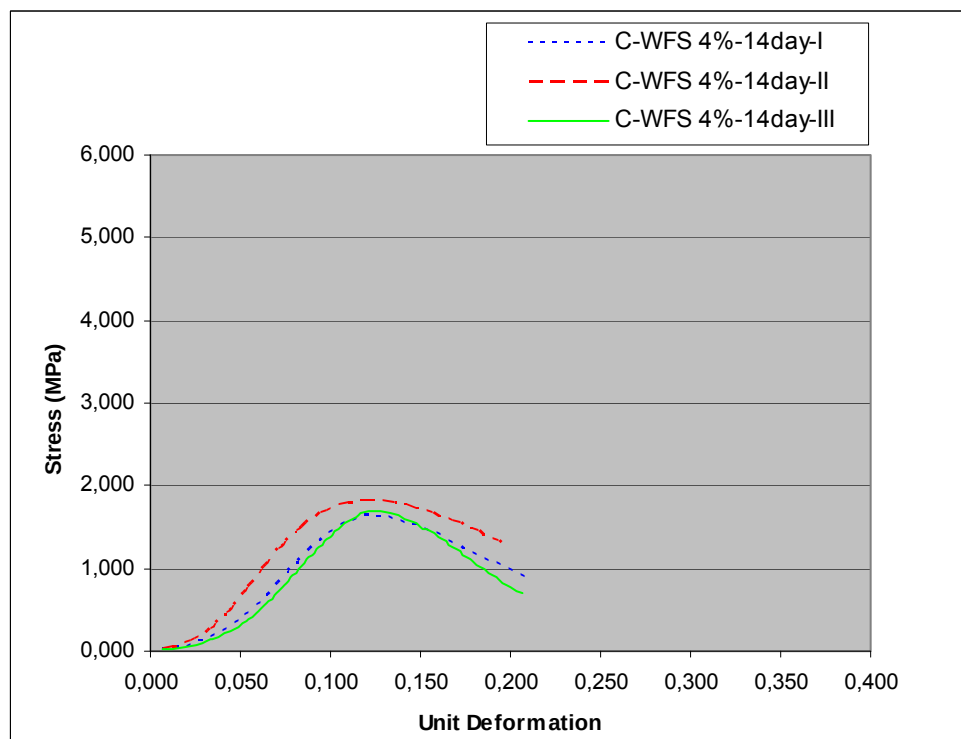


**Figure B.22 :** Stress – Unit Deformation Diagram of C-WFS 4%-14day Samples.

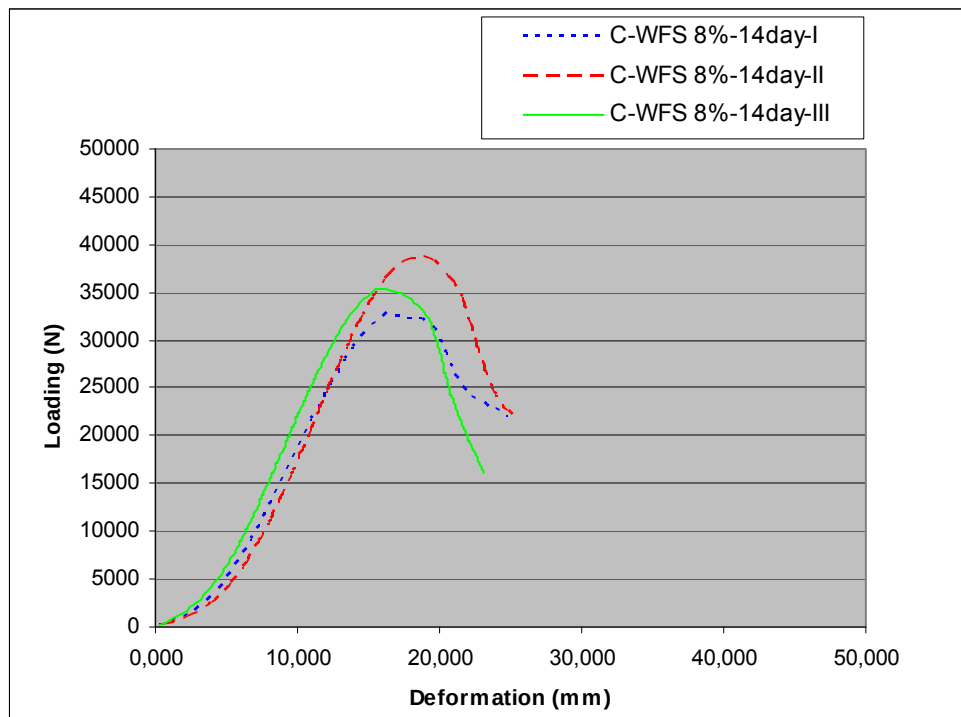


**Figure B.23 :** Loading – Deformation Diagram of C-WFS 8%-14day Samples.

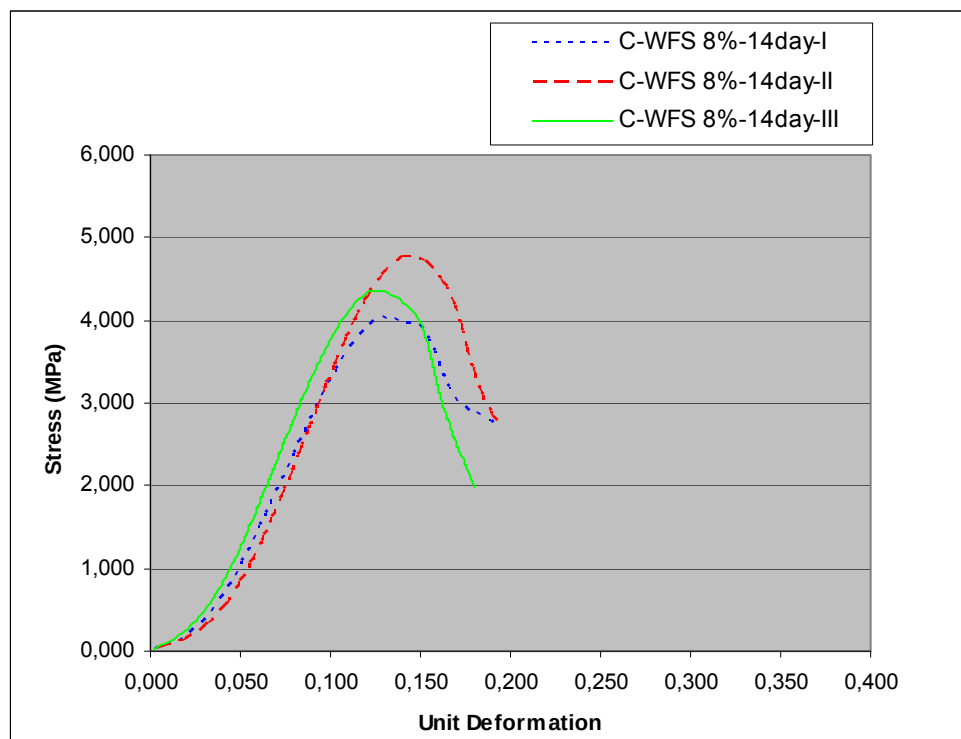


**Figure B.24 :** Stress – Unit Deformation Diagram of C-WFS 8%-14day Samples.

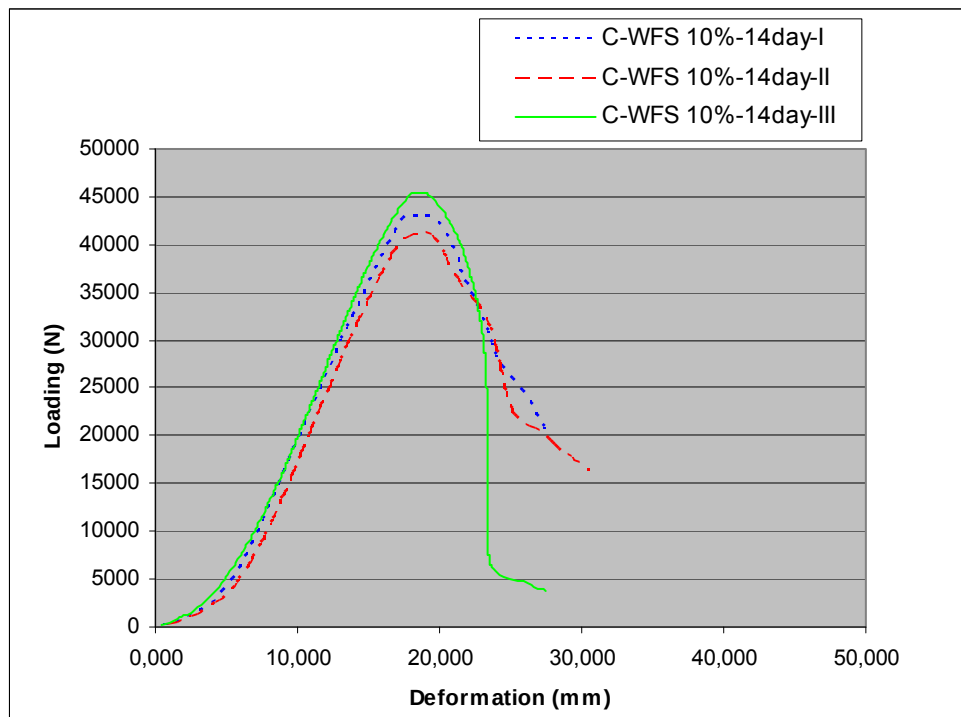


**Figure B.25 :** Loading – Deformation Diagram of C-WFS 10%-14day Samples.

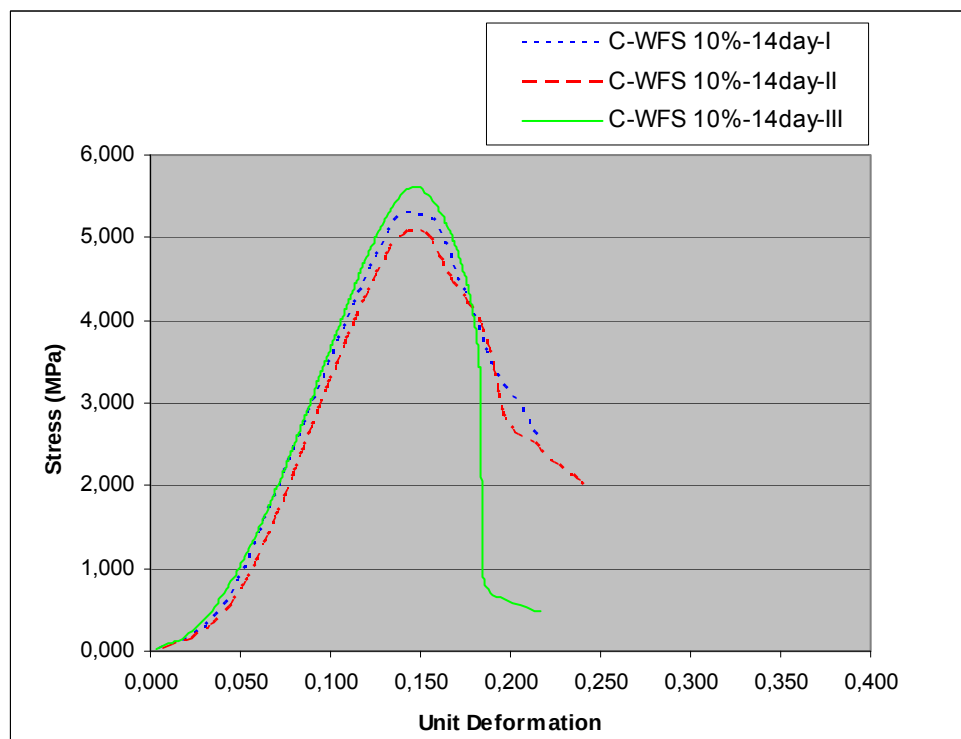


**Figure B.26 :** Stress – Unit Deformation Diagram of C-WFS 10%-14day Samples.

**Table B.3 : E Values of Cement Stabilized and 14-day Cured Samples.**

| Amount of Additives                    | Definition of Sample   | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|----------------------------------------|------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Cement  | C-WFS 2%-14day-I       | 25,771                           | 7079,308                      | 0,204                              | 0,873                          | 8,561                    |
|                                        | C-WFS 2%-14day-II      | 22,109                           | 8977,367                      | 0,175                              | 1,107                          | 12,655                   |
|                                        | C-WFS 2%-14day-III     | 18,744                           | 9329,229                      | 0,148                              | 1,151                          | 15,550                   |
| <b>Average Values</b>                  | <b>C-WFS 2%-14day</b>  | <b>22,208</b>                    | <b>8461,968</b>               | <b>0,176</b>                       | <b>1,044</b>                   | <b>12,255</b>            |
| WFS Samples Stabilized With 4% Cement  | C-WFS 4%-14day-I       | 15,344                           | 13272,110                     | 0,120                              | 1,637                          | 27,284                   |
|                                        | C-WFS 4%-14day-II      | 15,763                           | 14689,200                     | 0,123                              | 1,812                          | 29,461                   |
|                                        | C-WFS 4%-14day-III     | 16,353                           | 13750,230                     | 0,127                              | 1,696                          | 26,709                   |
| <b>Average Values</b>                  | <b>C-WFS 4%-14day</b>  | <b>15,820</b>                    | <b>13903,847</b>              | <b>0,123</b>                       | <b>1,715</b>                   | <b>27,818</b>            |
| WFS Samples Stabilized With 8% Cement  | C-WFS 8%-14day-I       | 16,397                           | 32741,900                     | 0,128                              | 4,039                          | 63,103                   |
|                                        | C-WFS 8%-14day-II      | 18,803                           | 38691,710                     | 0,147                              | 4,772                          | 64,931                   |
|                                        | C-WFS 8%-14day-III     | 15,793                           | 35304,410                     | 0,123                              | 4,355                          | 70,807                   |
| <b>Average Values</b>                  | <b>C-WFS 8%-14day</b>  | <b>16,998</b>                    | <b>35579,340</b>              | <b>0,133</b>                       | <b>4,389</b>                   | <b>66,280</b>            |
| WFS Samples Stabilized With 10% Cement | C-WFS 10%-14day-I      | 18,555                           | 42927,150                     | 0,146                              | 5,295                          | 72,532                   |
|                                        | C-WFS 10%-14day-II     | 19,053                           | 41187,840                     | 0,150                              | 5,080                          | 67,738                   |
|                                        | C-WFS 10%-14day-III    | 18,974                           | 45484,720                     | 0,149                              | 5,610                          | 75,306                   |
| <b>Average Values</b>                  | <b>C-WFS 10%-14day</b> | <b>18,861</b>                    | <b>43199,903</b>              | <b>0,148</b>                       | <b>5,329</b>                   | <b>71,859</b>            |

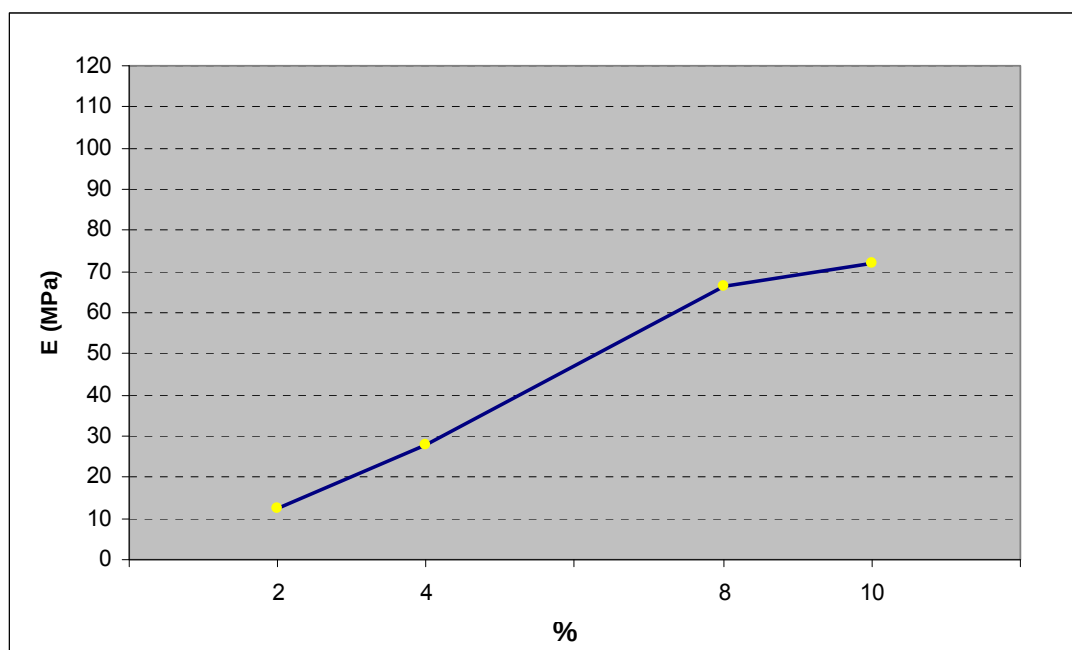


**Figure B.27 : E Values of Cement Stabilized and 14-day Cured Samples.**

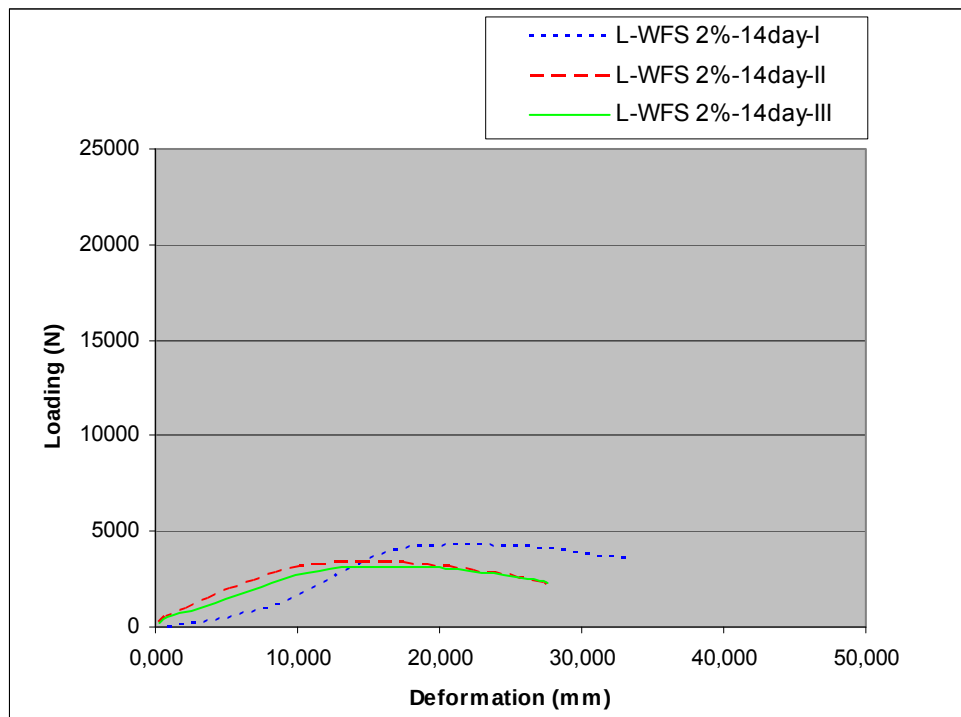


**Figure B.28 :** Loading – Deformation Diagram of L-WFS 2%-14day Samples.

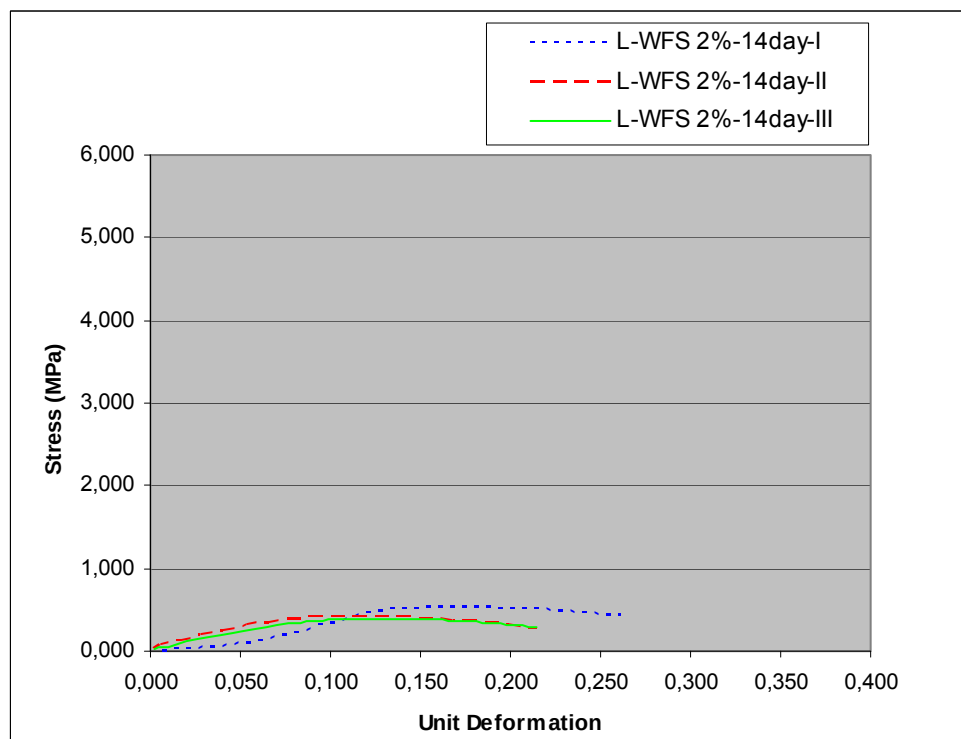


**Figure B.29 :** Stress – Unit Deformation Diagram of L-WFS 2%-14day Samples.

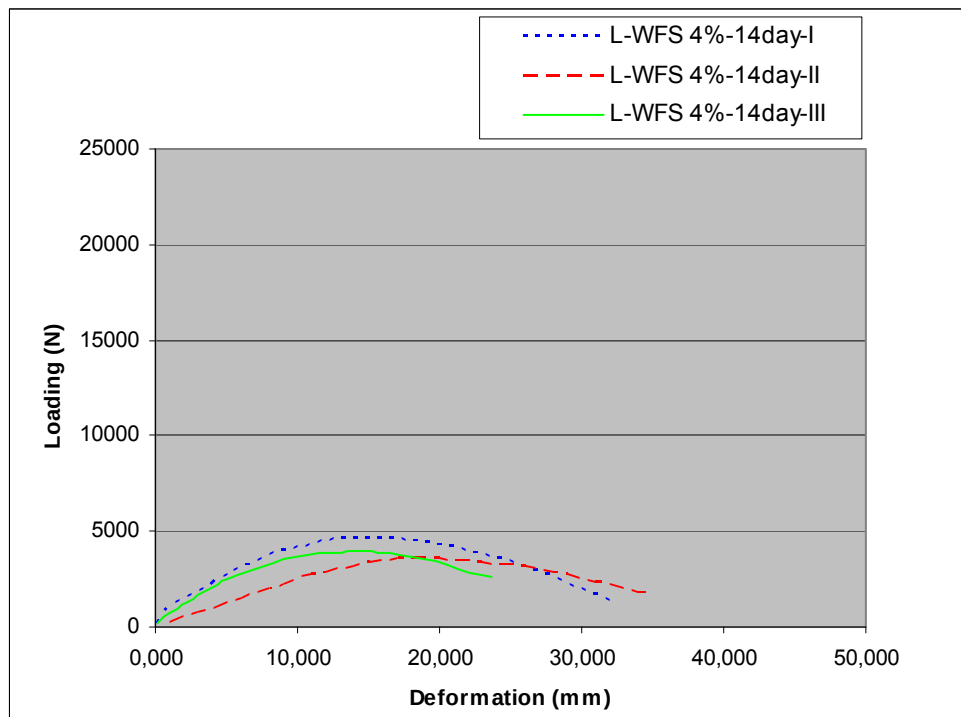


**Figure B.30 :** Loading – Deformation Diagram of L-WFS 4%-14day Samples.

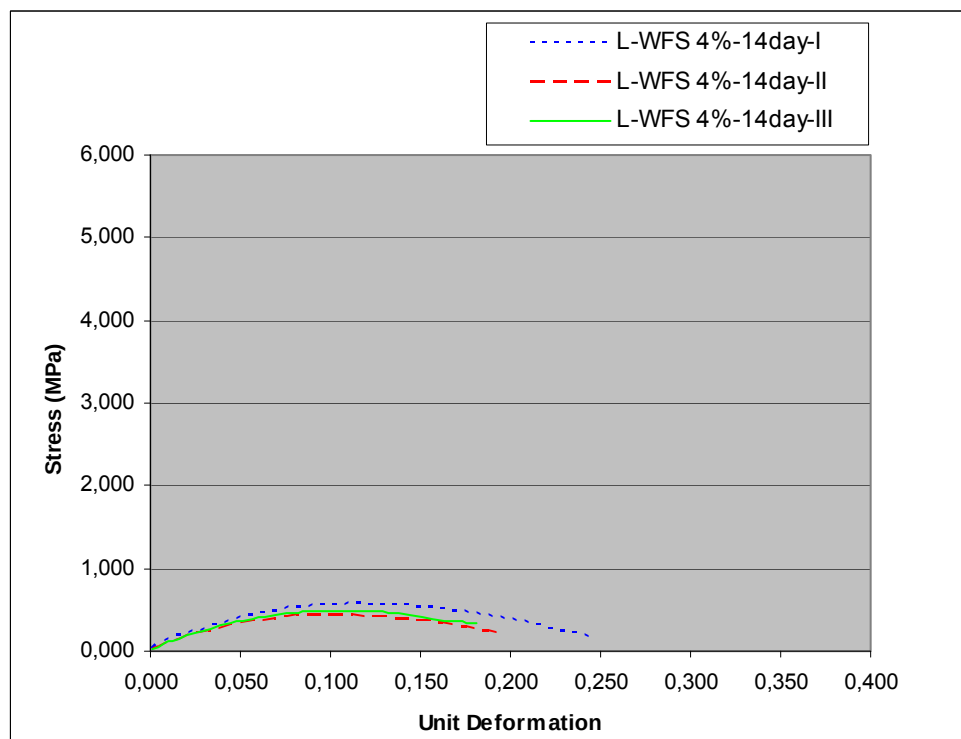


**Figure B.31 :** Stress – Unit Deformation Diagram of L-WFS 4%-14day Samples.

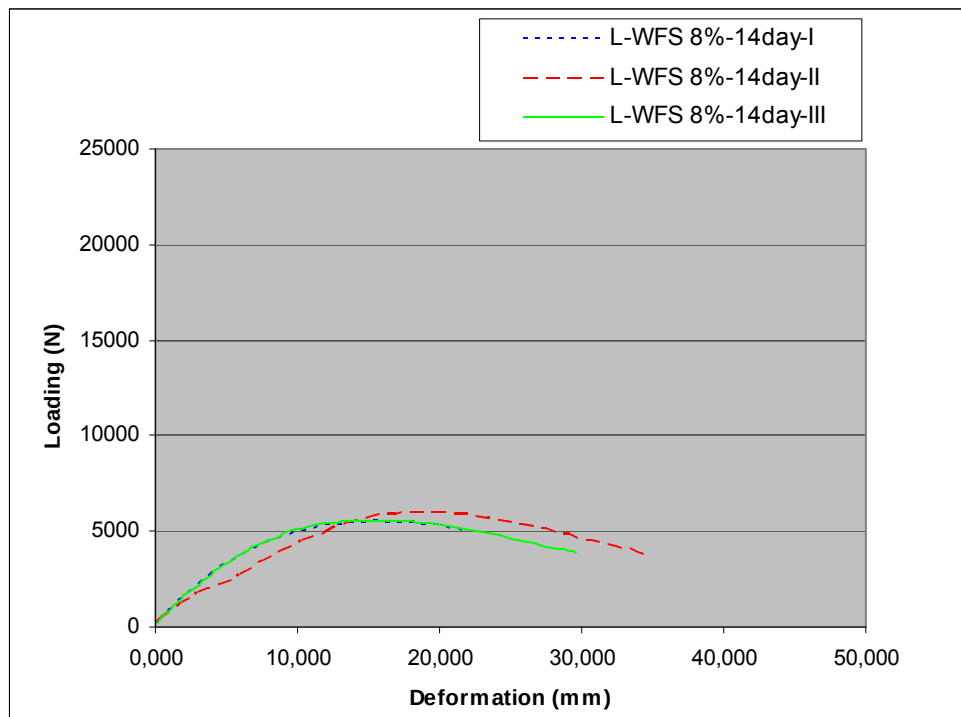


**Figure B.32 :** Loading – Deformation Diagram of L-WFS 8%-14day Samples.

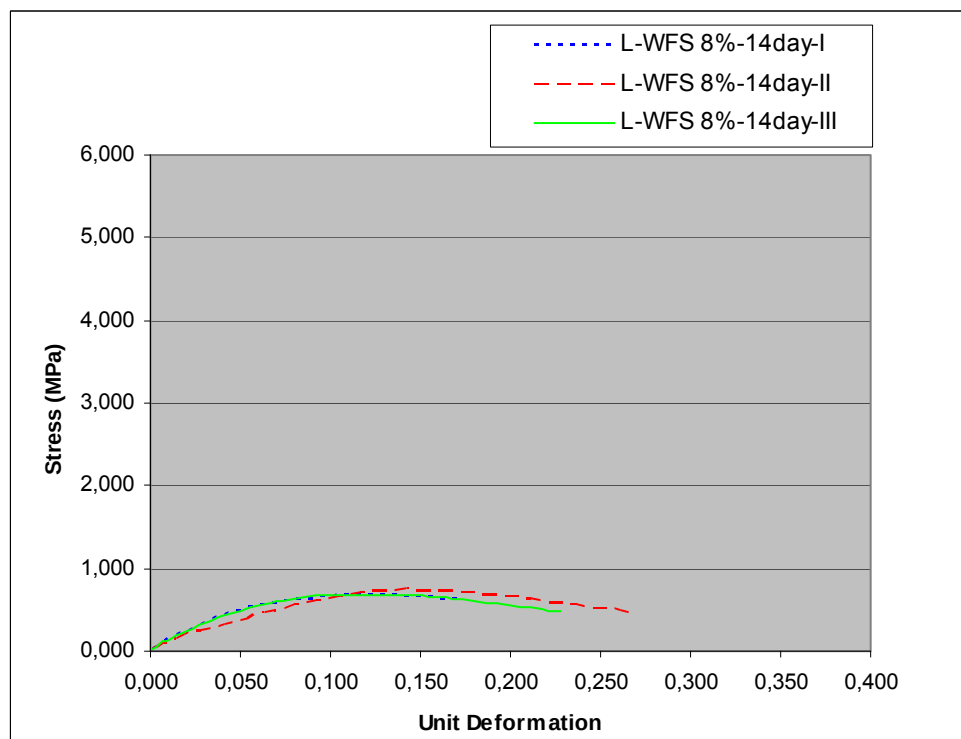


**Figure B.33 :** Stress – Unit Deformation Diagram of L-WFS 8%-14day Samples.

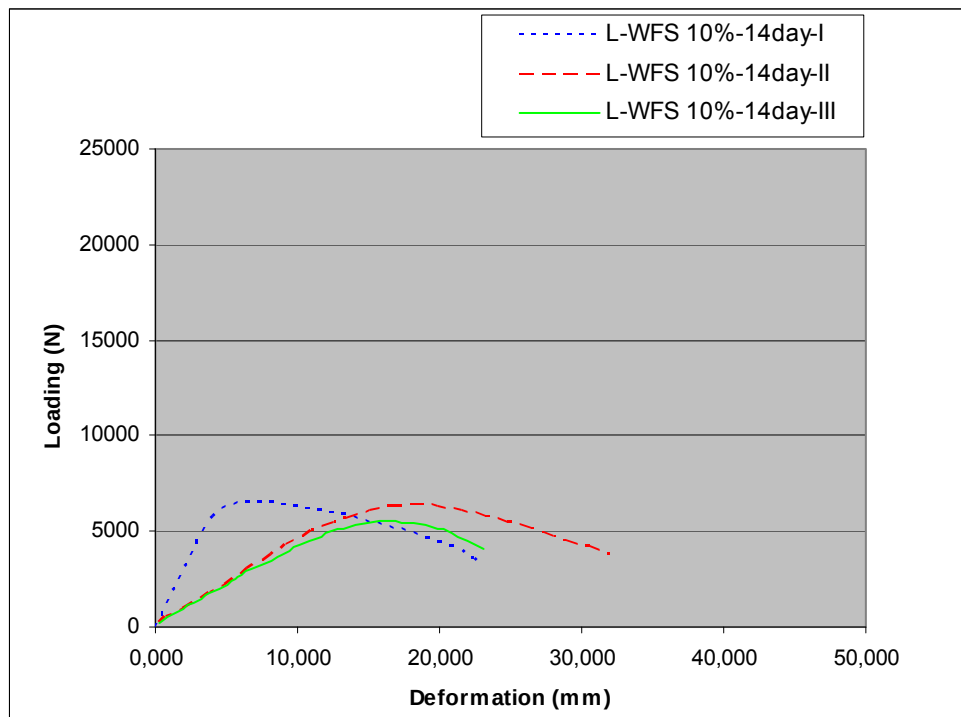


**Figure B.34 :** Loading – Deformation Diagram of L-WFS 10%-14day Samples.

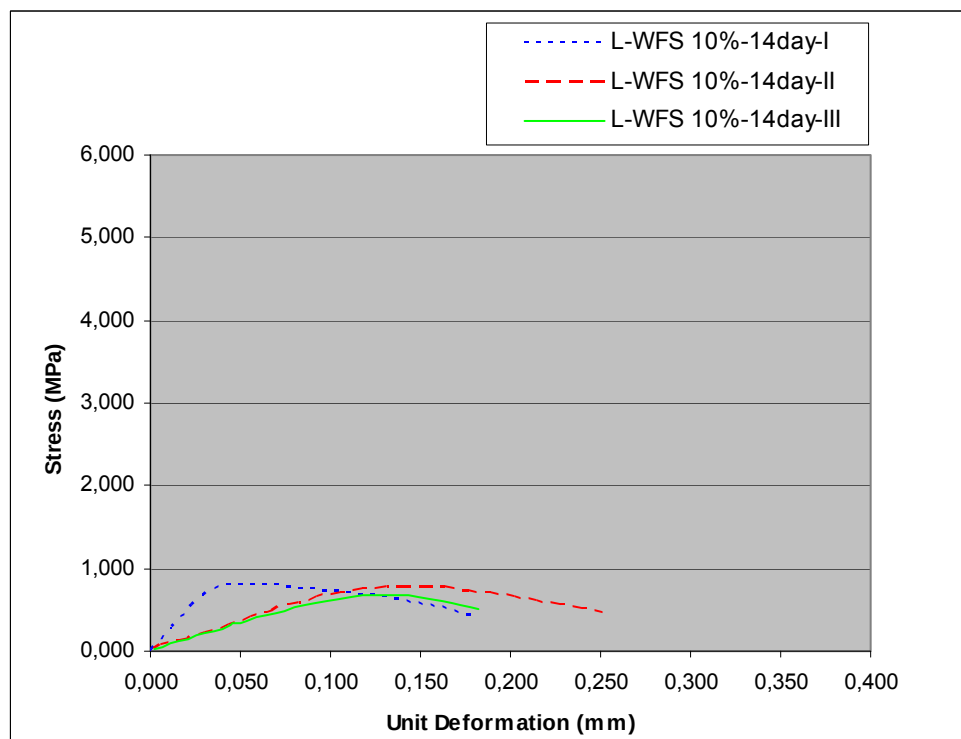


**Figure B.35 :** Stress – Unit Deformation Diagram of L-WFS 10%-14day Samples.

**Table B.4 : E Values of Lime Stabilized and 14-day Cured Samples.**

| Amount of Additives                  | Definition of Sample   | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|--------------------------------------|------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Lime  | L-WFS 2%-14day-I       | 21,604                           | 4262,204                      | 0,168                              | 0,526                          | 6,259                    |
|                                      | L-WFS 2%-14day-II      | 15,010                           | 3385,280                      | 0,117                              | 0,418                          | 7,138                    |
|                                      | L-WFS 2%-14day-III     | 15,589                           | 3172,205                      | 0,121                              | 0,391                          | 6,467                    |
| <b>Average Values</b>                | <b>L-WFS 2%-14day</b>  | <b>17,401</b>                    | <b>3606,56</b>                | <b>0,135</b>                       | <b>0,445</b>                   | <b>6,621</b>             |
| WFS Samples Stabilized With 4% Lime  | L-WFS 4%-14day-I       | 15,357                           | 4624,796                      | 0,118                              | 0,570                          | 9,669                    |
|                                      | L-WFS 4%-14day-II      | 12,266                           | 3551,872                      | 0,094                              | 0,438                          | 9,321                    |
|                                      | L-WFS 4%-14day-III     | 14,785                           | 3926,367                      | 0,113                              | 0,484                          | 8,572                    |
| <b>Average Values</b>                | <b>L-WFS 4%-14day</b>  | <b>14,136</b>                    | <b>4034,345</b>               | <b>0,108</b>                       | <b>0,498</b>                   | <b>9,187</b>             |
| WFS Samples Stabilized With 8% Lime  | L-WFS 8%-14day-I       | 15,427                           | 5493,025                      | 0,119                              | 0,678                          | 11,387                   |
|                                      | L-WFS 8%-14day-II      | 18,470                           | 5989,056                      | 0,142                              | 0,739                          | 10,405                   |
|                                      | L-WFS 8%-14day-III     | 16,039                           | 5588,765                      | 0,123                              | 0,689                          | 11,209                   |
| <b>Average Values</b>                | <b>L-WFS 8%-14day</b>  | <b>16,645</b>                    | <b>5690,282</b>               | <b>0,128</b>                       | <b>0,702</b>                   | <b>11,000</b>            |
| WFS Samples Stabilized With 10% Lime | L-WFS 10%-14day-I      | 6,542                            | 6520,363                      | 0,052                              | 0,804                          | 30,933                   |
|                                      | L-WFS 10%-14day-II     | 19,105                           | 6370,218                      | 0,150                              | 0,786                          | 10,476                   |
|                                      | L-WFS 10%-14day-III    | 16,528                           | 5519,757                      | 0,130                              | 0,681                          | 10,474                   |
| <b>Average Values</b>                | <b>L-WFS 10%-14day</b> | <b>14,058</b>                    | <b>6136,779</b>               | <b>0,111</b>                       | <b>0,757</b>                   | <b>17,295</b>            |

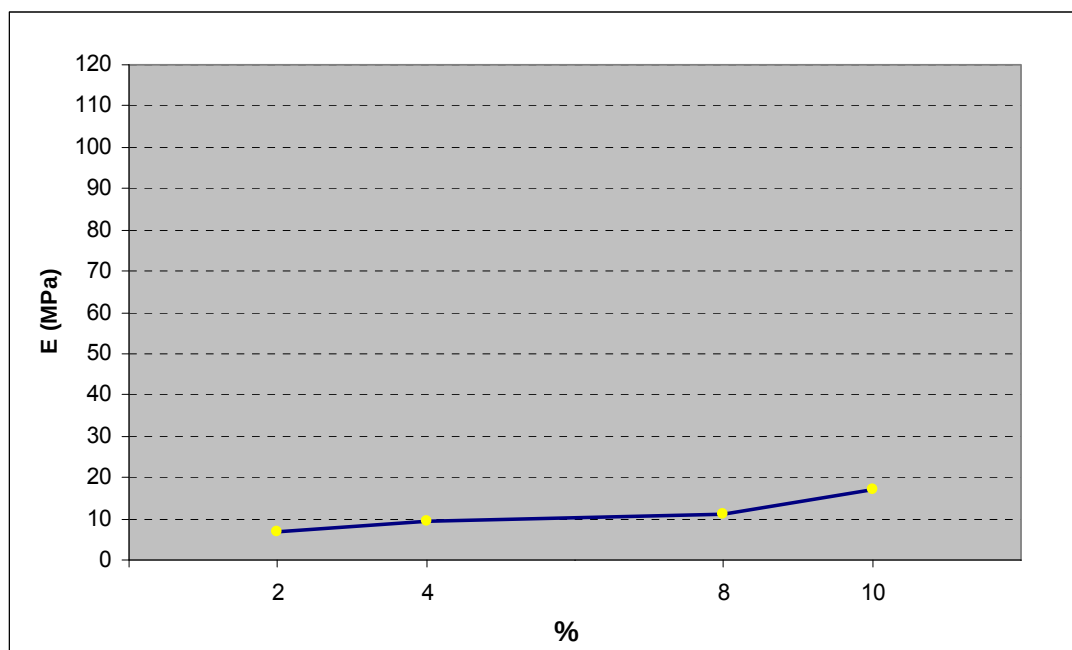


**Figure B.36 : E Values of Lime Stabilized and 14-day Cured Samples.**

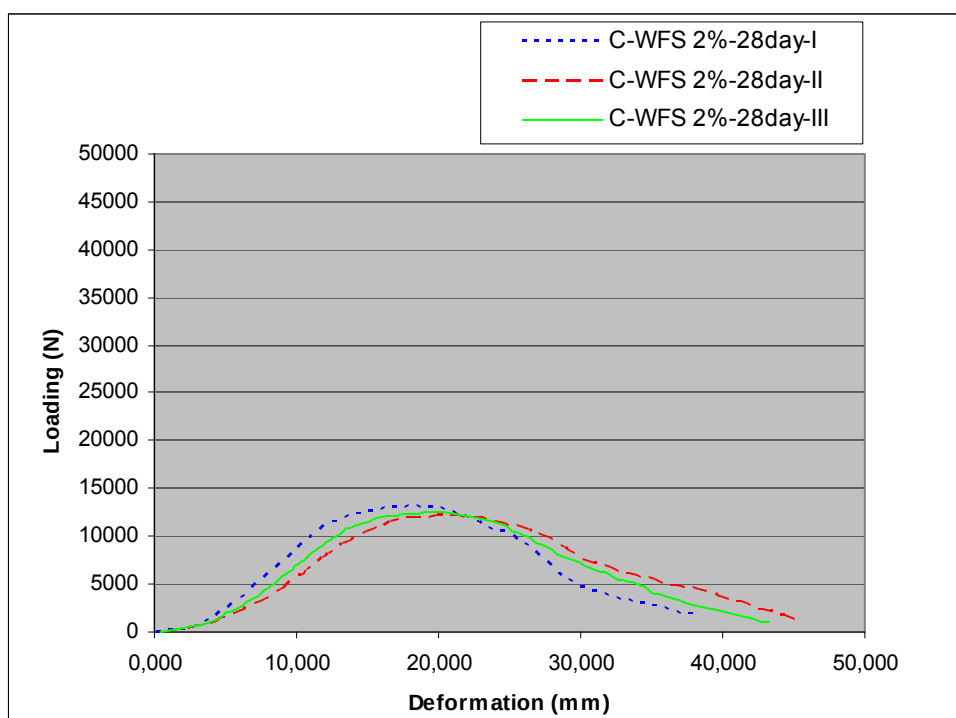


**Figure B.37 :** Loading – Deformation Diagram of C-WFS 2%-28day Samples.

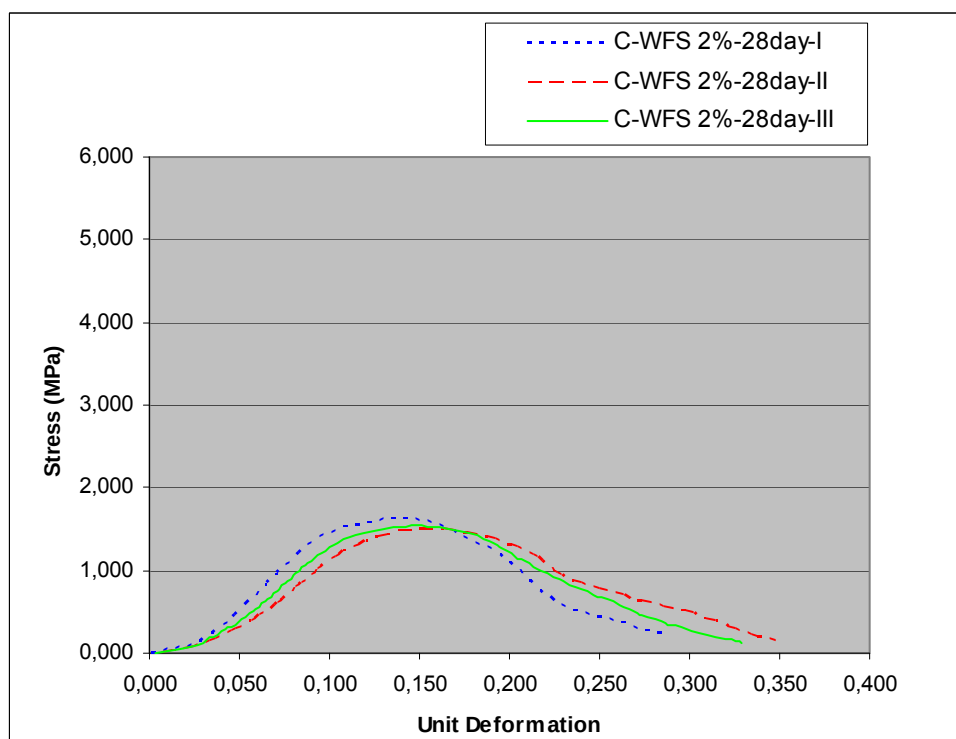


**Figure B.38 :** Stress – Unit Deformation Diagram of C-WFS 2%-28day Samples.

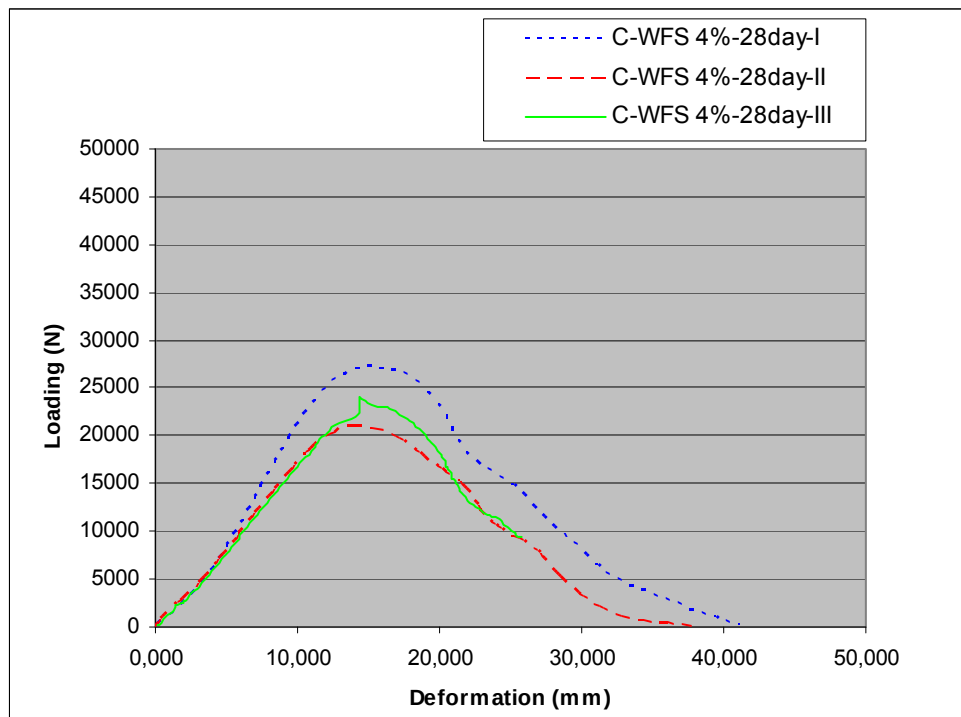


**Figure B.39 :** Loading – Deformation Diagram of C-WFS 4%-28day Samples.

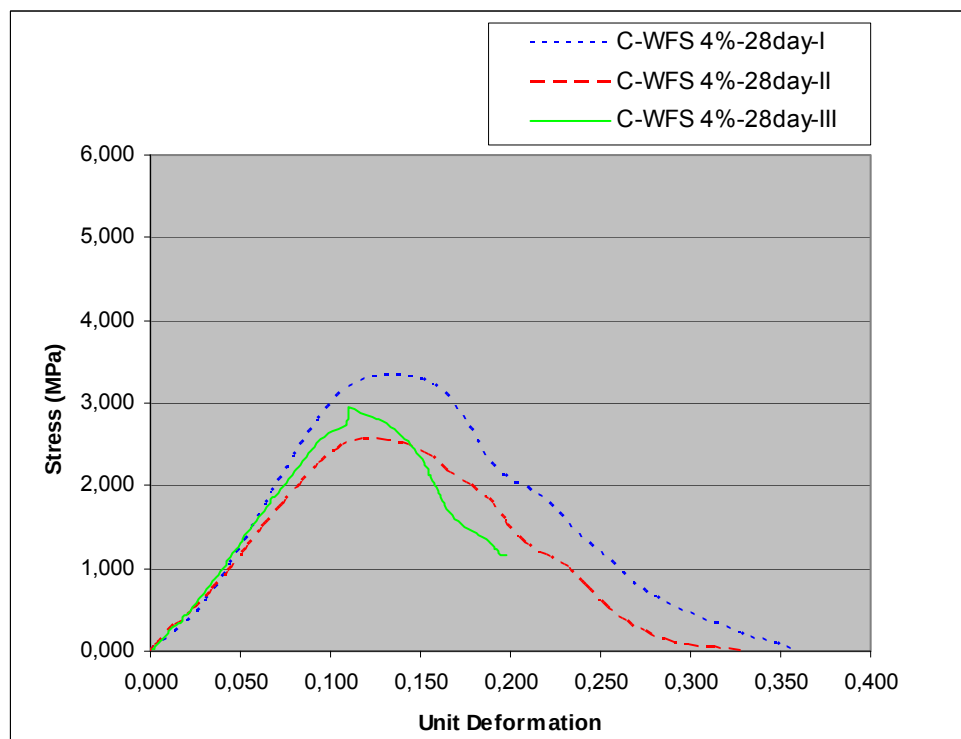


**Figure B.40 :** Stress – Unit Deformation Diagram of C-WFS 4%-28day Samples.

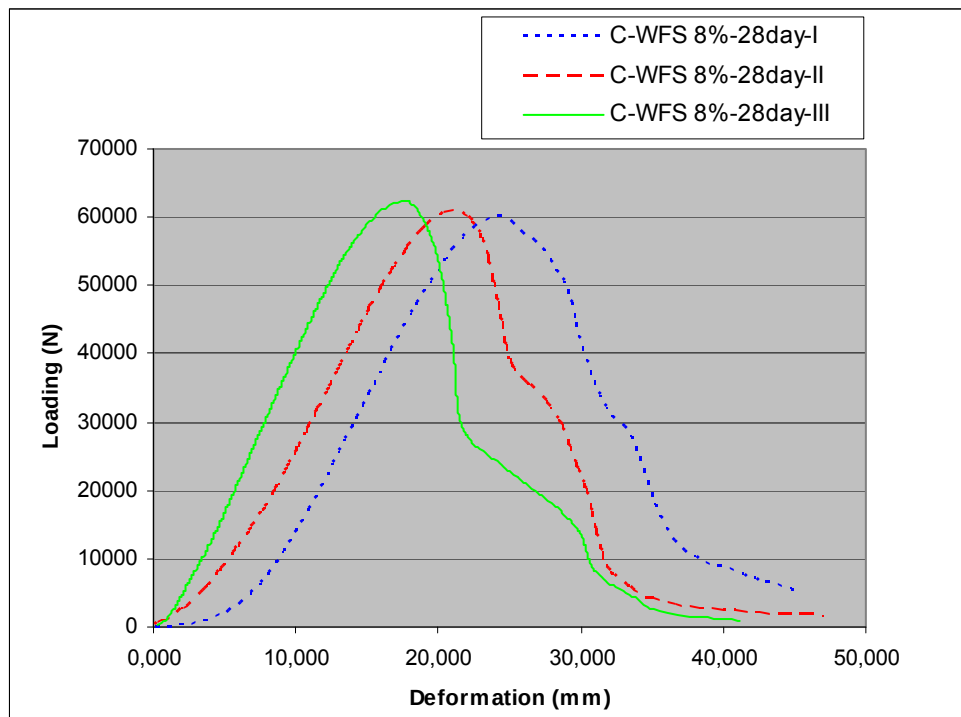


**Figure B.41 :** Loading – Deformation Diagram of C-WFS 8%-28day Samples.

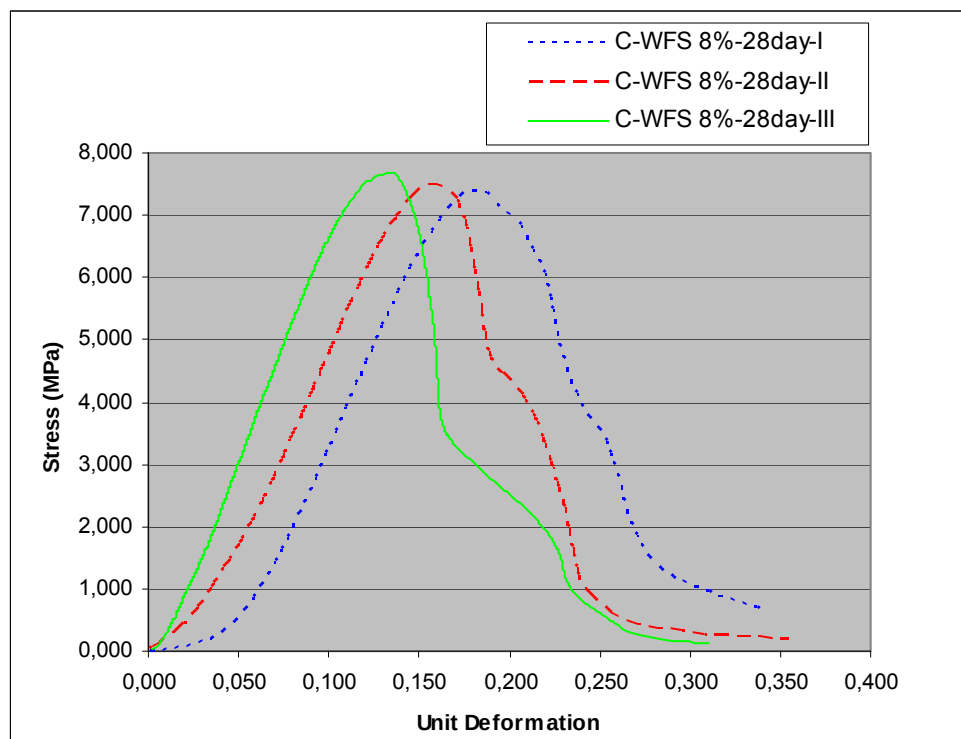


**Figure B.42 :** Stress – Unit Deformation Diagram of C-WFS 8%-28day Samples.

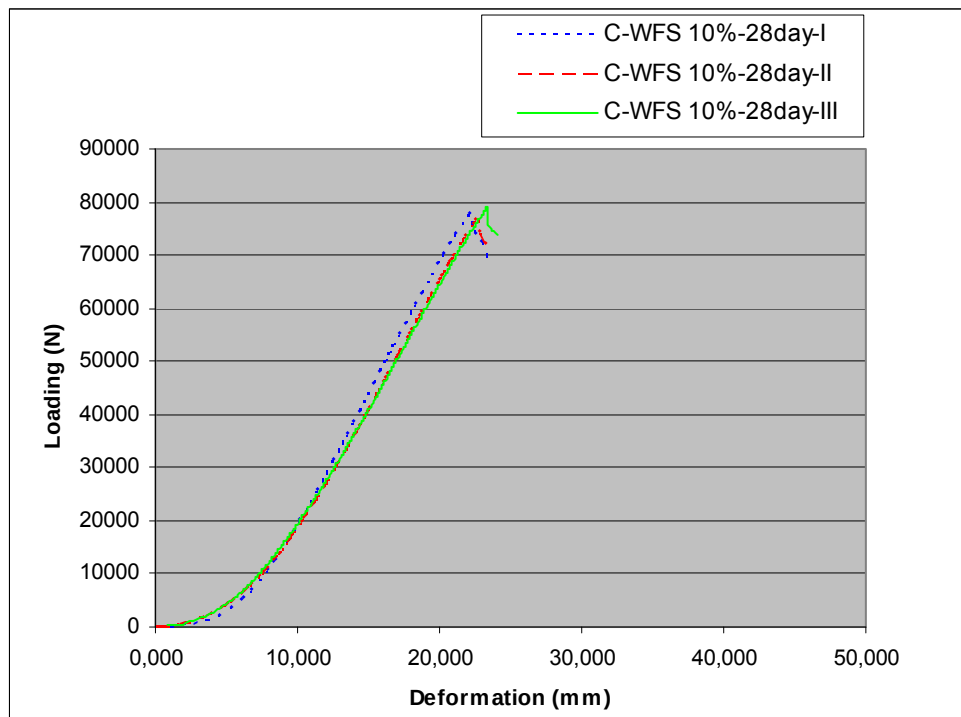


**Figure B.43 :** Loading – Deformation Diagram of C-WFS 10%-28day Samples.

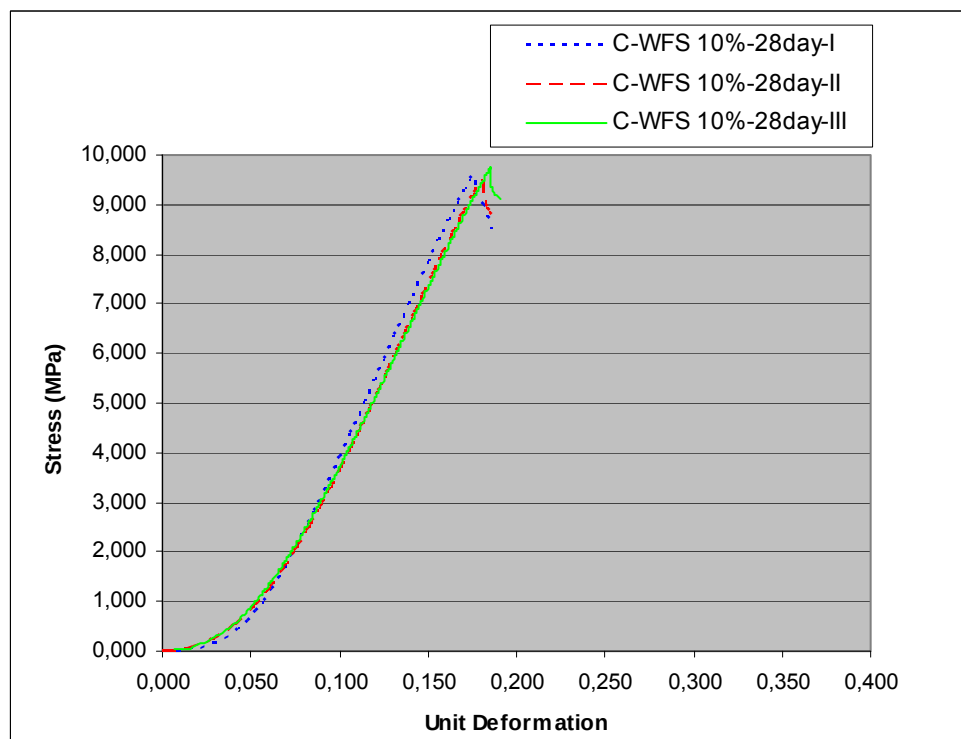


**Figure B.44 :** Stress – Unit Deformation Diagram of C-WFS 10%-28day Samples.

**Table B.5 : E Values of Cement Stabilized and 28-day Cured Samples.**

| Amount of Additives                    | Definition of Sample   | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|----------------------------------------|------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Cement  | C-WFS 2%-28day-I       | 18,342                           | 13108,350                     | 0,140                              | 1,617                          | 23,098                   |
|                                        | C-WFS 2%-28day-II      | 20,638                           | 12124,850                     | 0,157                              | 1,496                          | 19,052                   |
|                                        | C-WFS 2%-28day-III     | 19,490                           | 12616,600                     | 0,148                              | 1,556                          | 21,030                   |
| <b>Average Values</b>                  | <b>C-WFS 2%-28day</b>  | <b>19,490</b>                    | <b>12616,600</b>              | <b>0,148</b>                       | <b>1,556</b>                   | <b>21,060</b>            |
| WFS Samples Stabilized With 4% Cement  | C-WFS 4%-28day-I       | 15,140                           | 27094,980                     | 0,132                              | 3,342                          | 50,637                   |
|                                        | C-WFS 4%-28day-II      | 13,599                           | 20869,410                     | 0,118                              | 2,574                          | 43,630                   |
|                                        | C-WFS 4%-28day-III     | 14,369                           | 23982,195                     | 0,110                              | 2,958                          | 53,783                   |
| <b>Average Values</b>                  | <b>C-WFS 4%-28day</b>  | <b>14,369</b>                    | <b>23982,195</b>              | <b>0,120</b>                       | <b>2,958</b>                   | <b>49,350</b>            |
| WFS Samples Stabilized With 8% Cement  | C-WFS 8%-28day-I       | 24,416                           | 59953,390                     | 0,184                              | 7,395                          | 80,380                   |
|                                        | C-WFS 8%-28day-II      | 21,214                           | 60775,950                     | 0,160                              | 7,496                          | 93,705                   |
|                                        | C-WFS 8%-28day-III     | 17,166                           | 62336,900                     | 0,135                              | 7,689                          | 113,911                  |
| <b>Average Values</b>                  | <b>C-WFS 8%-28day</b>  | <b>20,932</b>                    | <b>61022,080</b>              | <b>0,160</b>                       | <b>7,527</b>                   | <b>95,999</b>            |
| WFS Samples Stabilized With 10% Cement | C-WFS 10%-28day-I      | 22,187                           | 77881,450                     | 0,176                              | 9,606                          | 109,163                  |
|                                        | C-WFS 10%-28day-II     | 22,723                           | 76959,440                     | 0,180                              | 9,493                          | 105,473                  |
|                                        | C-WFS 10%-28day-III    | 23,369                           | 78990,470                     | 0,185                              | 9,743                          | 105,331                  |
| <b>Average Values</b>                  | <b>C-WFS 10%-28day</b> | <b>22,760</b>                    | <b>77943,787</b>              | <b>0,180</b>                       | <b>9,614</b>                   | <b>106,656</b>           |

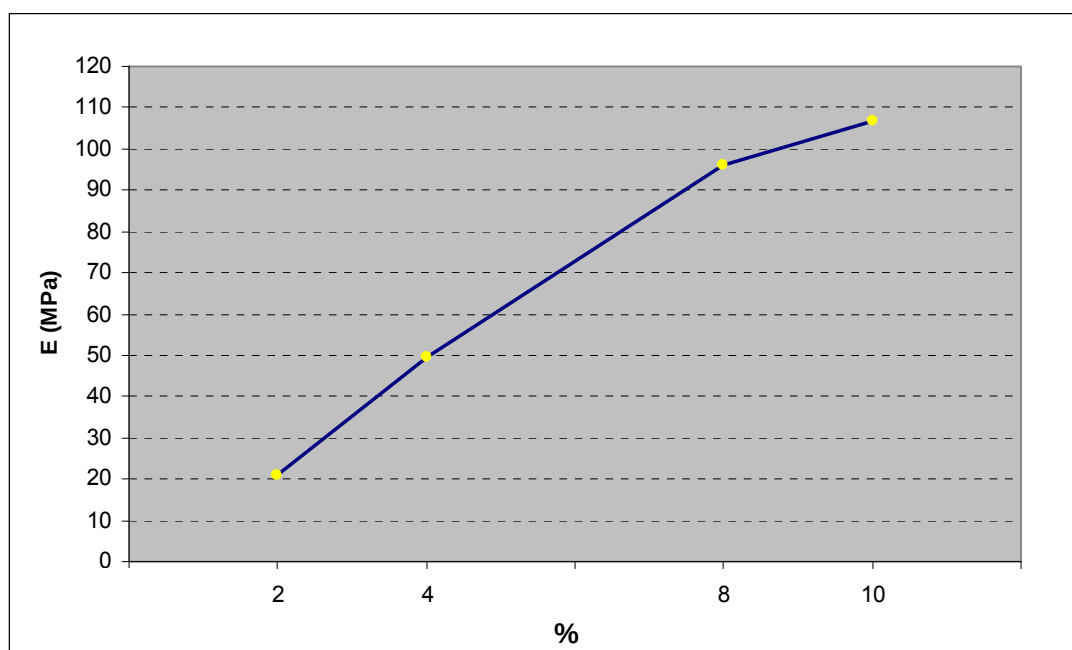


**Figure B.45 : E Values of Cement Stabilized and 28-day Cured Samples.**

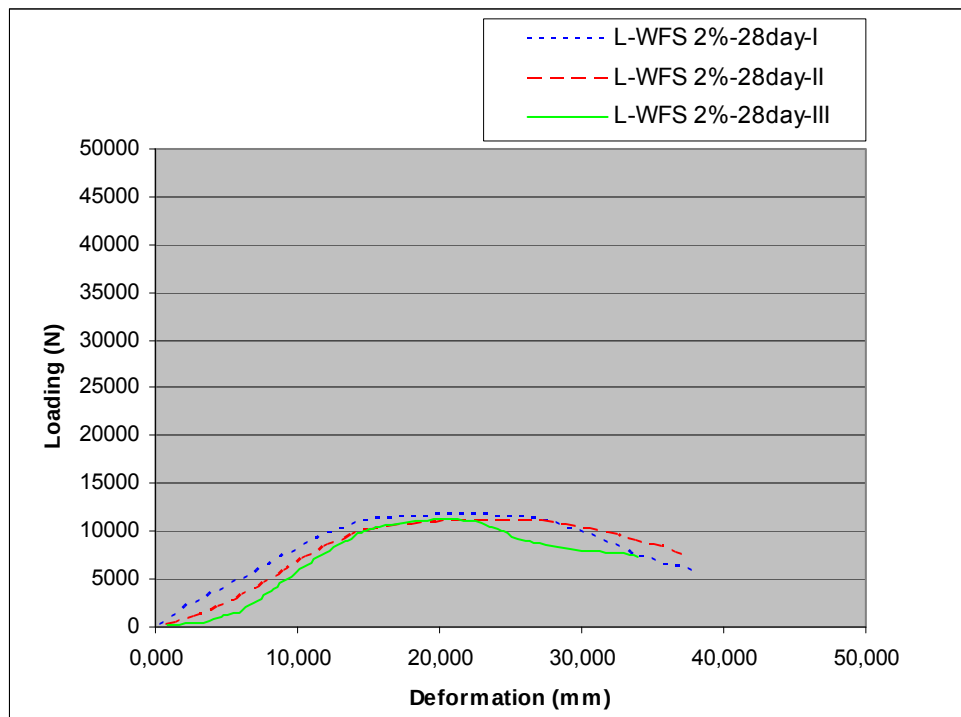


**Figure B.46 :** Loading – Deformation Diagram of L-WFS 2%-28day Samples.

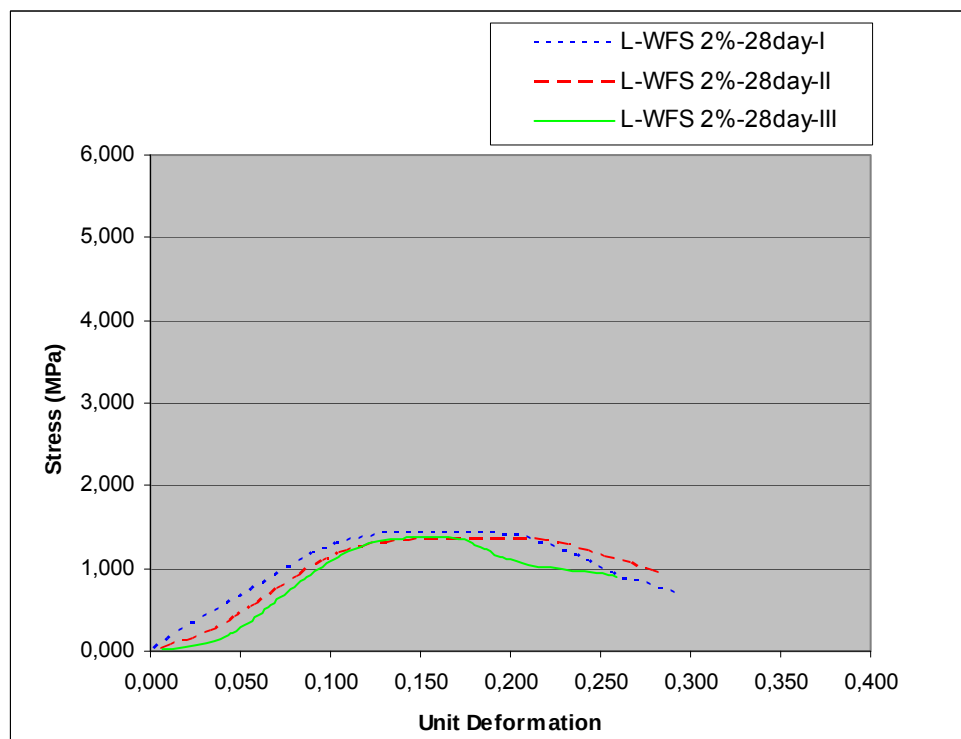


**Figure B.47 :** Stress – Unit Deformation Diagram of L-WFS 2%-28day Samples.

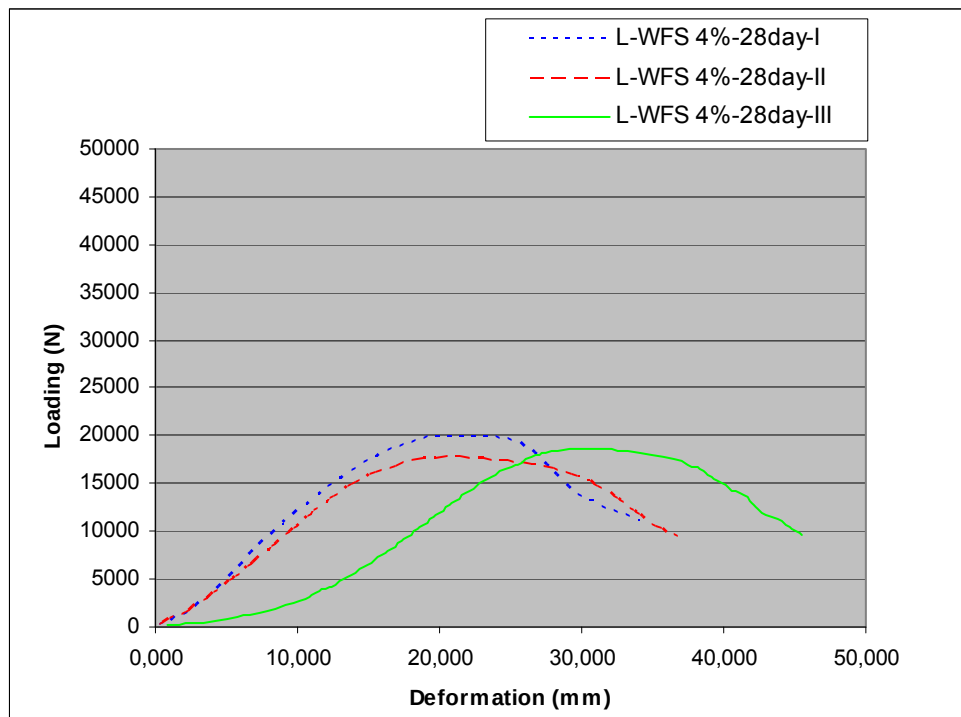


**Figure B.48 :** Loading – Deformation Diagram of L-WFS 4%-28day Samples.

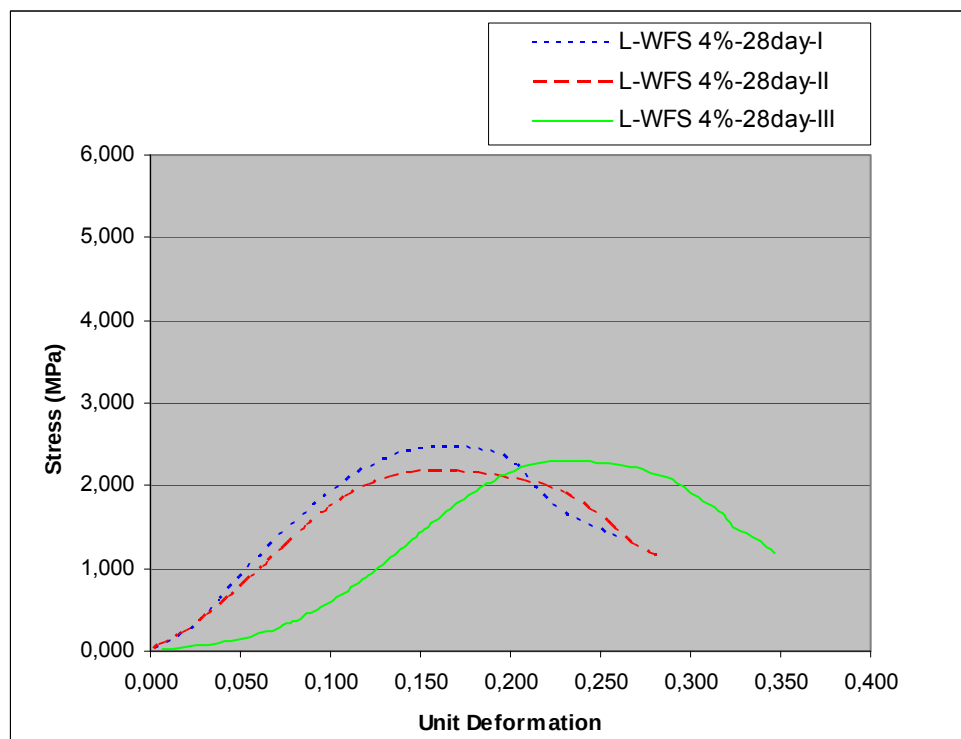


**Figure B.49 :** Stress – Unit Deformation Diagram of L-WFS 4%-28day Samples.

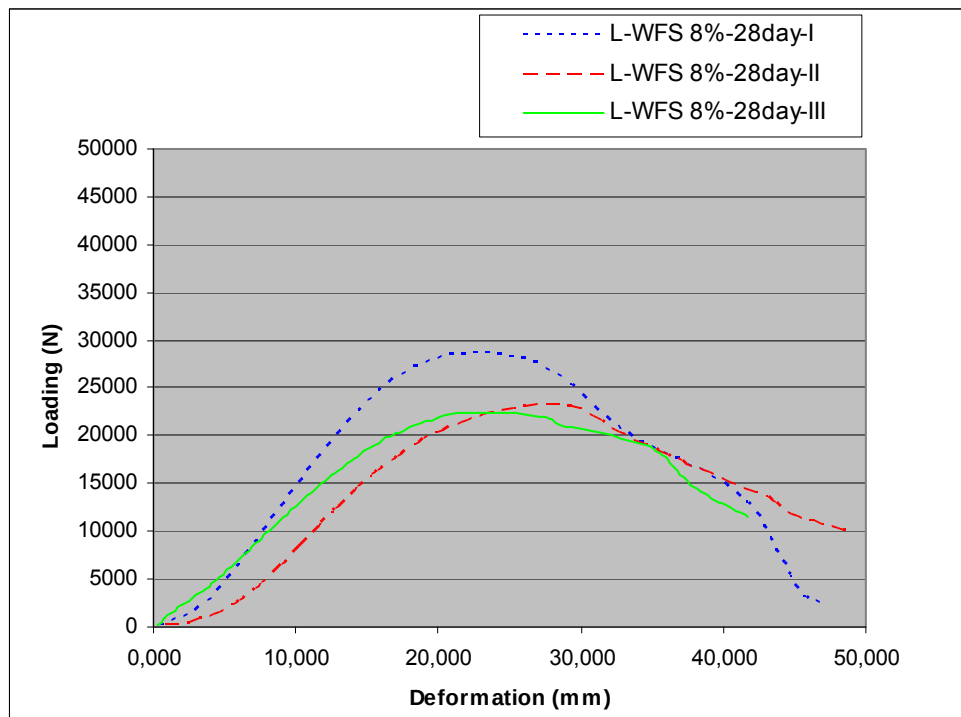


**Figure B.50 :** Loading – Deformation Diagram of L-WFS 8%-28day Samples.

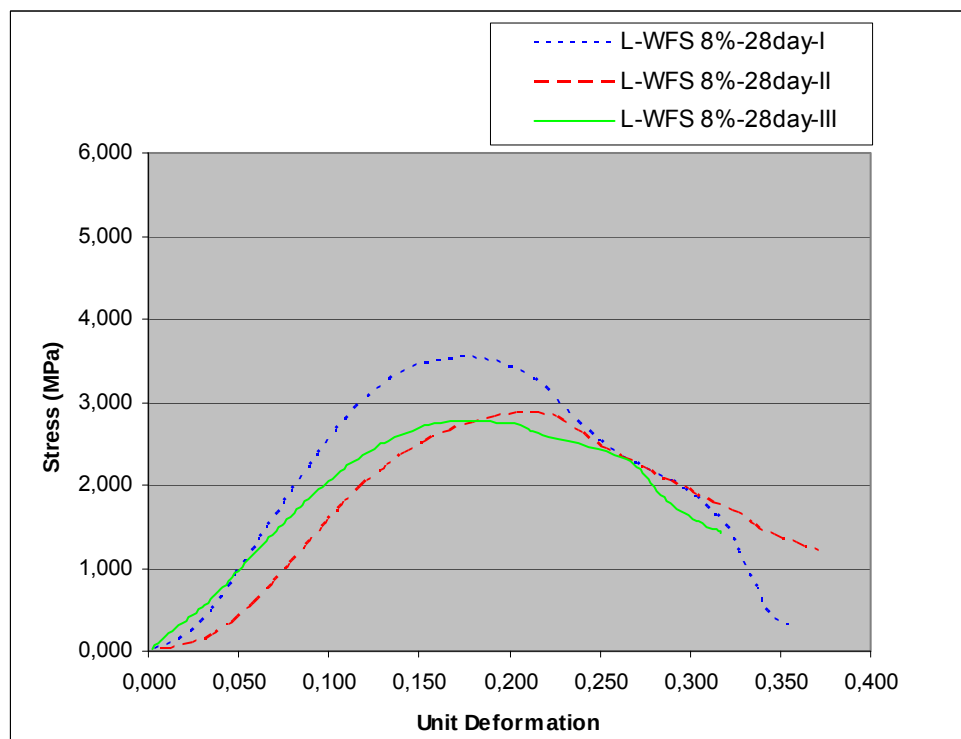


**Figure B.51 :** Stress – Unit Deformation Diagram of L-WFS 8%-28day Samples.

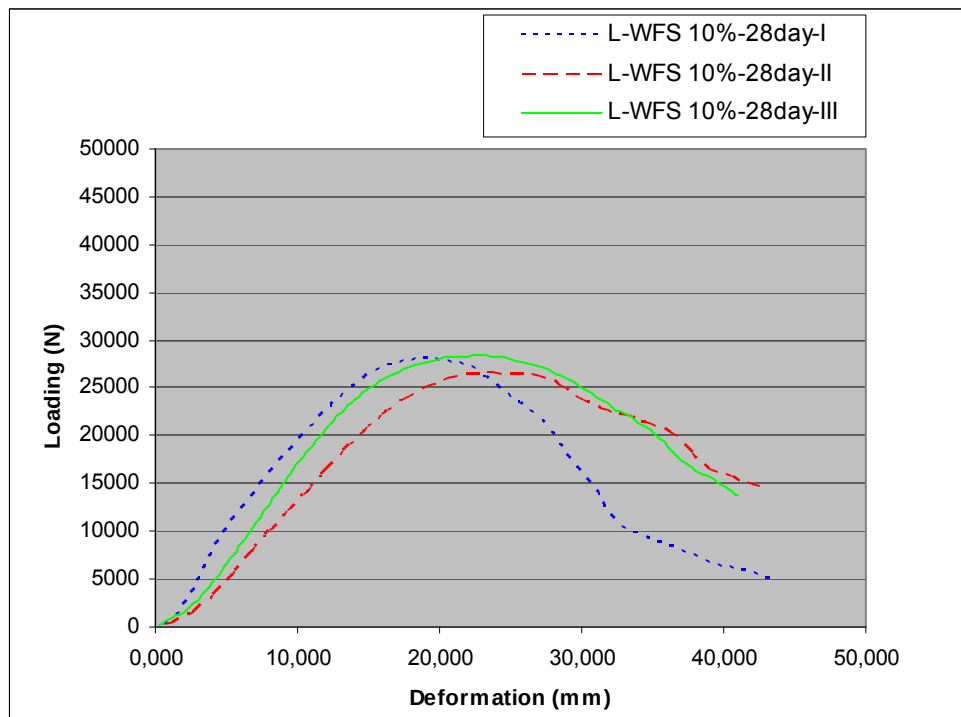


**Figure B.52 :** Loading – Deformation Diagram of L-WFS 10%-28day Samples.

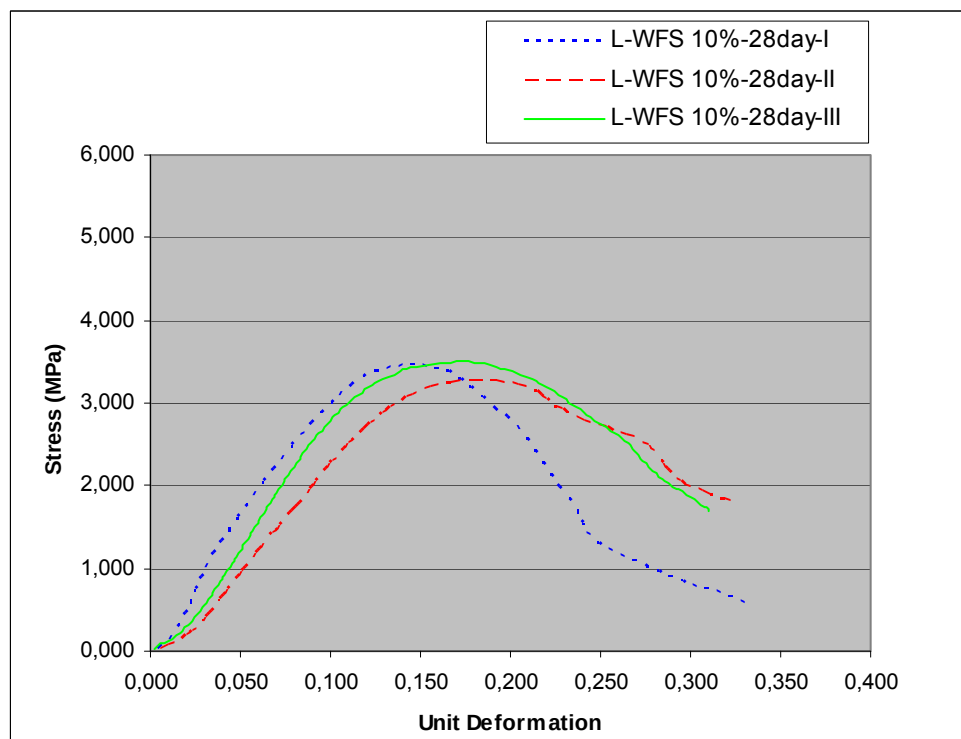


**Figure B.53 :** Stress – Unit Deformation Diagram of L-WFS 10%-28day Samples.

**Table B.6 : E Values of Lime Stabilized and 28-day Cured Samples.**

| Amount of Additives                  | Definition of Sample   | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|--------------------------------------|------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Lime  | L-WFS 2%-28day-I       | 21,530                           | 11652,350                     | 0,164                              | 1,437                          | 17,528                   |
|                                      | L-WFS 2%-28day-II      | 25,531                           | 11082,090                     | 0,194                              | 1,367                          | 14,092                   |
|                                      | L-WFS 2%-28day-III     | 20,011                           | 11207,200                     | 0,152                              | 1,382                          | 18,189                   |
| <b>Average Values</b>                | <b>L-WFS 2%-28day</b>  | <b>22,357</b>                    | <b>11313,880</b>              | <b>0,170</b>                       | <b>1,396</b>                   | <b>16,603</b>            |
| WFS Samples Stabilized With 4% Lime  | L-WFS 4%-28day-I       | 21,986                           | 19967,130                     | 0,168                              | 2,463                          | 29,320                   |
|                                      | L-WFS 4%-28day-II      | 20,591                           | 17736,790                     | 0,157                              | 2,188                          | 27,869                   |
|                                      | L-WFS 4%-28day-III     | 29,976                           | 18630,900                     | 0,229                              | 2,298                          | 20,070                   |
| <b>Average Values</b>                | <b>L-WFS 4%-28day</b>  | <b>24,184</b>                    | <b>18778,273</b>              | <b>0,185</b>                       | <b>2,316</b>                   | <b>25,753</b>            |
| WFS Samples Stabilized With 8% Lime  | L-WFS 8%-28day-I       | 23,581                           | 28624,990                     | 0,179                              | 3,531                          | 39,450                   |
|                                      | L-WFS 8%-28day-II      | 27,740                           | 23274,640                     | 0,210                              | 2,871                          | 27,341                   |
|                                      | L-WFS 8%-28day-III     | 22,142                           | 22423,920                     | 0,168                              | 2,766                          | 32,927                   |
| <b>Average Values</b>                | <b>L-WFS 8%-28day</b>  | <b>24,488</b>                    | <b>24774,517</b>              | <b>0,186</b>                       | <b>3,056</b>                   | <b>33,239</b>            |
| WFS Samples Stabilized With 10% Lime | L-WFS 10%-28day-I      | 18,757                           | 28050,500                     | 0,142                              | 3,460                          | 48,731                   |
|                                      | L-WFS 10%-28day-II     | 23,708                           | 26490,760                     | 0,180                              | 3,268                          | 36,306                   |
|                                      | L-WFS 10%-28day-III    | 22,870                           | 28358,970                     | 0,173                              | 3,498                          | 40,439                   |
| <b>Average Values</b>                | <b>L-WFS 10%-28day</b> | <b>21,778</b>                    | <b>27633,410</b>              | <b>0,165</b>                       | <b>3,408</b>                   | <b>41,825</b>            |

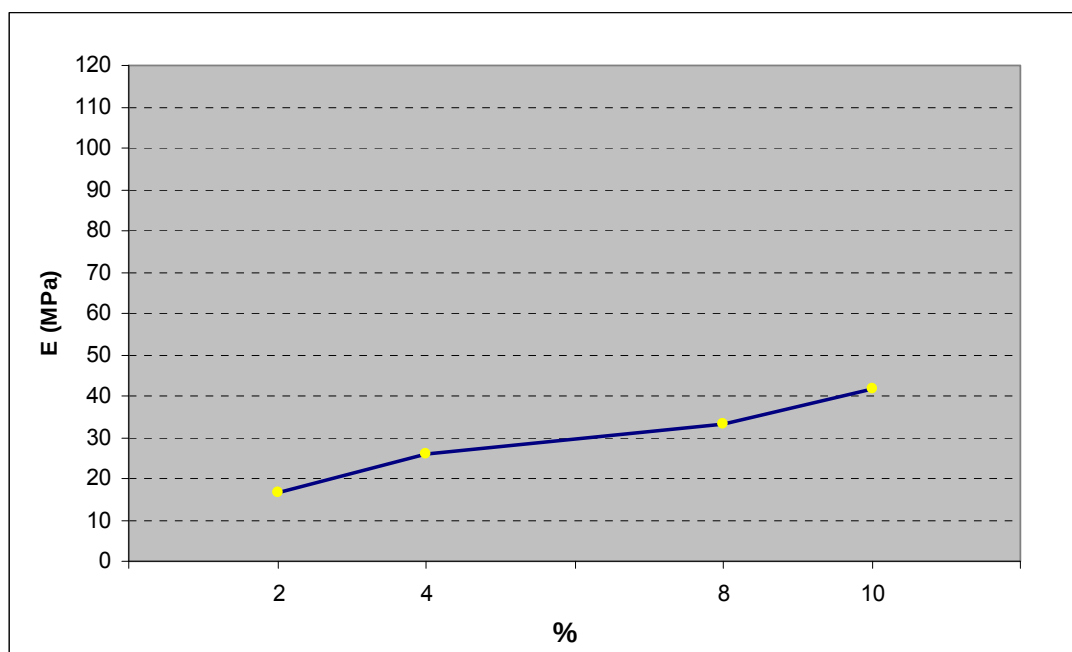


**Figure B.54 : E Values of Lime Stabilized and 28-day Cured Samples.**

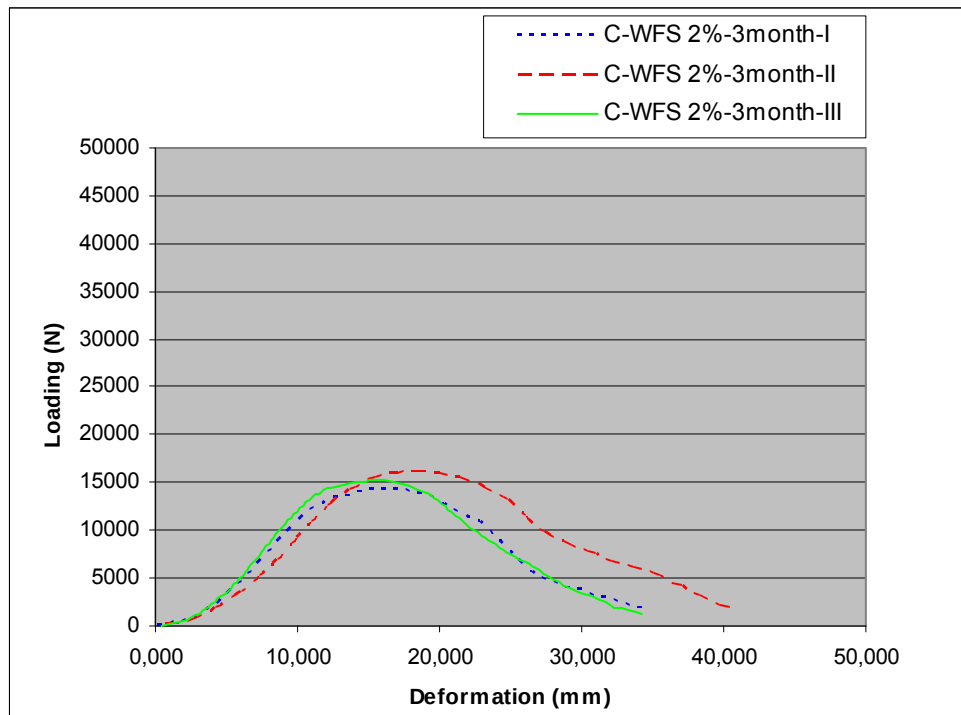


**Figure B.55 :** Loading – Deformation Diagram of C-WFS 2%-3month Samples.

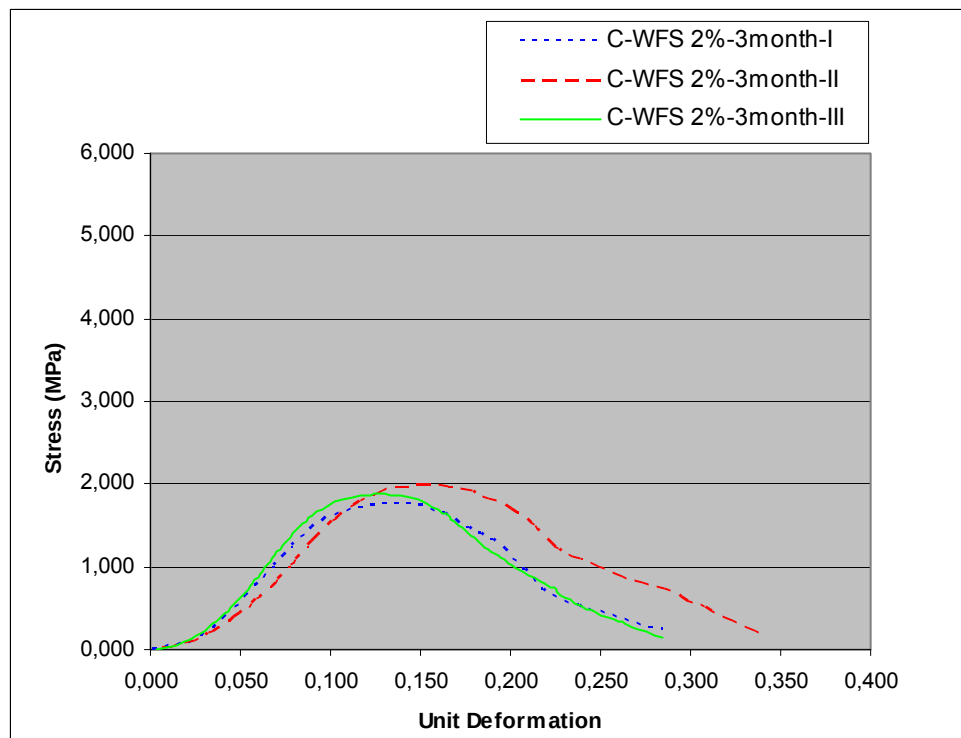


**Figure B.56 :** Stress – Unit Deformation Diagram of C-WFS 2%-3month Samples.

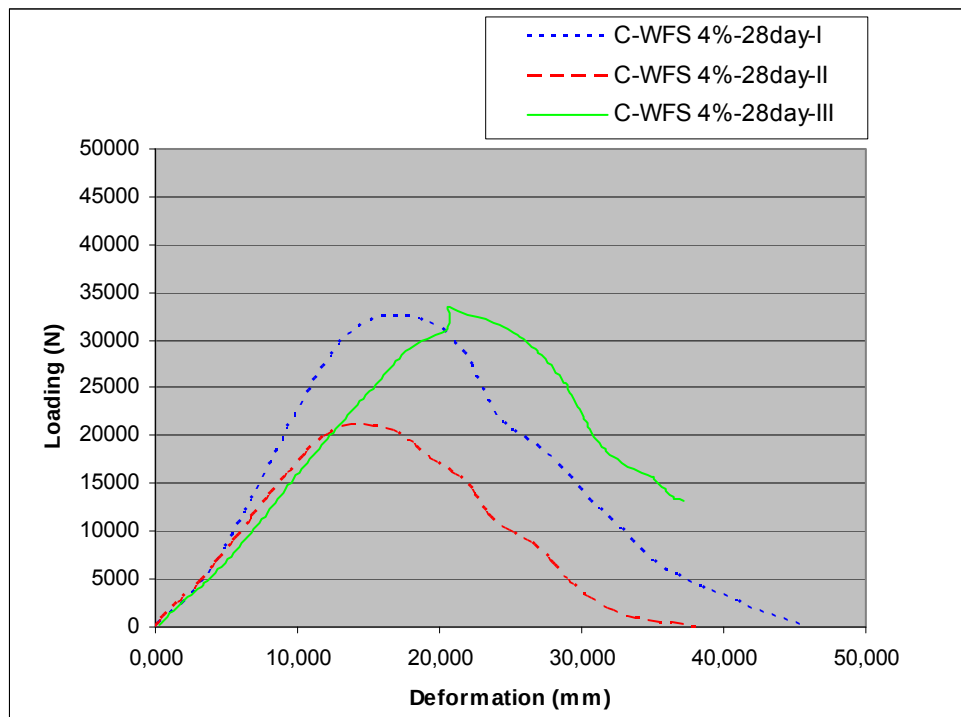


**Figure B.57 :** Loading – Deformation Diagram of C-WFS 4%-3month Samples.

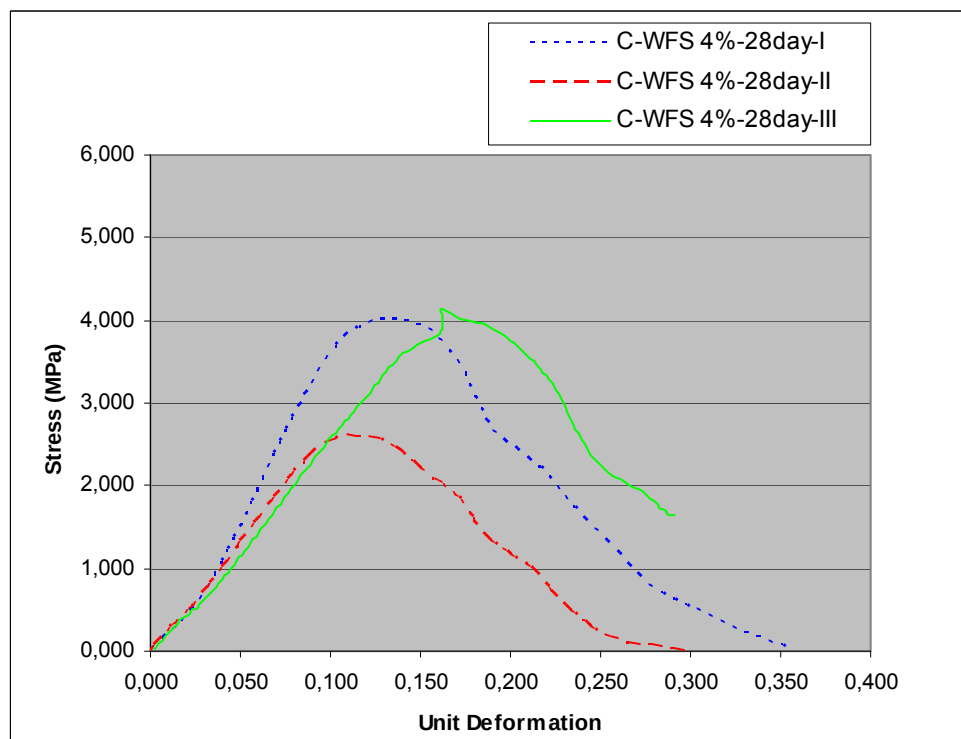


**Figure B.58 :** Stress – Unit Deformation Diagram of C-WFS 4%-3month Samples.

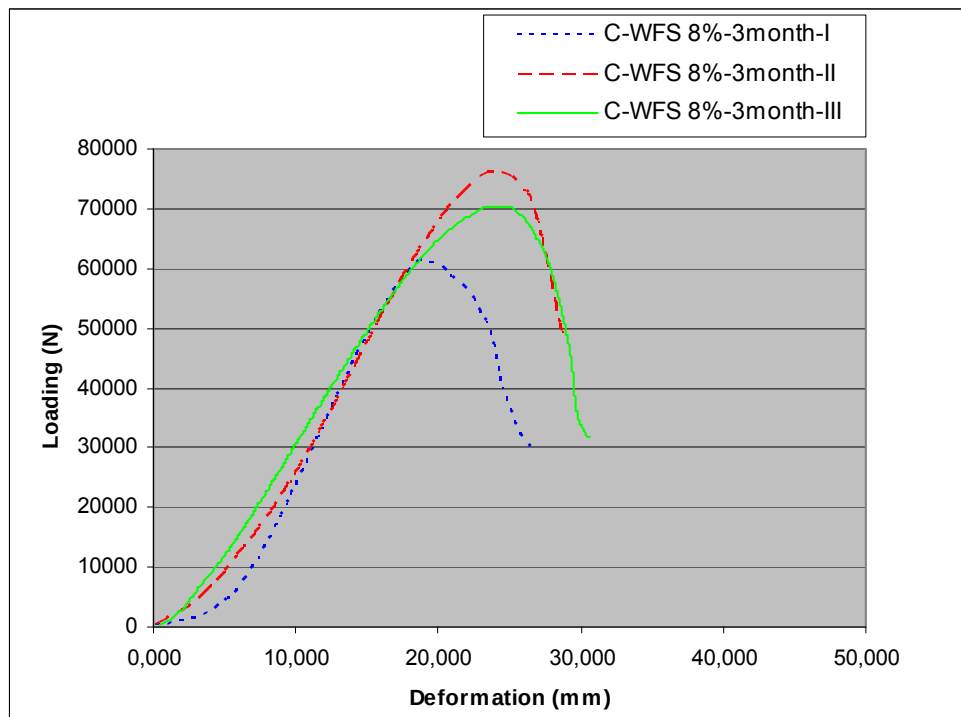


**Figure B.59 :** Loading – Deformation Diagram of C-WFS 8%-3month Samples.

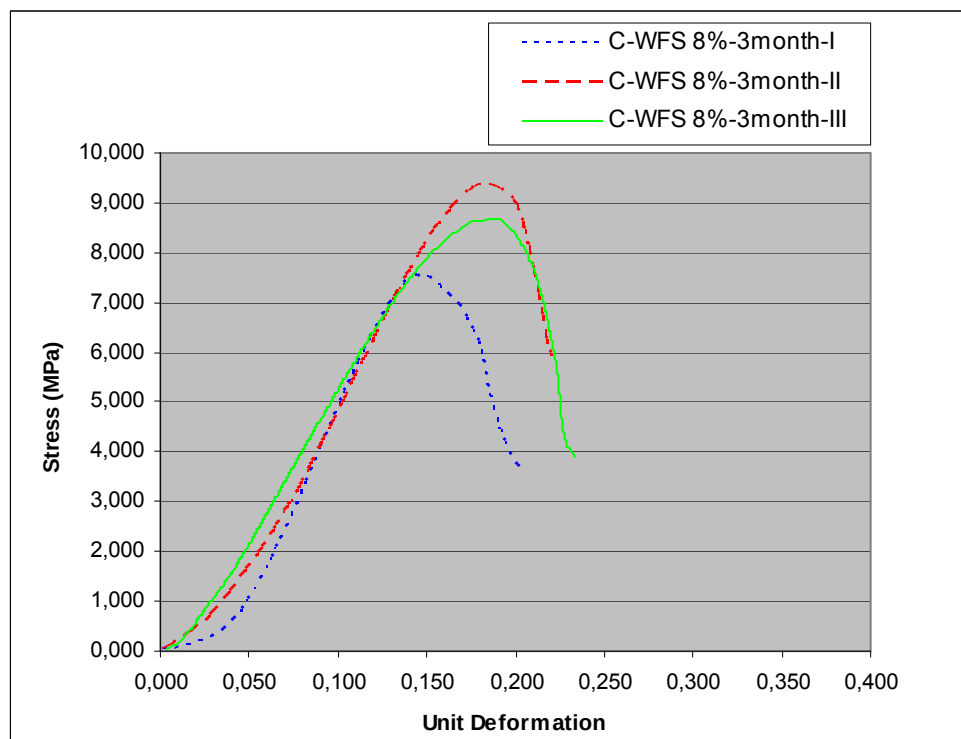


**Figure B.60 :** Stress – Unit Deformation Diagram of C-WFS 8%-3month Samples.

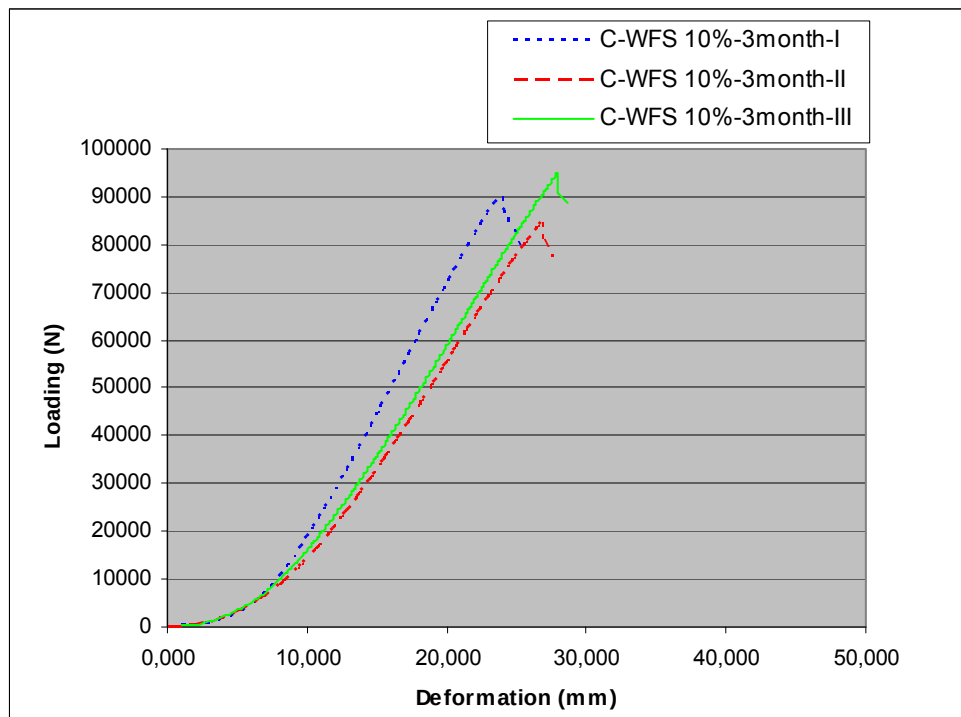


**Figure B.61 :** Loading – Deformation Diagram of C-WFS 10%-3month Samples.

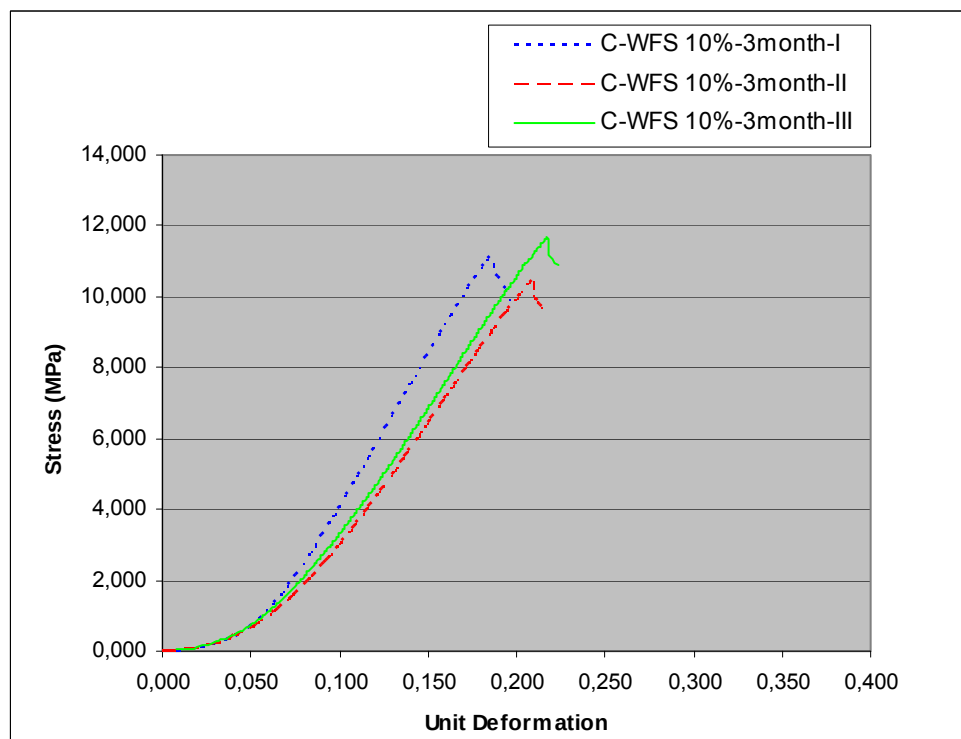


**Figure B.62 :** Stress – Unit Deformation Diagram of C-WFS 10%-3month Samples.

**Table B.7 : E Values of Cement Stabilized and 3-month Cured Samples.**

| Amount of Additives                    | Definition of Sample    | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|----------------------------------------|-------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Cement  | C-WFS 2%-3month-I       | 16,508                           | 14288,102                     | 0,137                              | 1,762                          | 25,728                   |
|                                        | C-WFS 2%-3month-II      | 18,075                           | 16126,051                     | 0,150                              | 1,989                          | 26,521                   |
|                                        | C-WFS 2%-3month-III     | 15,401                           | 15364,640                     | 0,128                              | 1,895                          | 29,612                   |
| <b>Average Values</b>                  | <b>C-WFS 2%-3month</b>  | <b>16,661</b>                    | <b>15259,597</b>              | <b>0,138</b>                       | <b>1,882</b>                   | <b>27,287</b>            |
| WFS Samples Stabilized With 4% Cement  | C-WFS 4%-28day-I        | 16,730                           | 32513,976                     | 0,131                              | 4,010                          | 61,228                   |
|                                        | C-WFS 4%-28day-II       | 13,735                           | 21119,843                     | 0,108                              | 2,605                          | 48,241                   |
|                                        | C-WFS 4%-28day-III      | 20,691                           | 33575,073                     | 0,162                              | 4,141                          | 51,128                   |
| <b>Average Values</b>                  | <b>C-WFS 4%-28day</b>   | <b>17,052</b>                    | <b>29069,631</b>              | <b>0,134</b>                       | <b>3,586</b>                   | <b>53,532</b>            |
| WFS Samples Stabilized With 8% Cement  | C-WFS 8%-3month-I       | 18,858                           | 61284,355                     | 0,144                              | 7,559                          | 104,988                  |
|                                        | C-WFS 8%-3month-II      | 24,396                           | 75969,938                     | 0,186                              | 9,371                          | 100,758                  |
|                                        | C-WFS 8%-3month-III     | 24,973                           | 70440,697                     | 0,191                              | 8,689                          | 90,979                   |
| <b>Average Values</b>                  | <b>C-WFS 8%-3month</b>  | <b>22,742</b>                    | <b>69231,663</b>              | <b>0,174</b>                       | <b>8,539</b>                   | <b>98,909</b>            |
| WFS Samples Stabilized With 10% Cement | C-WFS 10%-3month-I      | 23,884                           | 90342,482                     | 0,186                              | 11,143                         | 119,821                  |
|                                        | C-WFS 10%-3month-II     | 26,813                           | 84655,384                     | 0,209                              | 10,442                         | 99,922                   |
|                                        | C-WFS 10%-3month-III    | 27,926                           | 94788,564                     | 0,217                              | 11,692                         | 107,758                  |
| <b>Average Values</b>                  | <b>C-WFS 10%-3month</b> | <b>26,208</b>                    | <b>89928,810</b>              | <b>0,204</b>                       | <b>11,092</b>                  | <b>109,167</b>           |

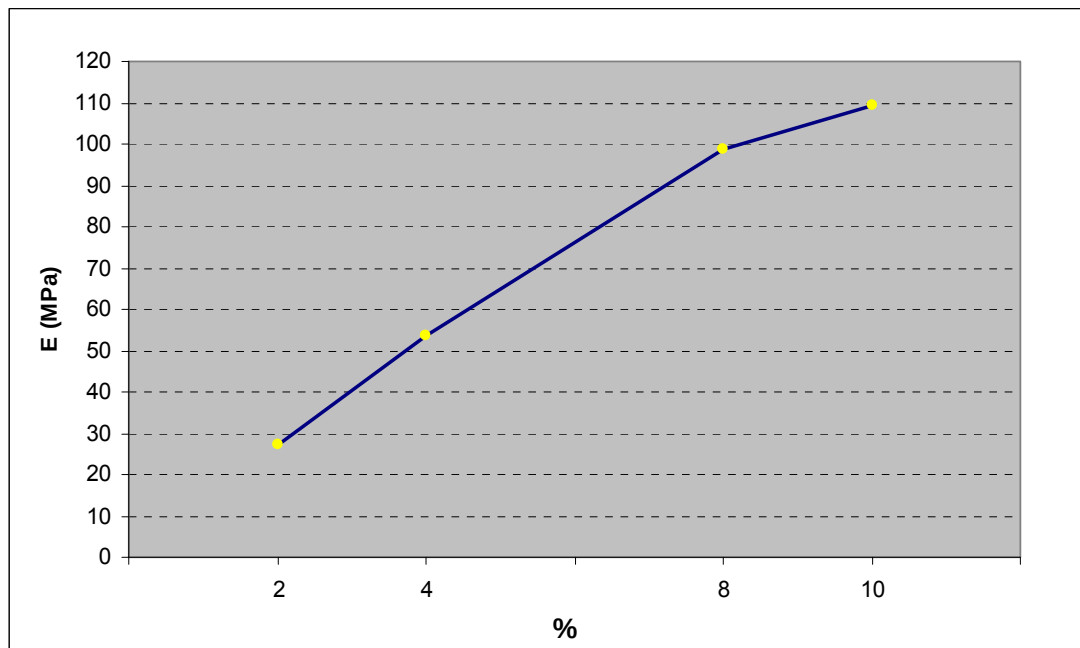


**Figure B.63 : E Values of Cement Stabilized and 3-month Cured Samples.**

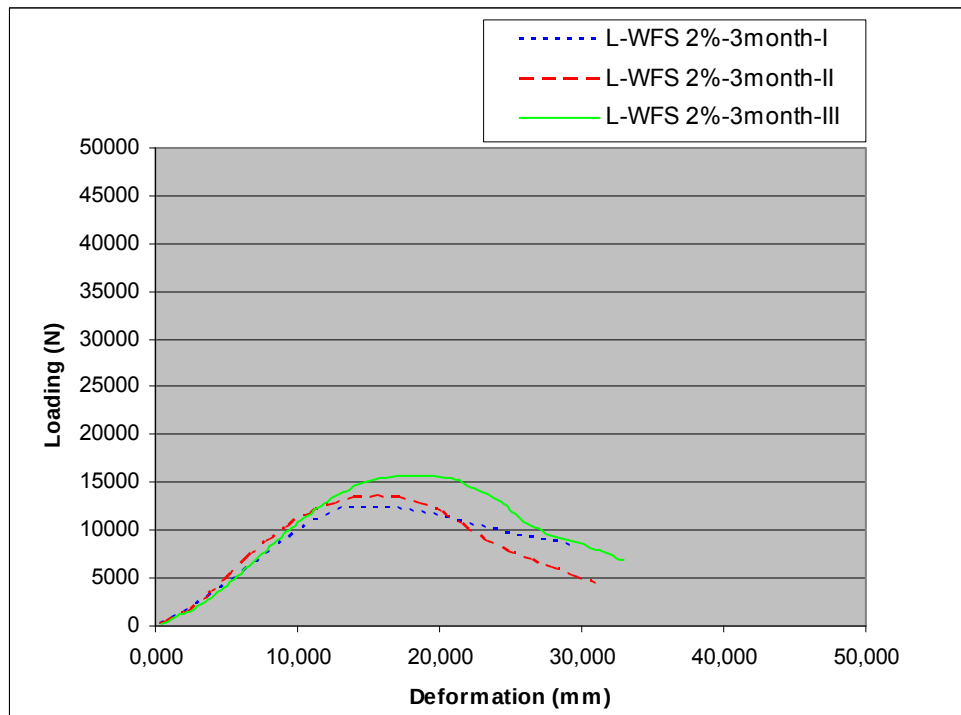


**Figure B.64 :** Loading – Deformation Diagram of L-WFS 2%-3month Samples.

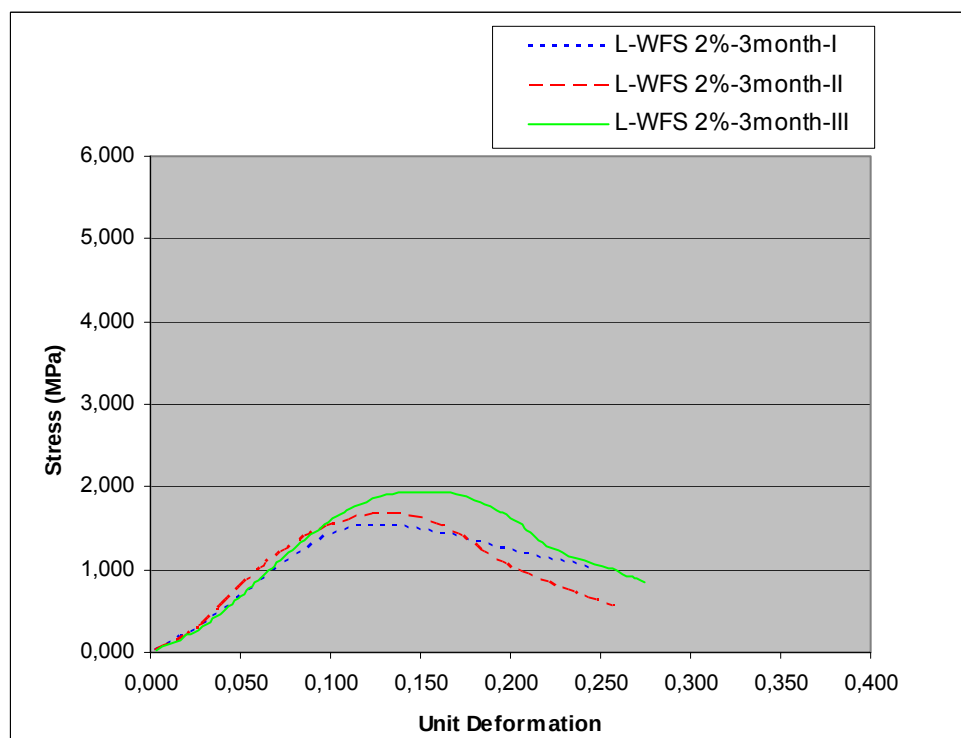


**Figure B.65 :** Stress – Unit Deformation Diagram of L-WFS 2%-3month Samples.

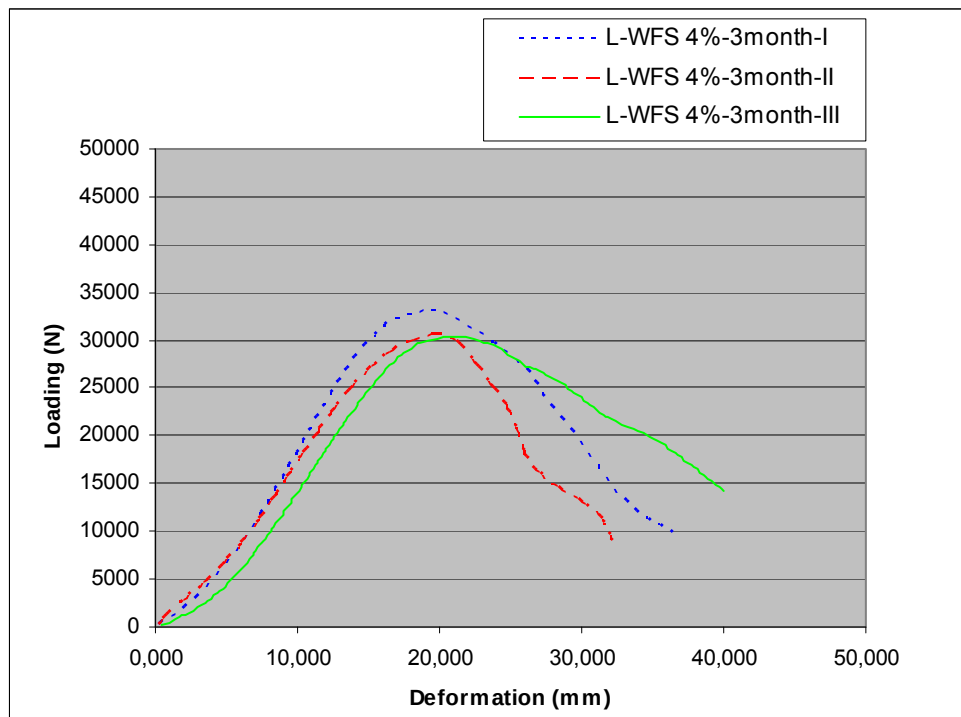


**Figure B.66 :** Loading – Deformation Diagram of L-WFS 4%-3month Samples.

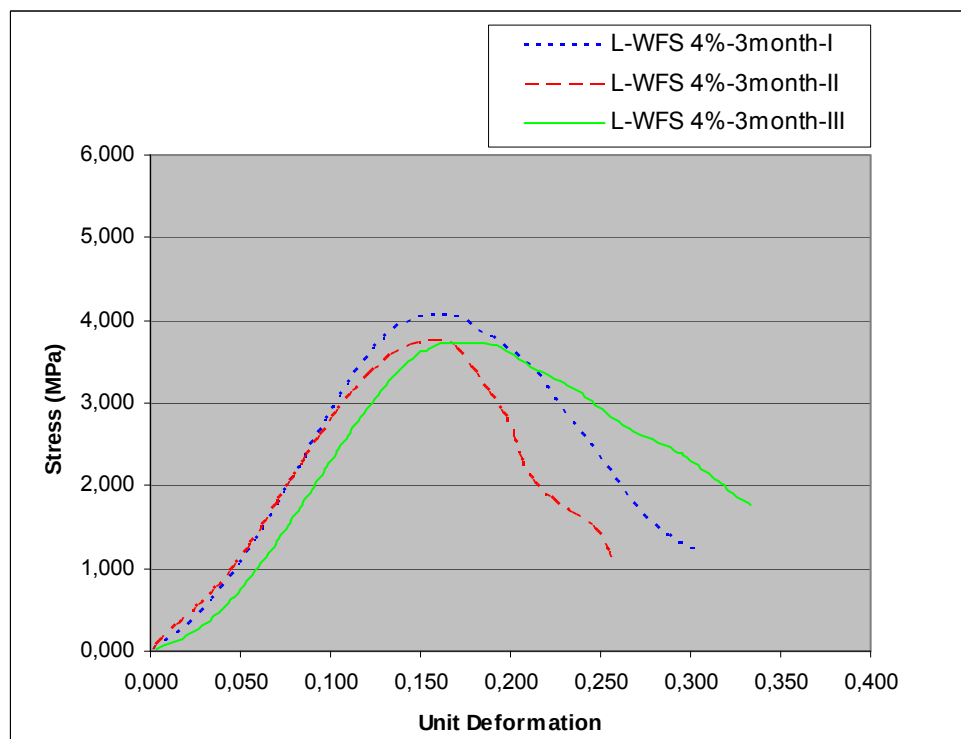


**Figure B.67 :** Stress – Unit Deformation Diagram of L-WFS 4%-3month Samples.

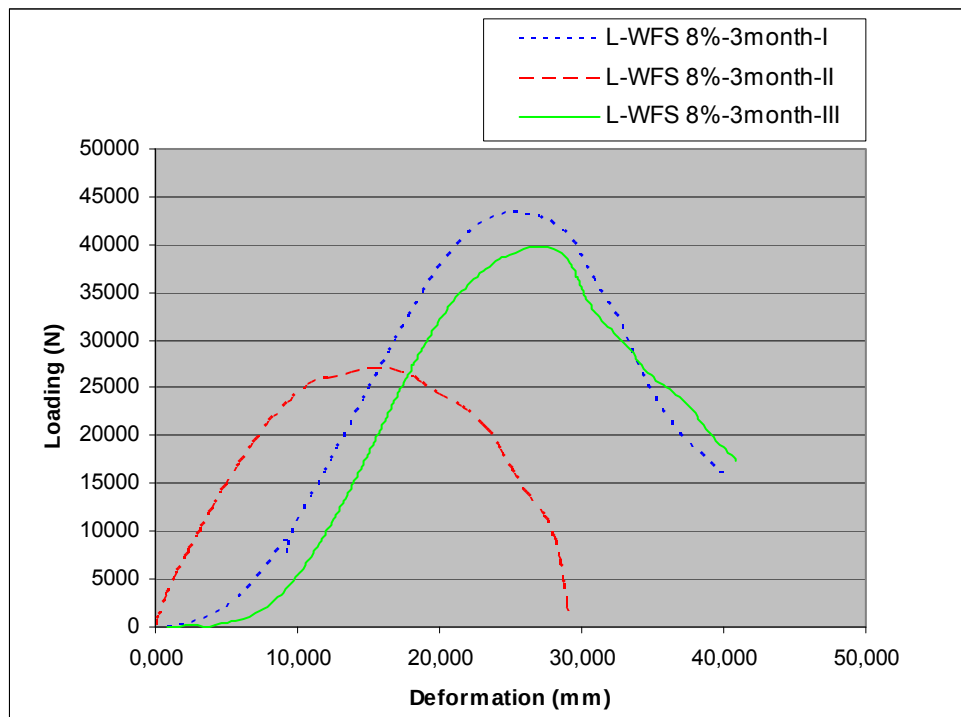


**Figure B.68 :** Loading – Deformation Diagram of L-WFS 8%-3month Samples.

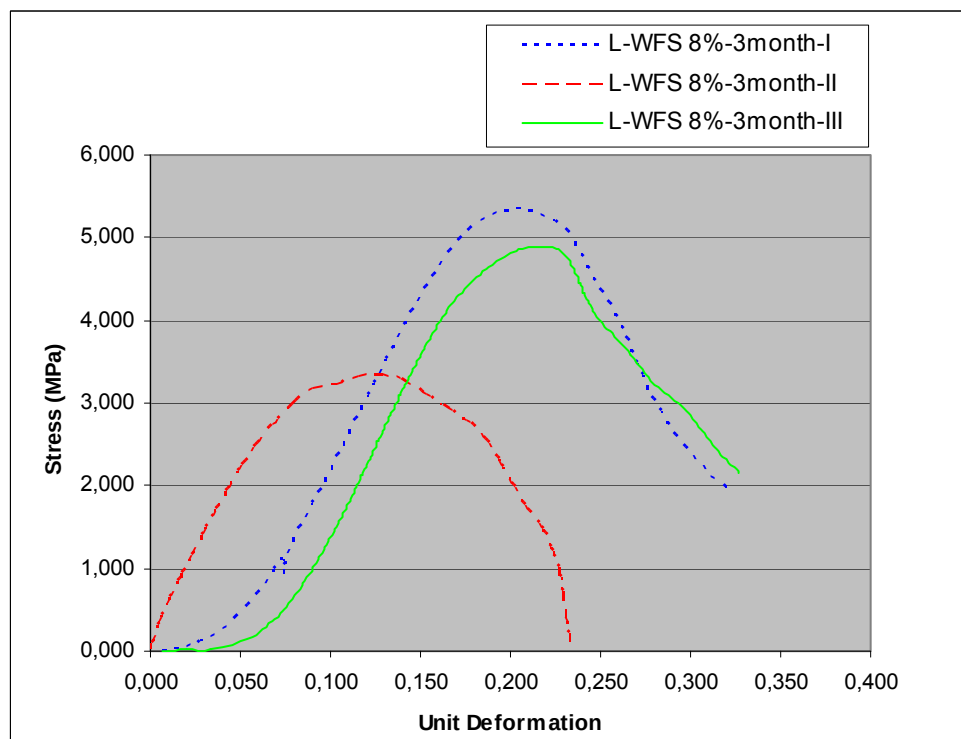


**Figure B.69 :** Stress – Unit Deformation Diagram of L-WFS 8%-3month Samples.

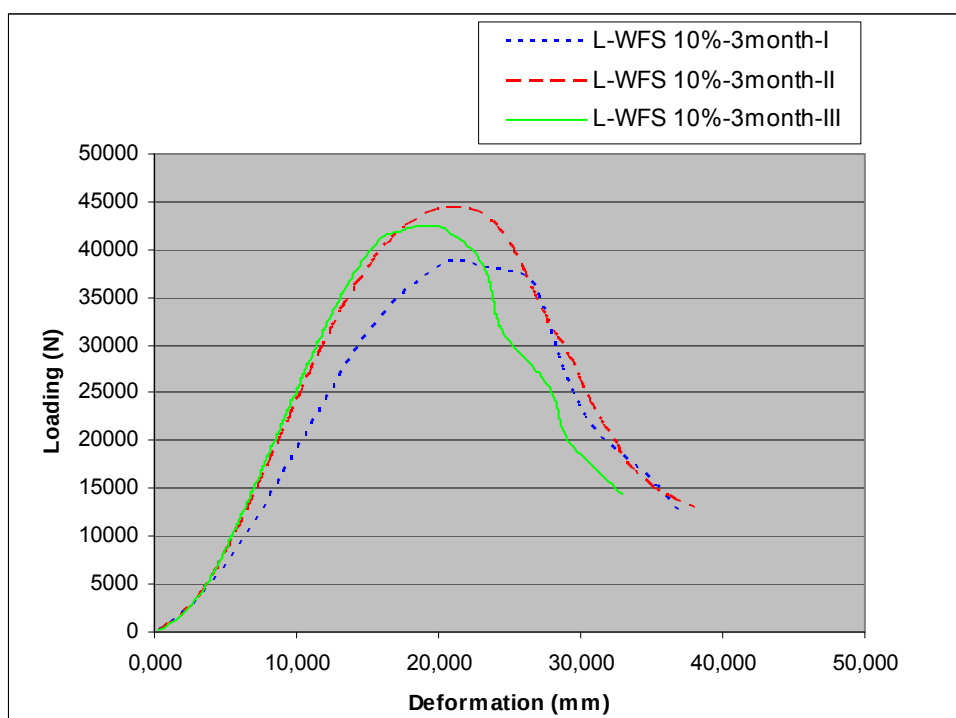


**Figure B.70 :** Loading – Deformation Diagram of L-WFS 10%-3month Samples.

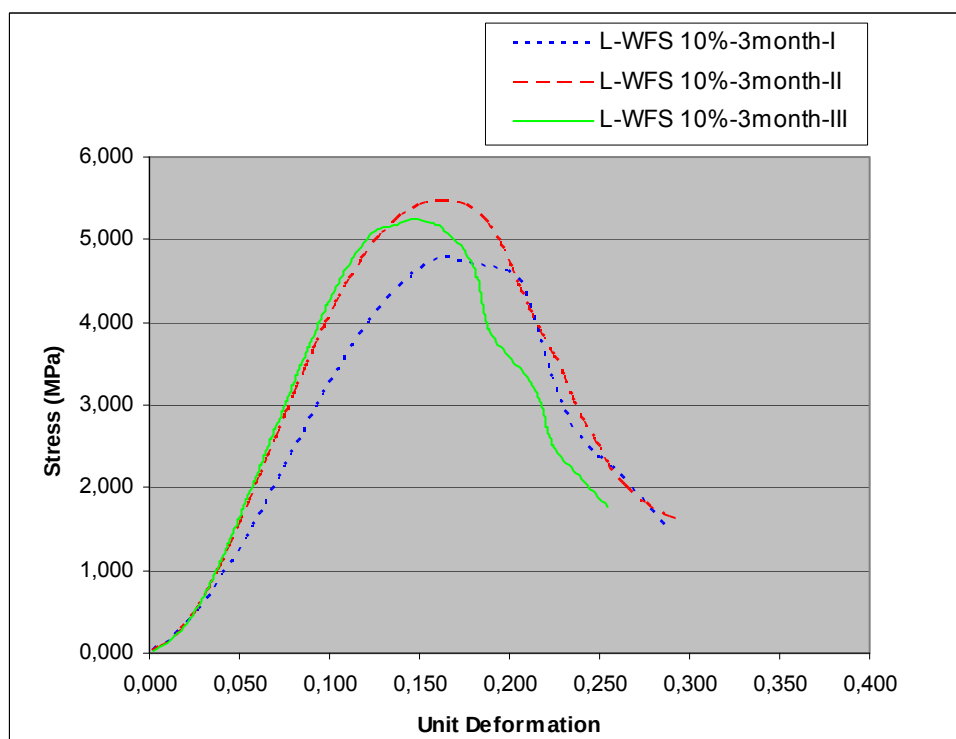


**Figure B.71 :** Stress – Unit Deformation Diagram of L-WFS 10%-3month Samples.

**Table B.8 : E Values of Lime Stabilized and 3-month Cured Samples.**

| Amount of Additives                  | Definition of Sample    | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|--------------------------------------|-------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Lime  | L-WFS 2%-3month-I       | 15,082                           | 12366,230                     | 0,126                              | 1,525                          | 24,211                   |
|                                      | L-WFS 2%-3month-II      | 15,581                           | 13502,120                     | 0,130                              | 1,665                          | 25,622                   |
|                                      | L-WFS 2%-3month-III     | 17,860                           | 15745,040                     | 0,149                              | 1,942                          | 26,068                   |
| <b>Average Values</b>                | <b>L-WFS 2%-3month</b>  | <b>16,174</b>                    | <b>13871,130</b>              | <b>0,135</b>                       | <b>1,711</b>                   | <b>25,300</b>            |
| WFS Samples Stabilized With 4% Lime  | L-WFS 4%-3month-I       | 19,841                           | 32975,880                     | 0,165                              | 4,067                          | 49,302                   |
|                                      | L-WFS 4%-3month-II      | 20,245                           | 30444,480                     | 0,162                              | 3,755                          | 46,360                   |
|                                      | L-WFS 4%-3month-III     | 20,839                           | 30279,310                     | 0,173                              | 3,735                          | 43,177                   |
| <b>Average Values</b>                | <b>L-WFS 4%-3month</b>  | <b>20,308</b>                    | <b>31233,223</b>              | <b>0,167</b>                       | <b>3,852</b>                   | <b>46,280</b>            |
| WFS Samples Stabilized With 8% Lime  | L-WFS 8%-3month-I       | 25,499                           | 43253,620                     | 0,204                              | 5,335                          | 52,305                   |
|                                      | L-WFS 8%-3month-II      | 16,150                           | 27083,730                     | 0,129                              | 3,341                          | 51,793                   |
|                                      | L-WFS 8%-3month-III     | 26,726                           | 39667,560                     | 0,214                              | 4,893                          | 45,727                   |
| <b>Average Values</b>                | <b>L-WFS 8%-3month</b>  | <b>22,792</b>                    | <b>36668,303</b>              | <b>0,182</b>                       | <b>4,523</b>                   | <b>49,942</b>            |
| WFS Samples Stabilized With 10% Lime | L-WFS 10%-3month-I      | 21,675                           | 38773,140                     | 0,168                              | 4,782                          | 56,934                   |
|                                      | L-WFS 10%-3month-II     | 21,549                           | 44379,500                     | 0,167                              | 5,474                          | 65,557                   |
|                                      | L-WFS 10%-3month-III    | 18,808                           | 42506,430                     | 0,145                              | 5,243                          | 72,317                   |
| <b>Average Values</b>                | <b>L-WFS 10%-3month</b> | <b>20,677</b>                    | <b>41886,357</b>              | <b>0,160</b>                       | <b>5,166</b>                   | <b>64,936</b>            |

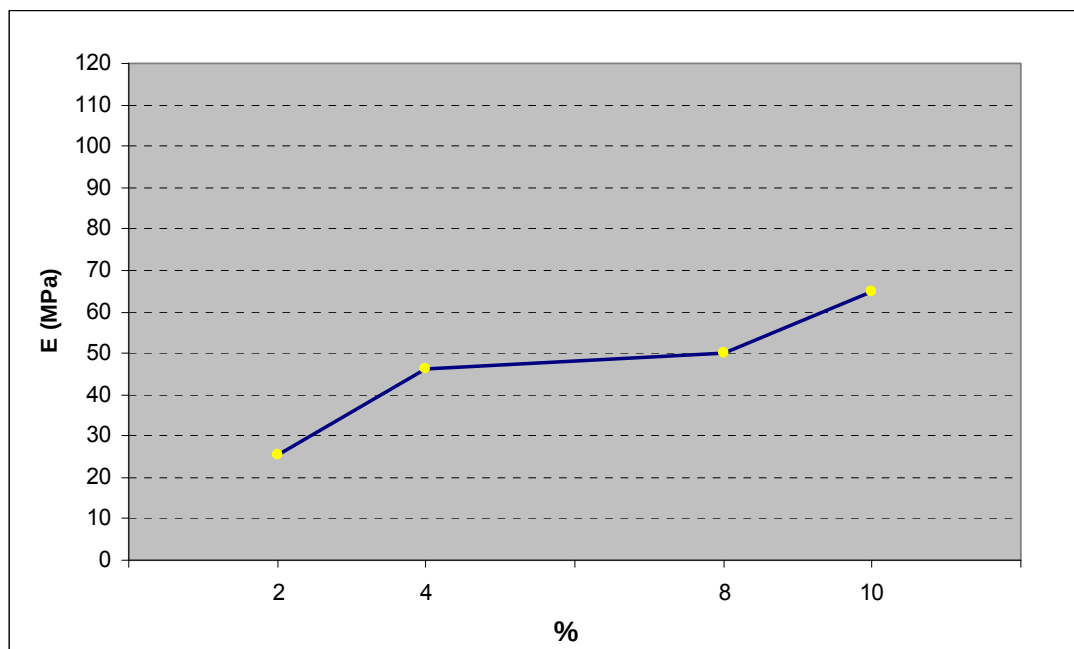


**Figure B.72 : E Values of Lime Stabilized and 3-month Cured Samples.**

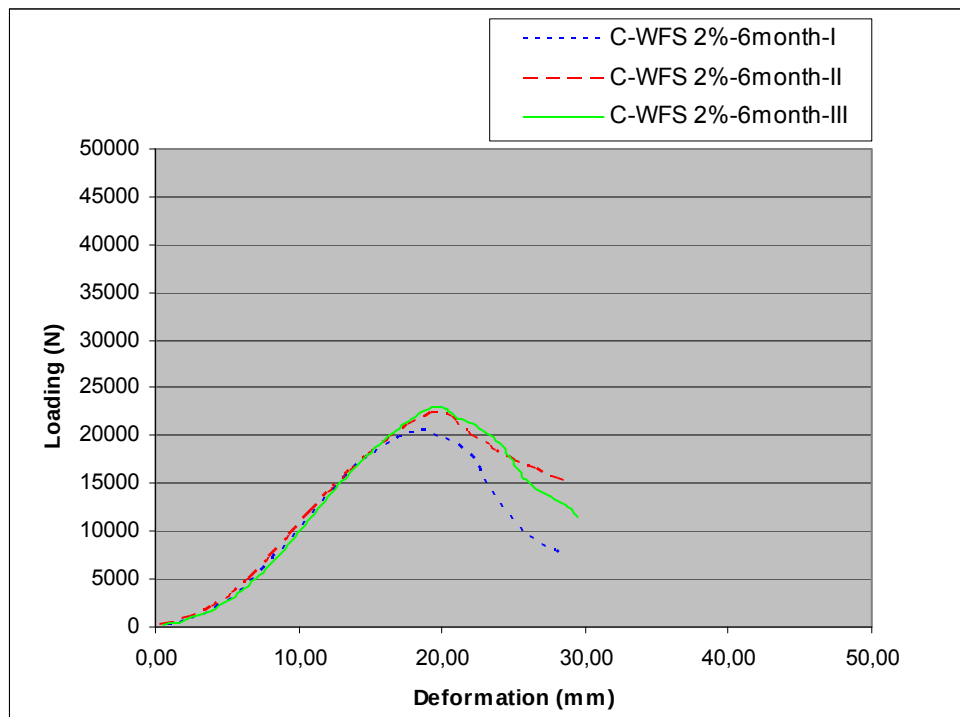


**Figure B.73 :** Loading – Deformation Diagram of C-WFS 2%-6month Samples.

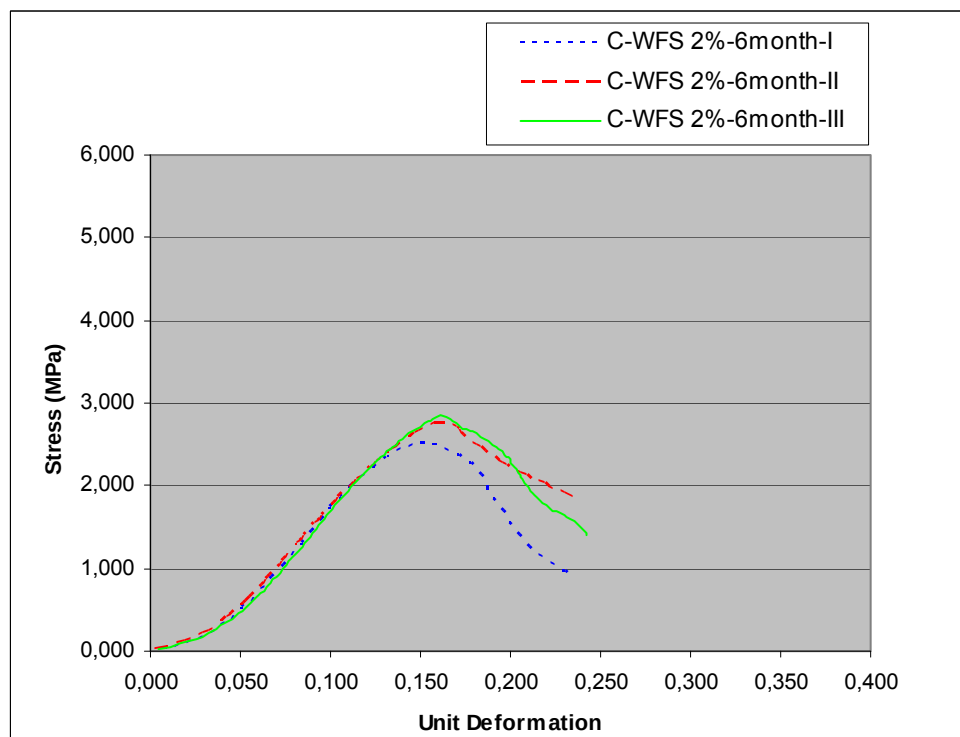


**Figure B.74 :** Stress – Unit Deformation Diagram of C-WFS 2%-6month Samples.

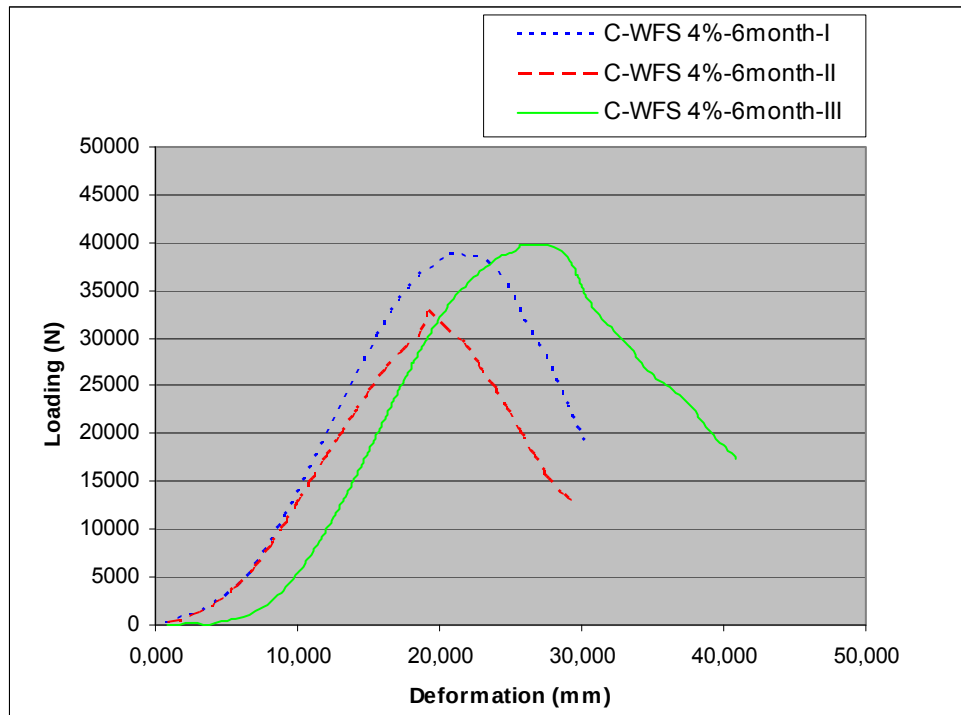


**Figure B.75 :** Loading – Deformation Diagram of C-WFS 4%-6month Samples.

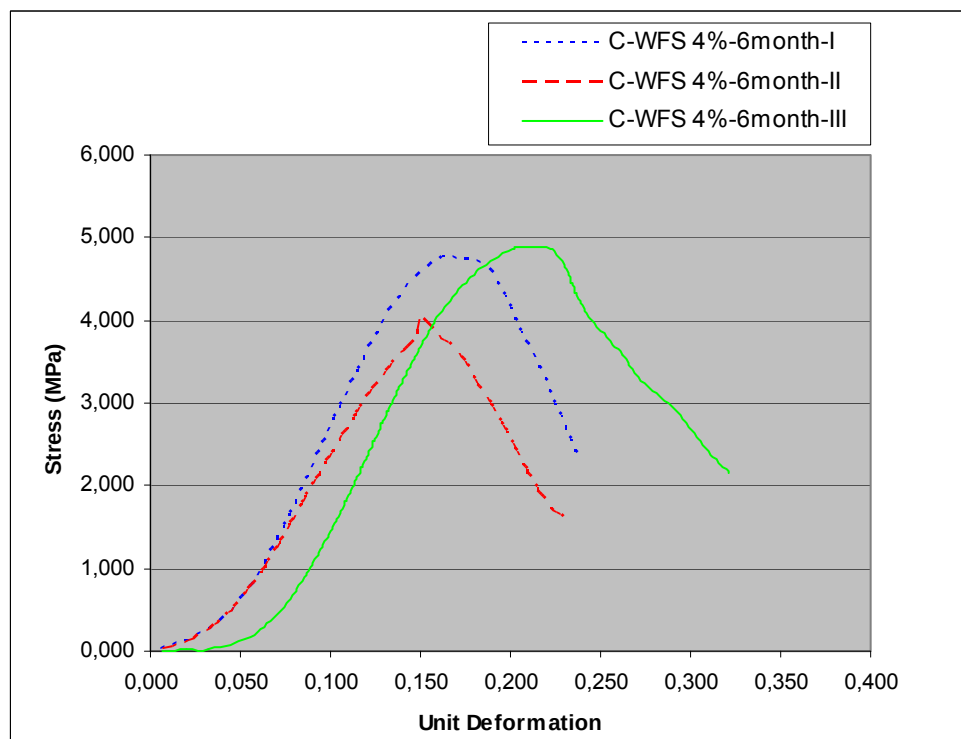


**Figure B.76 :** Stress – Unit Deformation Diagram of C-WFS 4%-6month Samples.

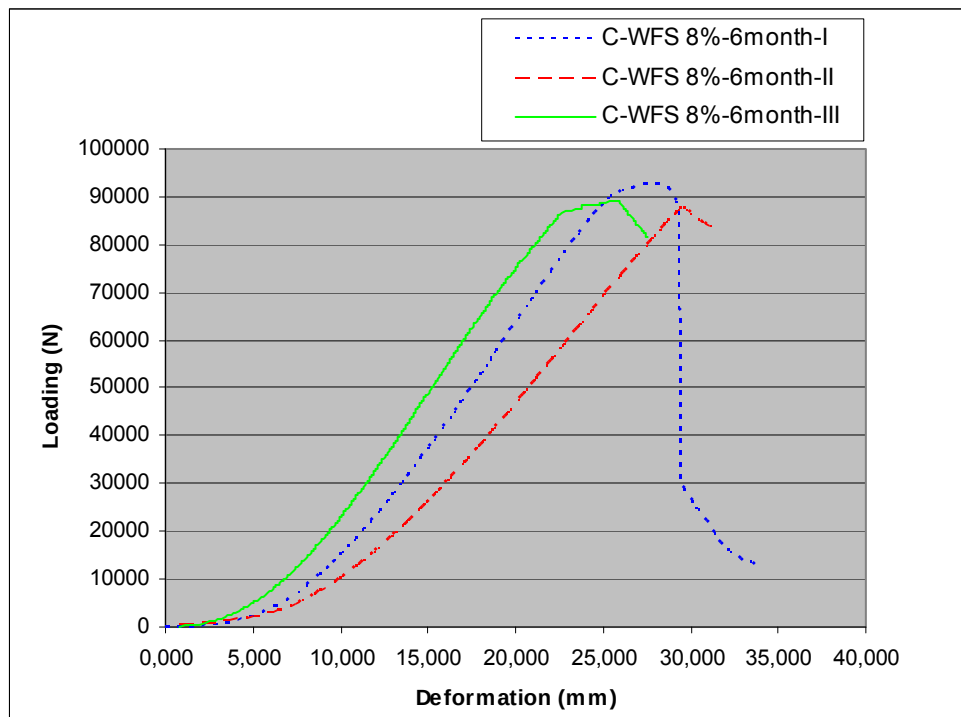


**Figure B.77 :** Loading – Deformation Diagram of C-WFS 8%-6month Samples.

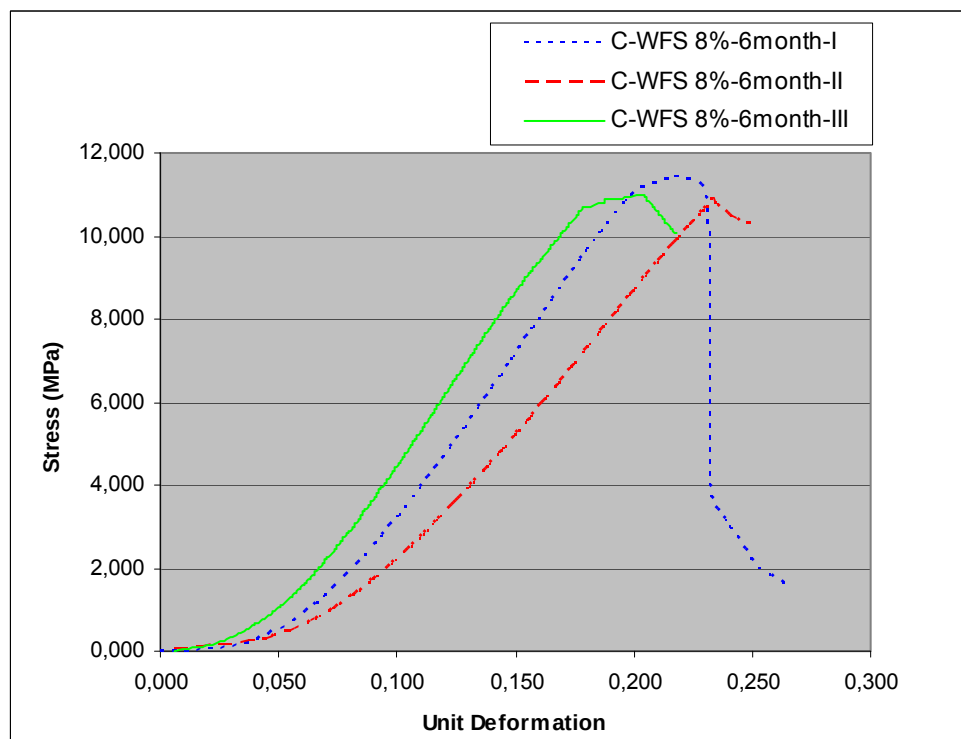


**Figure B.78 :** Stress – Unit Deformation Diagram of C-WFS 8%-6month Samples.

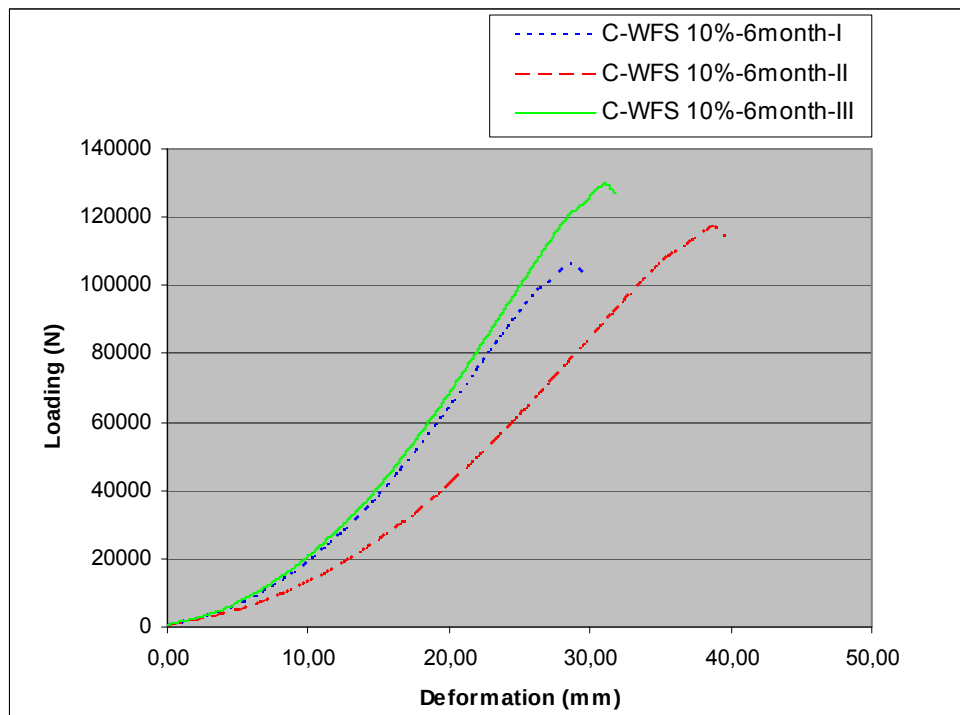


**Figure B.79 :** Loading – Deformation Diagram of C-WFS 10%-6month Samples.

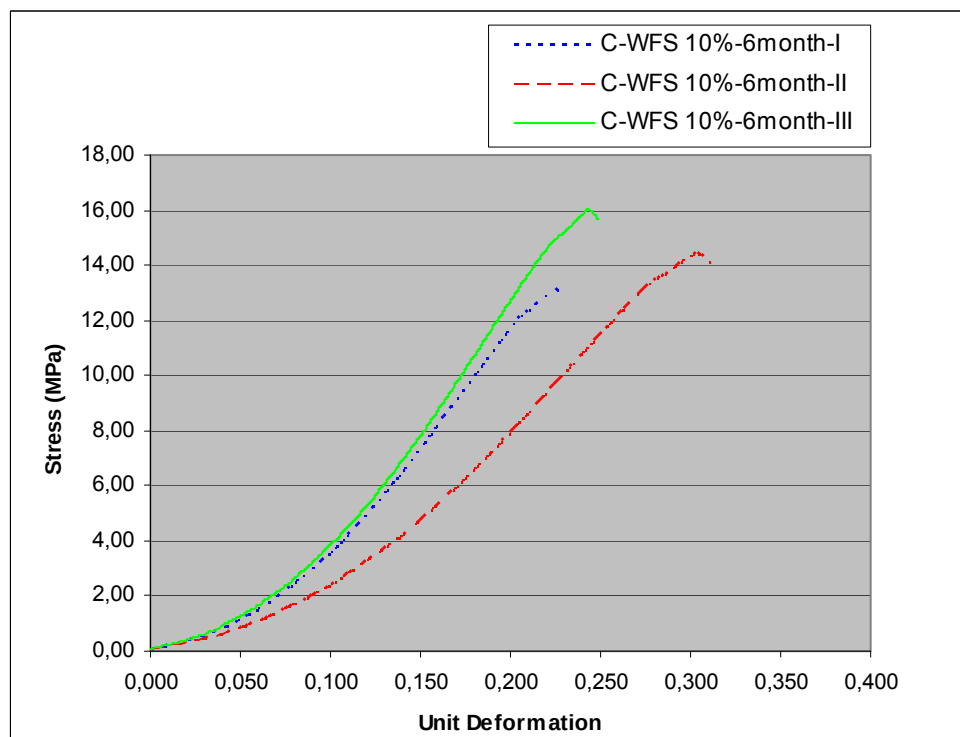
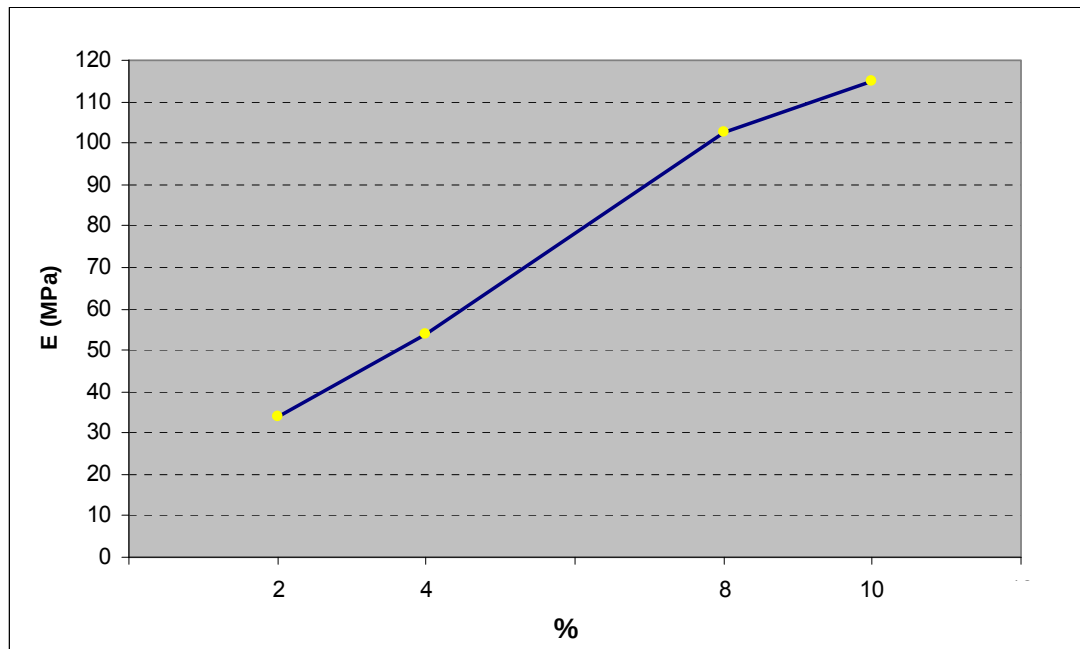


**Figure B.80 :** Stress – Unit Deformation Diagram of C-WFS 10%-6month Samples.

**Table B.9 : E Values of Cement Stabilized and 6-month Cured Samples.**

| Amount of Additives                    | Definition of Sample    | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|----------------------------------------|-------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Cement  | C-WFS 2%-6month-I       | 18,700                           | 20440,260                     | 0,154                              | 2,521                          | 32,743                   |
|                                        | C-WFS 2%-6month-II      | 20,021                           | 22448,480                     | 0,165                              | 2,769                          | 33,563                   |
|                                        | C-WFS 2%-6month-III     | 19,567                           | 23057,560                     | 0,161                              | 2,844                          | 35,330                   |
| <b>Average Values</b>                  | <b>C-WFS 2%-6month</b>  | <b>19,429</b>                    | <b>21982,100</b>              | <b>0,160</b>                       | <b>2,711</b>                   | <b>33,878</b>            |
| WFS Samples Stabilized With 4% Cement  | C-WFS 4%-6month-I       | 20,601                           | 38636,680                     | 0,162                              | 4,766                          | 58,835                   |
|                                        | C-WFS 4%-6month-II      | 19,099                           | 32903,800                     | 0,150                              | 4,059                          | 54,114                   |
|                                        | C-WFS 4%-6month-III     | 25,826                           | 39667,560                     | 0,203                              | 4,893                          | 48,205                   |
| <b>Average Values</b>                  | <b>C-WFS 4%-6month</b>  | <b>21,842</b>                    | <b>37069,347</b>              | <b>0,172</b>                       | <b>4,572</b>                   | <b>53,718</b>            |
| WFS Samples Stabilized With 8% Cement  | C-WFS 8%-6month-I       | 27,223                           | 92529,900                     | 0,215                              | 11,413                         | 106,169                  |
|                                        | C-WFS 8%-6month-II      | 29,553                           | 88887,130                     | 0,233                              | 10,964                         | 94,110                   |
|                                        | C-WFS 8%-6month-III     | 25,859                           | 89117,430                     | 0,204                              | 10,992                         | 107,767                  |
| <b>Average Values</b>                  | <b>C-WFS 8%-6month</b>  | <b>27,545</b>                    | <b>90178,15</b>               | <b>0,217</b>                       | <b>11,123</b>                  | <b>102,682</b>           |
| WFS Samples Stabilized With 10% Cement | C-WFS 10%-6month-I      | 28,643                           | 106559,881                    | 0,224                              | 13,144                         | 117,354                  |
|                                        | C-WFS 10%-6month-II     | 38,758                           | 117215,870                    | 0,304                              | 14,458                         | 95,119                   |
|                                        | C-WFS 10%-6month-III    | 31,089                           | 130239,035                    | 0,244                              | 16,064                         | 131,675                  |
| <b>Average Values</b>                  | <b>C-WFS 10%-6month</b> | <b>32,830</b>                    | <b>118004,93</b>              | <b>0,257</b>                       | <b>14,555</b>                  | <b>114,716</b>           |

**Table B.81 : E Values of Cement Stabilized and 6-month Cured Samples.**

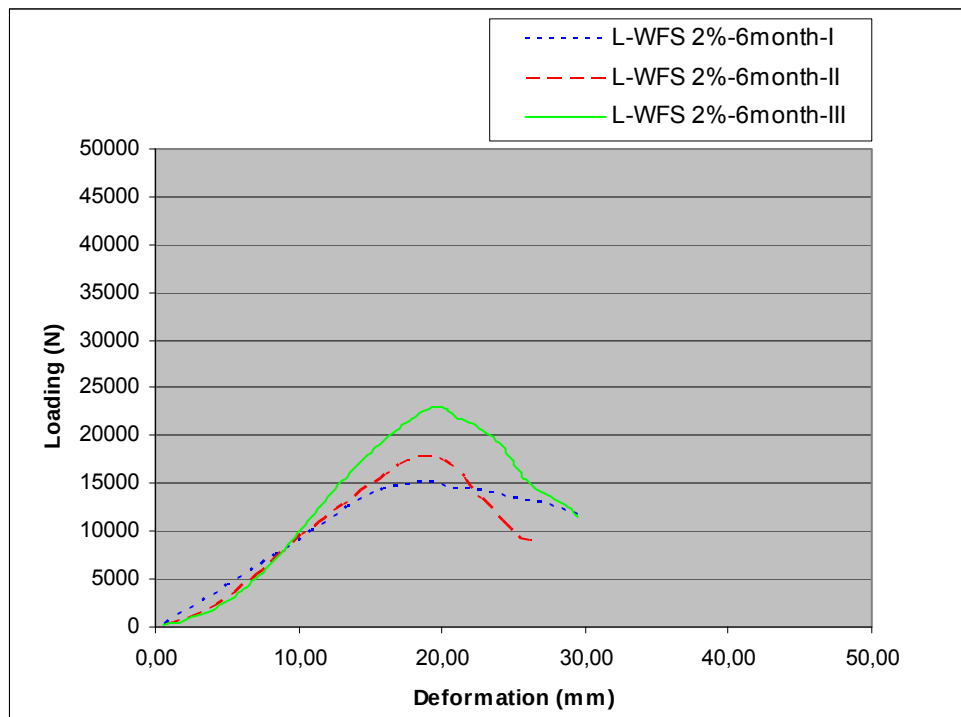


**Figure B.82 :** Loading – Deformation Diagram of L-WFS 2%-6month Samples.

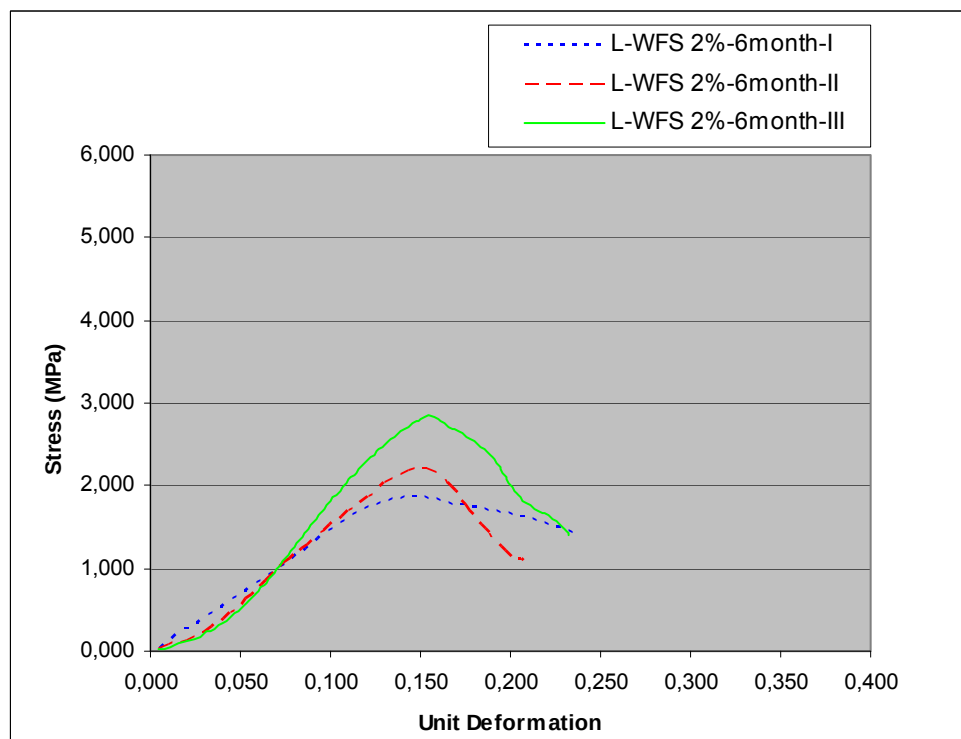


**Figure B.83 :** Stress – Unit Deformation Diagram of L-WFS 2%-6month Samples.

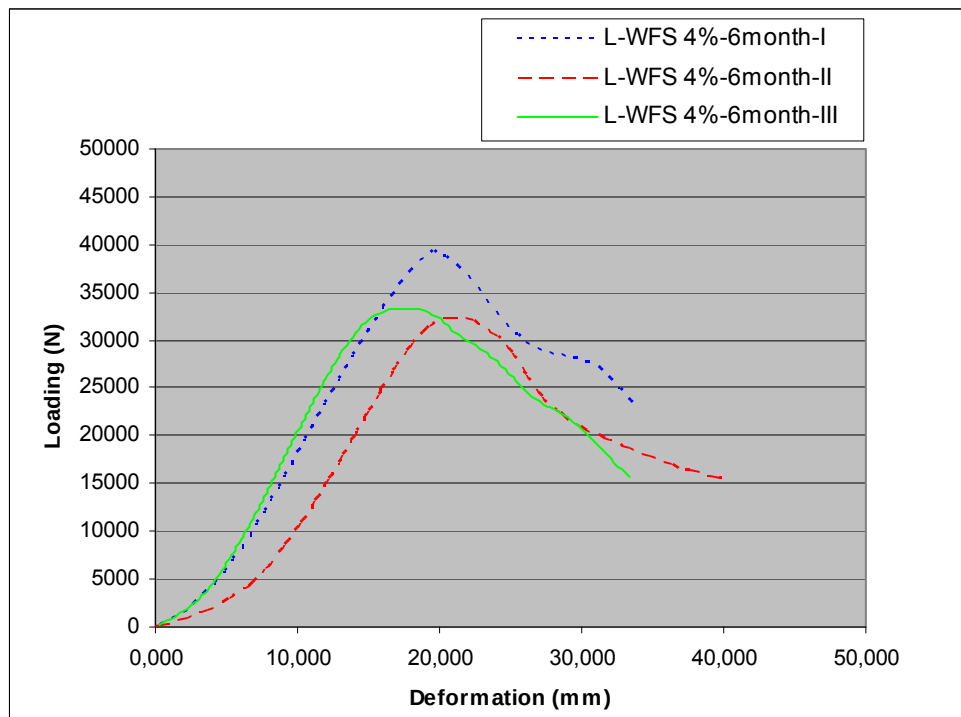


**Figure B.84 :** Loading – Deformation Diagram of L-WFS 4%-6month Samples.

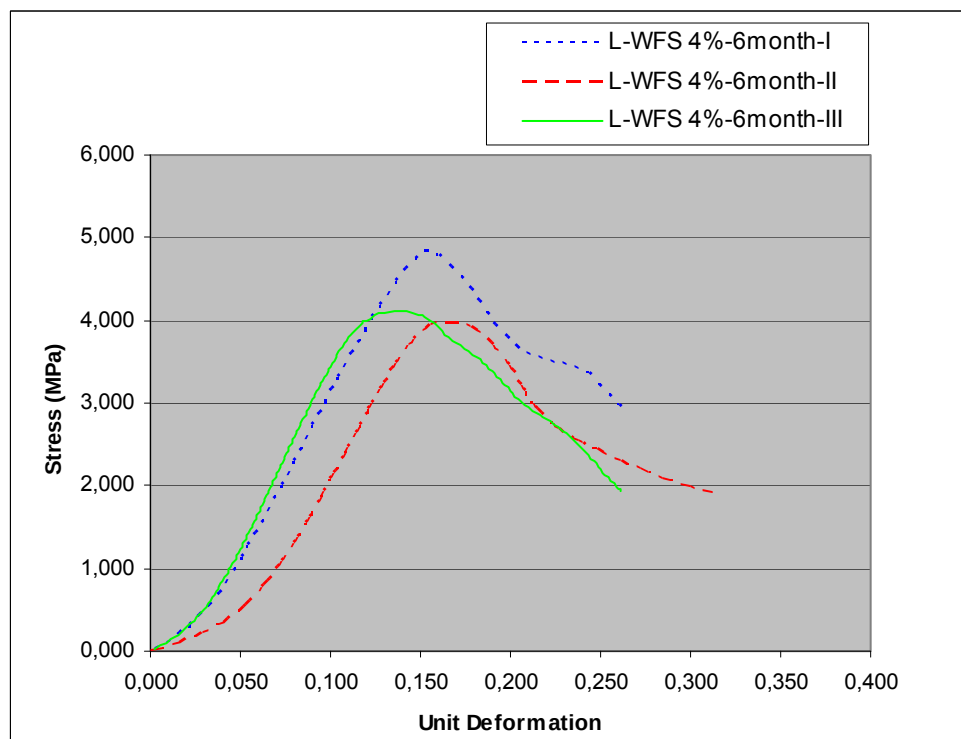


**Figure B.85 :** Stress – Unit Deformation Diagram of L-WFS 4%-6month Samples.

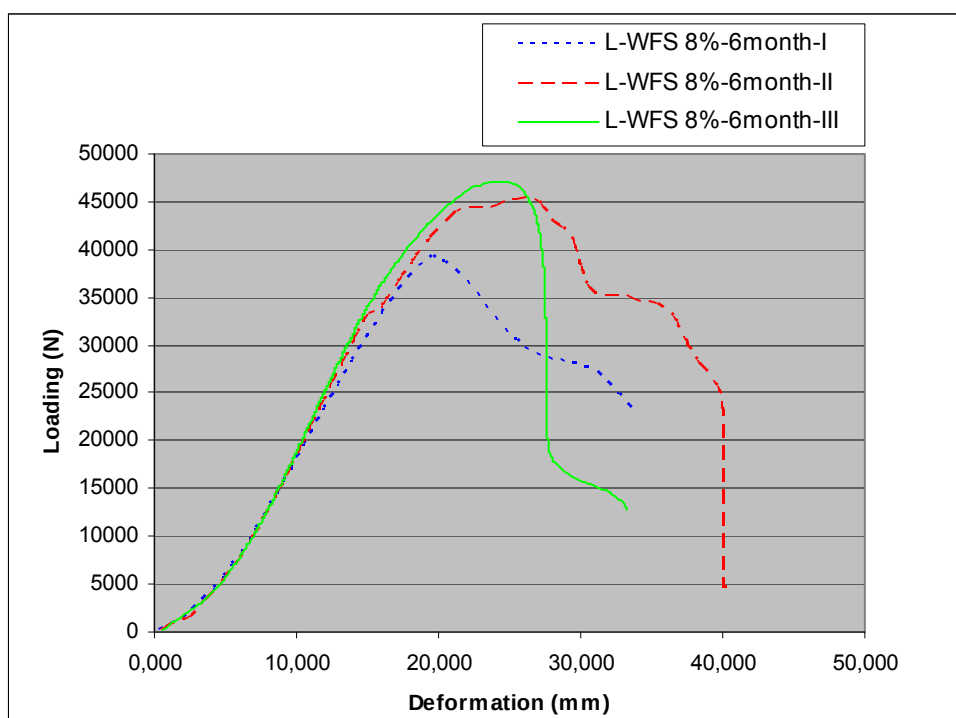


**Figure B.86 :** Loading – Deformation Diagram of L-WFS 8%-6month Samples.

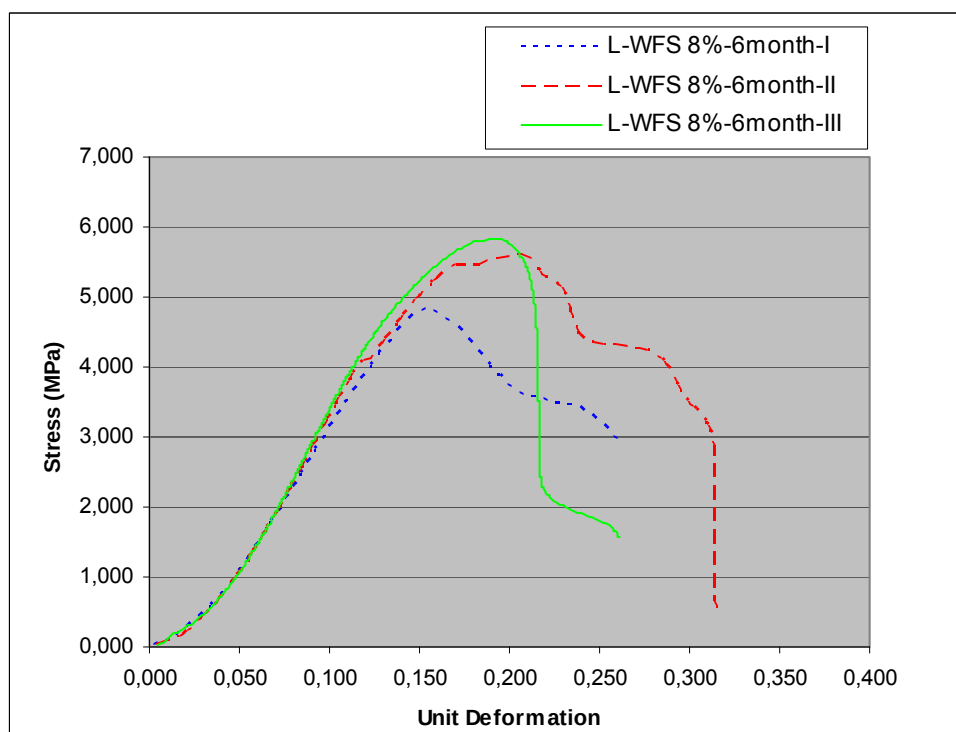


**Figure B.87 :** Stress – Unit Deformation Diagram of L-WFS 8%-6month Samples.

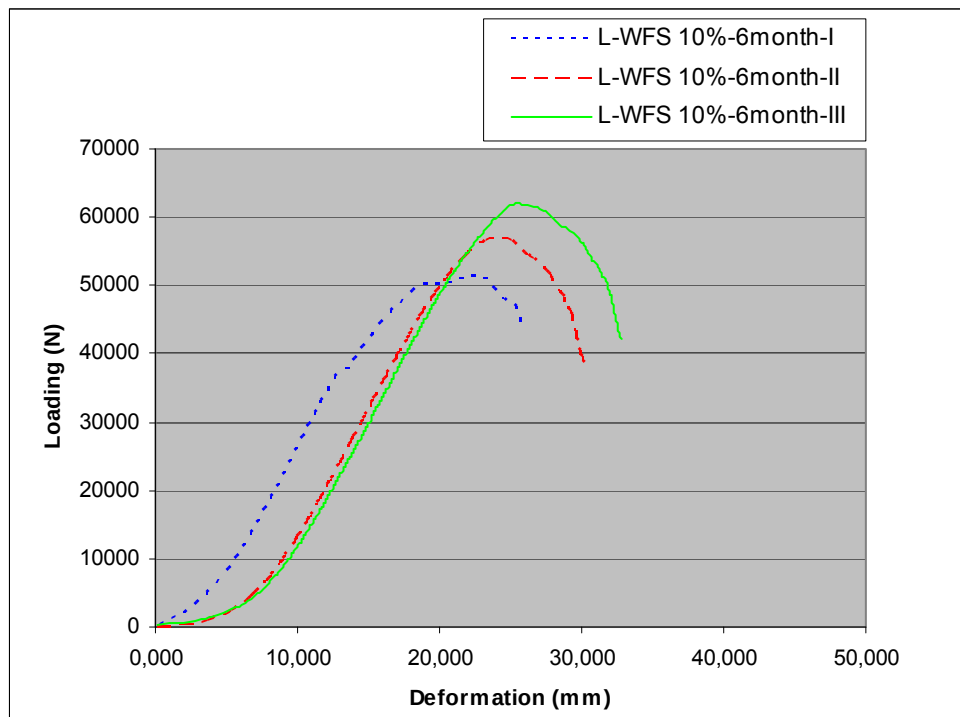


**Figure B.88 :** Loading – Deformation Diagram of L-WFS 10%-6month Samples.

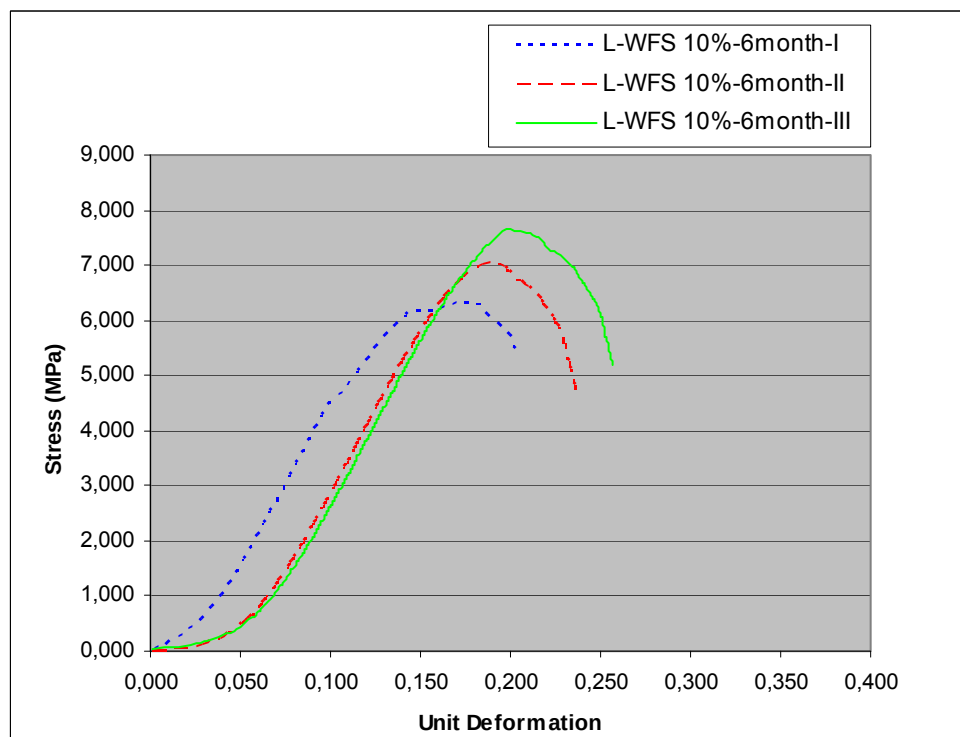


**Figure B.89 :** Stress – Unit Deformation Diagram of L-WFS 10%-6month Samples.

**Table B.10 : E Values of Lime Stabilized and 6-month Cured Samples.**

| Amount of Additives                  | Definition of Sample    | Extension at fracture point (mm) | Loading at fracture point (N) | Unit Deformation at fracture point | Stress at fracture point (Mpa) | Elasticity Modulus (MPa) |
|--------------------------------------|-------------------------|----------------------------------|-------------------------------|------------------------------------|--------------------------------|--------------------------|
| WFS Samples Stabilized With 2% Lime  | L-WFS 2%-6month-I       | 19,191                           | 15112,219                     | 0,151                              | 1,864                          | 24,689                   |
|                                      | L-WFS 2%-6month-II      | 18,870                           | 17840,150                     | 0,149                              | 2,200                          | 29,537                   |
|                                      | L-WFS 2%-6month-III     | 19,567                           | 23057,560                     | 0,154                              | 2,844                          | 36,936                   |
| <b>Average Values</b>                | <b>L-WFS 2%-6month</b>  | <b>19,209</b>                    | <b>18669,976</b>              | <b>0,151</b>                       | <b>2,303</b>                   | <b>30,387</b>            |
| WFS Samples Stabilized With 4% Lime  | L-WFS 4%-6month-I       | 19,533                           | 39257,250                     | 0,153                              | 4,842                          | 63,297                   |
|                                      | L-WFS 4%-6month-II      | 21,694                           | 32255,296                     | 0,170                              | 3,979                          | 46,806                   |
|                                      | L-WFS 4%-6month-III     | 17,366                           | 33307,241                     | 0,136                              | 4,108                          | 60,416                   |
| <b>Average Values</b>                | <b>L-WFS 4%-6month</b>  | <b>19,531</b>                    | <b>34939,929</b>              | <b>0,153</b>                       | <b>4,310</b>                   | <b>56,840</b>            |
| WFS Samples Stabilized With 8% Lime  | L-WFS 8%-6month-I       | 19,533                           | 39257,250                     | 0,153                              | 4,842                          | 63,297                   |
|                                      | L-WFS 8%-6month-II      | 26,338                           | 45301,528                     | 0,206                              | 5,588                          | 54,250                   |
|                                      | L-WFS 8%-6month-III     | 24,501                           | 47152,278                     | 0,192                              | 5,816                          | 60,583                   |
| <b>Average Values</b>                | <b>L-WFS 8%-6month</b>  | <b>23,457</b>                    | <b>43903,685</b>              | <b>0,184</b>                       | <b>5,415</b>                   | <b>59,377</b>            |
| WFS Samples Stabilized With 10% Lime | L-WFS 10%-6month-I      | 22,751                           | 51242,71                      | 0,178                              | 6,321                          | 71,017                   |
|                                      | L-WFS 10%-6month-II     | 24,416                           | 56955,72                      | 0,191                              | 7,025                          | 73,563                   |
|                                      | L-WFS 10%-6month-III    | 25,435                           | 62081,74                      | 0,199                              | 7,657                          | 76,960                   |
| <b>Average Values</b>                | <b>L-WFS 10%-6month</b> | <b>24,201</b>                    | <b>56760,056</b>              | <b>0,189</b>                       | <b>7,001</b>                   | <b>73,847</b>            |

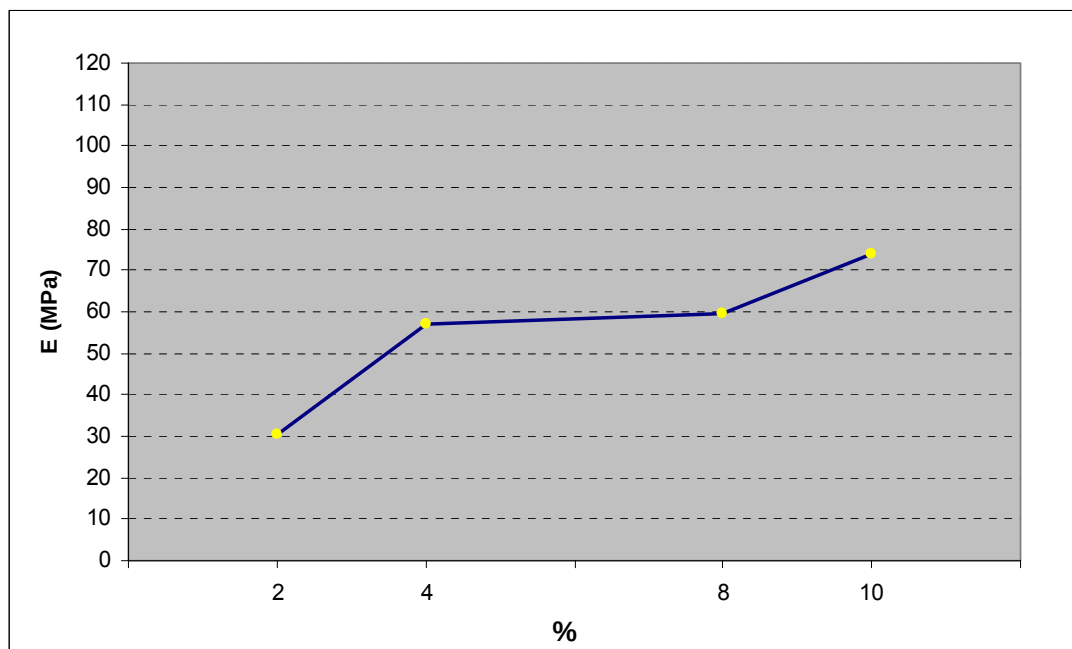


**Figure B.90 : E Values of Lime Stabilized and 6-month Cured Samples.**

## **APPENDIX C : KENLAYER COMPUTER PROGRAM ANALYSIS**

**Table C.1:** Vertical Displacements of C-WFS 2% 7-day

| 2% Cement Stabilized and 7-day Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,10048                                 | 0,06033  | 0,04672   | 0,04159   |
| <b>7,87</b>                                  | 0,10273                                 | 0,06443  | 0,05140   | 0,04651   |
| <b>9,84</b>                                  | 0,10476                                 | 0,06807  | 0,05554   | 0,05090   |
| <b>11,81</b>                                 | 0,10655                                 | 0,07133  | 0,05934   | 0,05491   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.2:** Vertical Displacements of C-WFS 4% 7-day

| 4% Cement Stabilized and 7-day Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,09705                                 | 0,05647  | 0,04254   | 0,03732   |
| <b>7,87</b>                                  | 0,09840                                 | 0,05944  | 0,04634   | 0,04137   |
| <b>9,84</b>                                  | 0,09940                                 | 0,06244  | 0,04966   | 0,04497   |
| <b>11,81</b>                                 | 0,10030                                 | 0,06499  | 0,05271   | 0,04822   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.3:** Vertical Displacements of C-WFS 8% 7-day

| 8% Cement Stabilized and 7-day Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08968                                 | 0,04840  | 0,03371   | 0,02828   |
| <b>7,87</b>                                  | 0,08870                                 | 0,04954  | 0,03561   | 0,03047   |
| <b>9,84</b>                                  | 0,08762                                 | 0,05049  | 0,03721   | 0,03241   |
| <b>11,81</b>                                 | 0,08642                                 | 0,05133  | 0,03867   | 0,03411   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.4:** Vertical Displacements of C-WFS 10% 7-day

| 10% Cement Stabilized and 7-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08730                                 | 0,04601  | 0,03111   | 0,02562   |
| <b>7,87</b>                                   | 0,08551                                 | 0,04652  | 0,03243   | 0,02725   |
| <b>9,84</b>                                   | 0,08370                                 | 0,04689  | 0,03352   | 0,02869   |
| <b>11,81</b>                                  | 0,08192                                 | 0,0472   | 0,03450   | 0,02994   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.5: Vertical Displacements of L-WFS 2% 7-day**

| 2% Lime Stabilized and 7-day Cured Samples |                                         |          |           |           |
|--------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                   | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                | 0,11454                                 | 0,07605  | 0,06340   | 0,05855   |
| <b>7,87</b>                                | 0,12048                                 | 0,08378  | 0,07160   | 0,06700   |
| <b>9,84</b>                                | 0,12615                                 | 0,09071  | 0,07893   | 0,07464   |
| <b>11,81</b>                               | 0,13128                                 | 0,09719  | 0,08579   | 0,08147   |
| CBR of Subgrade (%)                        | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.6: Vertical Displacements of L-WFS 4% 7-day**

| 4% Lime Stabilized and 7-day Cured Samples |                                         |          |           |           |
|--------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                   | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                | 0,11101                                 | 0,07213  | 0,05928   | 0,05437   |
| <b>7,87</b>                                | 0,11613                                 | 0,07897  | 0,06659   | 0,06193   |
| <b>9,84</b>                                | 0,12084                                 | 0,08506  | 0,07323   | 0,06880   |
| <b>11,81</b>                               | 0,12516                                 | 0,09076  | 0,07919   | 0,07497   |
| CBR of Subgrade (%)                        | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.7: Vertical Displacements of L-WFS 8% 7-day**

| 8% Lime Stabilized and 7-day Cured Samples |                                         |          |           |           |
|--------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                   | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                | 0,11007                                 | 0,07109  | 0,05818   | 0,05325   |
| <b>7,87</b>                                | 0,11495                                 | 0,07769  | 0,06526   | 0,06059   |
| <b>9,84</b>                                | 0,11943                                 | 0,08357  | 0,07169   | 0,06724   |
| <b>11,81</b>                               | 0,12353                                 | 0,08905  | 0,07754   | 0,07320   |
| CBR of Subgrade (%)                        | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.8: Vertical Displacements of L-WFS 10% 7-day**

| 10% Lime Stabilized and 7-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,10693                                 | 0,06758  | 0,05446   | 0,04947   |
| <b>7,87</b>                                 | 0,11096                                 | 0,07336  | 0,06078   | 0,05599   |
| <b>9,84</b>                                 | 0,11465                                 | 0,07857  | 0,06643   | 0,06191   |
| <b>11,81</b>                                | 0,11802                                 | 0,08327  | 0,07153   | 0,06721   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.9: Vertical Displacements of C-WFS 2% 14-day**

| 2% Cement Stabilized and 14-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,09950                                 | 0,05922  | 0,04552   | 0,04037   |
| <b>7,87</b>                                   | 0,10147                                 | 0,06305  | 0,04995   | 0,04504   |
| <b>9,84</b>                                   | 0,10323                                 | 0,06646  | 0,05385   | 0,04920   |
| <b>11,81</b>                                  | 0,10476                                 | 0,06948  | 0,05744   | 0,05298   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.10: Vertical Displacements of C-WFS 4% 14-day**

| 4% Cement Stabilized and 14-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,09066                                 | 0,04943  | 0,03484   | 0,02944   |
| <b>7,87</b>                                   | 0,09001                                 | 0,05084  | 0,03699   | 0,03187   |
| <b>9,84</b>                                   | 0,08923                                 | 0,05203  | 0,03881   | 0,03402   |
| <b>11,81</b>                                  | 0,08830                                 | 0,05309  | 0,04047   | 0,03592   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.11: Vertical Displacements of C-WFS 8% 14-day**

| 8% Cement Stabilized and 14-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08387                                 | 0,04296  | 0,02788   | 0,02232   |
| <b>7,87</b>                                   | 0,08092                                 | 0,04261  | 0,02841   | 0,02326   |
| <b>9,84</b>                                   | 0,07804                                 | 0,04222  | 0,02887   | 0,02405   |
| <b>11,81</b>                                  | 0,07566                                 | 0,04193  | 0,02927   | 0,02476   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.12: Vertical Displacements of C-WFS 10% 14-day**

| 10% Cement Stabilized and 14-day Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08327                                 | 0,04247  | 0,02738   | 0,02182   |
| <b>7,87</b>                                    | 0,08013                                 | 0,04198  | 0,02780   | 0,02265   |
| <b>9,84</b>                                    | 0,07708                                 | 0,04148  | 0,02816   | 0,02335   |
| <b>11,81</b>                                   | 0,07455                                 | 0,04109  | 0,02846   | 0,02397   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.13: Vertical Displacements of L-WFS 2% 14-day**

| 2% Lime Stabilized and 14-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,10981                                 | 0,07080  | 0,05788   | 0,05294   |
| <b>7,87</b>                                 | 0,11462                                 | 0,07734  | 0,06489   | 0,06021   |
| <b>9,84</b>                                 | 0,11904                                 | 0,08315  | 0,07126   | 0,06680   |
| <b>11,81</b>                                | 0,12308                                 | 0,08858  | 0,07705   | 0,07271   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.14: Vertical Displacements of L-WFS 4% 14-day**

| 4% Lime Stabilized and 14-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,10379                                 | 0,06406  | 0,05072   | 0,04566   |
| <b>7,87</b>                                 | 0,10697                                 | 0,06903  | 0,05625   | 0,05140   |
| <b>9,84</b>                                 | 0,10987                                 | 0,07349  | 0,06116   | 0,05659   |
| <b>11,81</b>                                | 0,11248                                 | 0,07750  | 0,06570   | 0,06133   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.15: Vertical Displacements of L-WFS 8% 14-day**

| 8% Lime Stabilized and 14-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,10101                                 | 0,06093  | 0,04736   | 0,04224   |
| <b>7,87</b>                                 | 0,10342                                 | 0,06517  | 0,05218   | 0,04730   |
| <b>9,84</b>                                 | 0,10558                                 | 0,06894  | 0,05644   | 0,05182   |
| <b>11,81</b>                                | 0,10750                                 | 0,07232  | 0,06036   | 0,05595   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.16: Vertical Displacements of L-WFS 10% 14-day**

| 10% Lime Stabilized and 14-day Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,09529                                 | 0,05450  | 0,04039   | 0,03513   |
| <b>7,87</b>                                  | 0,09611                                 | 0,05719  | 0,04374   | 0,03873   |
| <b>9,84</b>                                  | 0,09671                                 | 0,05955  | 0,04665   | 0,04193   |
| <b>11,81</b>                                 | 0,09705                                 | 0,06168  | 0,04930   | 0,04479   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.17: Vertical Displacements of C-WFS 2% 28-day**

| 2% Cement Stabilized and 28-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,09324                                 | 0,05222  | 0,03790   | 0,03258   |
| <b>7,87</b>                                   | 0,09342                                 | 0,05435  | 0,04072   | 0,03565   |
| <b>9,84</b>                                   | 0,09342                                 | 0,05619  | 0,04314   | 0,03839   |
| <b>11,81</b>                                  | 0,09321                                 | 0,05785  | 0,04535   | 0,04081   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.18: Vertical Displacements of C-WFS 4% 28-day**

| 4% Cement Stabilized and 28-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08608                                 | 0,04487  | 0,02988   | 0,02436   |
| <b>7,87</b>                                   | 0,08387                                 | 0,04505  | 0,03091   | 0,02574   |
| <b>9,84</b>                                   | 0,08155                                 | 0,04514  | 0,03179   | 0,02692   |
| <b>11,81</b>                                  | 0,07957                                 | 0,04520  | 0,03251   | 0,02796   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.19: Vertical Displacements of C-WFS 8% 28-day**

| 8% Cement Stabilized and 28-day Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08107                                 | 0,04088  | 0,02555   | 0,02020   |
| <b>7,87</b>                                   | 0,07712                                 | 0,03988  | 0,02579   | 0,02066   |
| <b>9,84</b>                                   | 0,07375                                 | 0,03898  | 0,02582   | 0,02104   |
| <b>11,81</b>                                  | 0,07064                                 | 0,03825  | 0,02583   | 0,02139   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.20: Vertical Displacements of C-WFS 10% 28-day**

| 10% Cement Stabilized and 28-day Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08024                                 | 0,04031  | 0,02526   | 0,01967   |
| <b>7,87</b>                                    | 0,07607                                 | 0,03915  | 0,02513   | 0,02001   |
| <b>9,84</b>                                    | 0,07260                                 | 0,03812  | 0,02504   | 0,02029   |
| <b>11,81</b>                                   | 0,06925                                 | 0,03728  | 0,02497   | 0,02055   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.21: Vertical Displacements of L-WFS 2% 28-day**

| 2% Lime Stabilized and 28-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,09575                                 | 0,05501  | 0,04095   | 0,03569   |
| <b>7,87</b>                                 | 0,09670                                 | 0,05782  | 0,04441   | 0,03941   |
| <b>9,84</b>                                 | 0,09743                                 | 0,06029  | 0,04742   | 0,04271   |
| <b>11,81</b>                                | 0,09789                                 | 0,06253  | 0,05018   | 0,04567   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.22: Vertical Displacements of L-WFS 4% 28-day**

| 4% Lime Stabilized and 28-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,09135                                 | 0,05016  | 0,03564   | 0,03026   |
| <b>7,87</b>                                 | 0,09091                                 | 0,05176  | 0,03796   | 0,03285   |
| <b>9,84</b>                                 | 0,09035                                 | 0,05312  | 0,03994   | 0,03516   |
| <b>11,81</b>                                | 0,08961                                 | 0,05434  | 0,04175   | 0,03720   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.23: Vertical Displacements of L-WFS 8% 28-day**

| 8% Lime Stabilized and 28-day Cured Samples |                                         |          |           |           |
|---------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                    | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                 | 0,08916                                 | 0,04786  | 0,03312   | 0,02768   |
| <b>7,87</b>                                 | 0,08801                                 | 0,04887  | 0,03489   | 0,02974   |
| <b>9,84</b>                                 | 0,08677                                 | 0,04968  | 0,03638   | 0,03157   |
| <b>11,81</b>                                | 0,08541                                 | 0,05040  | 0,03773   | 0,03317   |
| CBR of Subgrade (%)                         | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.24: Vertical Displacements of L-WFS 10% 28-day**

| 10% Lime Stabilized and 28-day Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08734                                 | 0,04605  | 0,03115   | 0,02566   |
| <b>7,87</b>                                  | 0,08556                                 | 0,04656  | 0,03248   | 0,02729   |
| <b>9,84</b>                                  | 0,08376                                 | 0,04694  | 0,03357   | 0,02875   |
| <b>11,81</b>                                 | 0,08199                                 | 0,04726  | 0,03456   | 0,03000   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.25: Vertical Displacements of C-WFS 2% 3-month**

| 2% Cement Stabilized and 3-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,09083                                 | 0,04961  | 0,03504   | 0,02964   |
| <b>7,87</b>                                    | 0,09023                                 | 0,05107  | 0,03723   | 0,03211   |
| <b>9,84</b>                                    | 0,08951                                 | 0,05230  | 0,03909   | 0,03431   |
| <b>11,81</b>                                   | 0,08862                                 | 0,05340  | 0,04079   | 0,03623   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.26: Vertical Displacements of C-WFS 4% 3-month**

| 4% Cement Stabilized and 3-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08547                                 | 0,04432  | 0,02929   | 0,02376   |
| <b>7,87</b>                                    | 0,08305                                 | 0,04435  | 0,03019   | 0,02502   |
| <b>9,84</b>                                    | 0,08063                                 | 0,04430  | 0,03091   | 0,02609   |
| <b>11,81</b>                                   | 0,07841                                 | 0,04424  | 0,03157   | 0,02702   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.27: Vertical Displacements of C-WFS 8% 3-month**

| 8% Cement Stabilized and 3-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08083                                 | 0,04072  | 0,02561   | 0,02005   |
| <b>7,87</b>                                    | 0,07682                                 | 0,03966  | 0,02560   | 0,02047   |
| <b>9,84</b>                                    | 0,07349                                 | 0,03873  | 0,02559   | 0,02082   |
| <b>11,81</b>                                   | 0,07024                                 | 0,03797  | 0,02558   | 0,02115   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.28: Vertical Displacements of C-WFS 10% 3-month**

| 10% Cement Stabilized and 3-month Cured Samples |                                         |          |           |           |
|-------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                        | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                     | 0,08006                                 | 0,04019  | 0,02514   | 0,01956   |
| <b>7,87</b>                                     | 0,07584                                 | 0,03899  | 0,02499   | 0,01987   |
| <b>9,84</b>                                     | 0,07233                                 | 0,03794  | 0,02488   | 0,02013   |
| <b>11,81</b>                                    | 0,06894                                 | 0,03708  | 0,02478   | 0,02037   |
| CBR of Subgrade (%)                             | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.29: Vertical Displacements of L-WFS 2% 3-month**

| 2% Lime Stabilized and 3-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,09151                                 | 0,05033  | 0,03583   | 0,03045   |
| <b>7,87</b>                                  | 0,09113                                 | 0,05198  | 0,03819   | 0,03309   |
| <b>9,84</b>                                  | 0,09061                                 | 0,05338  | 0,04021   | 0,03543   |
| <b>11,81</b>                                 | 0,08991                                 | 0,05463  | 0,04205   | 0,03750   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.30: Vertical Displacements of L-WFS 4% 3-month**

| 4% Lime Stabilized and 3-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08656                                 | 0,04531  | 0,03036   | 0,02485   |
| <b>7,87</b>                                  | 0,08452                                 | 0,04562  | 0,03150   | 0,02634   |
| <b>9,84</b>                                  | 0,08248                                 | 0,04582  | 0,03244   | 0,02761   |
| <b>11,81</b>                                 | 0,08050                                 | 0,04598  | 0,03329   | 0,02873   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.31: Vertical Displacements of L-WFS 8% 3-month**

| 8% Lime Stabilized and 3-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08599                                 | 0,04478  | 0,02979   | 0,02427   |
| <b>7,87</b>                                  | 0,08375                                 | 0,04495  | 0,03081   | 0,02563   |
| <b>9,84</b>                                  | 0,08140                                 | 0,04501  | 0,03162   | 0,02680   |
| <b>11,81</b>                                 | 0,07940                                 | 0,04505  | 0,03237   | 0,02781   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.32: Vertical Displacements of L-WFS 10% 3-month**

| 10% Lime Stabilized and 3-month Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08402                                 | 0,04308  | 0,02801   | 0,02245   |
| <b>7,87</b>                                   | 0,08113                                 | 0,04277  | 0,02857   | 0,02342   |
| <b>9,84</b>                                   | 0,07829                                 | 0,04241  | 0,02906   | 0,02424   |
| <b>11,81</b>                                  | 0,07594                                 | 0,04215  | 0,02948   | 0,02497   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.33: Vertical Displacements of C-WFS 2% 6-month**

| 2% Cement Stabilized and 6-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08901                                 | 0,04770  | 0,03295   | 0,02750   |
| <b>7,87</b>                                    | 0,08780                                 | 0,04866  | 0,03468   | 0,02953   |
| <b>9,84</b>                                    | 0,08651                                 | 0,04944  | 0,03613   | 0,03132   |
| <b>11,81</b>                                   | 0,08511                                 | 0,05013  | 0,03745   | 0,03289   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.34: Vertical Displacements of C-WFS 4% 6-month**

| 4% Cement Stabilized and 6-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08544                                 | 0,04429  | 0,02927   | 0,02374   |
| <b>7,87</b>                                    | 0,08302                                 | 0,04432  | 0,03016   | 0,02499   |
| <b>9,84</b>                                    | 0,08058                                 | 0,04426  | 0,03087   | 0,02605   |
| <b>11,81</b>                                   | 0,07836                                 | 0,04420  | 0,03153   | 0,02698   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.35: Vertical Displacements of C-WFS 8% 6-month**

| 8% Cement Stabilized and 6-month Cured Samples |                                         |          |           |           |
|------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                       | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                    | 0,08054                                 | 0,04052  | 0,02543   | 0,01986   |
| <b>7,87</b>                                    | 0,07645                                 | 0,03941  | 0,02536   | 0,02024   |
| <b>9,84</b>                                    | 0,07305                                 | 0,03843  | 0,02532   | 0,02056   |
| <b>11,81</b>                                   | 0,06975                                 | 0,03763  | 0,02528   | 0,02085   |
| CBR of Subgrade (%)                            | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.36: Vertical Displacements of C-WFS 10% 6-month**

| 10% Cement Stabilized and 6-month Cured Samples |                                         |          |           |           |
|-------------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                        | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                     | 0,07966                                 | 0,03992  | 0,02490   | 0,01932   |
| <b>7,87</b>                                     | 0,07533                                 | 0,03866  | 0,02469   | 0,01958   |
| <b>9,84</b>                                     | 0,07174                                 | 0,03761  | 0,02453   | 0,01979   |
| <b>11,81</b>                                    | 0,06829                                 | 0,03664  | 0,02436   | 0,02000   |
| CBR of Subgrade (%)                             | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.37: Vertical Displacements of L-WFS 2% 6-month**

| 2% Lime Stabilized and 6-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08991                                 | 0,04863  | 0,03396   | 0,02854   |
| <b>7,87</b>                                  | 0,08900                                 | 0,04984  | 0,03592   | 0,03078   |
| <b>9,84</b>                                  | 0,08799                                 | 0,05084  | 0,03758   | 0,03278   |
| <b>11,81</b>                                 | 0,08685                                 | 0,05173  | 0,03908   | 0,03452   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.38: Vertical Displacements of L-WFS 4% 6-month**

| 4% Lime Stabilized and 6-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08502                                 | 0,04392  | 0,02888   | 0,02334   |
| <b>7,87</b>                                  | 0,08245                                 | 0,04385  | 0,02968   | 0,02450   |
| <b>9,84</b>                                  | 0,07990                                 | 0,04370  | 0,03031   | 0,02549   |
| <b>11,81</b>                                 | 0,07757                                 | 0,04358  | 0,03090   | 0,02636   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.39: Vertical Displacements of L-WFS 8% 6-month**

| 8% Lime Stabilized and 6-month Cured Samples |                                         |          |           |           |
|----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                     | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                  | 0,08469                                 | 0,04364  | 0,02859   | 0,02304   |
| <b>7,87</b>                                  | 0,08202                                 | 0,04349  | 0,02930   | 0,02414   |
| <b>9,84</b>                                  | 0,07937                                 | 0,04327  | 0,02989   | 0,02507   |
| <b>11,81</b>                                 | 0,07696                                 | 0,04313  | 0,03042   | 0,02590   |
| CBR of Subgrade (%)                          | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

**Table C.40: Vertical Displacements of L-WFS 10% 6-month**

| 10% Lime Stabilized and 6-month Cured Samples |                                         |          |           |           |
|-----------------------------------------------|-----------------------------------------|----------|-----------|-----------|
| Thickness of Base (inch)                      | Vertical Displacement at Point 3 (inch) |          |           |           |
| <b>5,90</b>                                   | 0,08306                                 | 0,04231  | 0,02722   | 0,02166   |
| <b>7,87</b>                                   | 0,07985                                 | 0,04178  | 0,02759   | 0,02245   |
| <b>9,84</b>                                   | 0,07675                                 | 0,04123  | 0,02792   | 0,02311   |
| <b>11,81</b>                                  | 0,07417                                 | 0,04080  | 0,02820   | 0,02371   |
| CBR of Subgrade (%)                           | <b>2</b>                                | <b>5</b> | <b>10</b> | <b>15</b> |

## **APPENDIX D : CBR Results of WFS Samples**

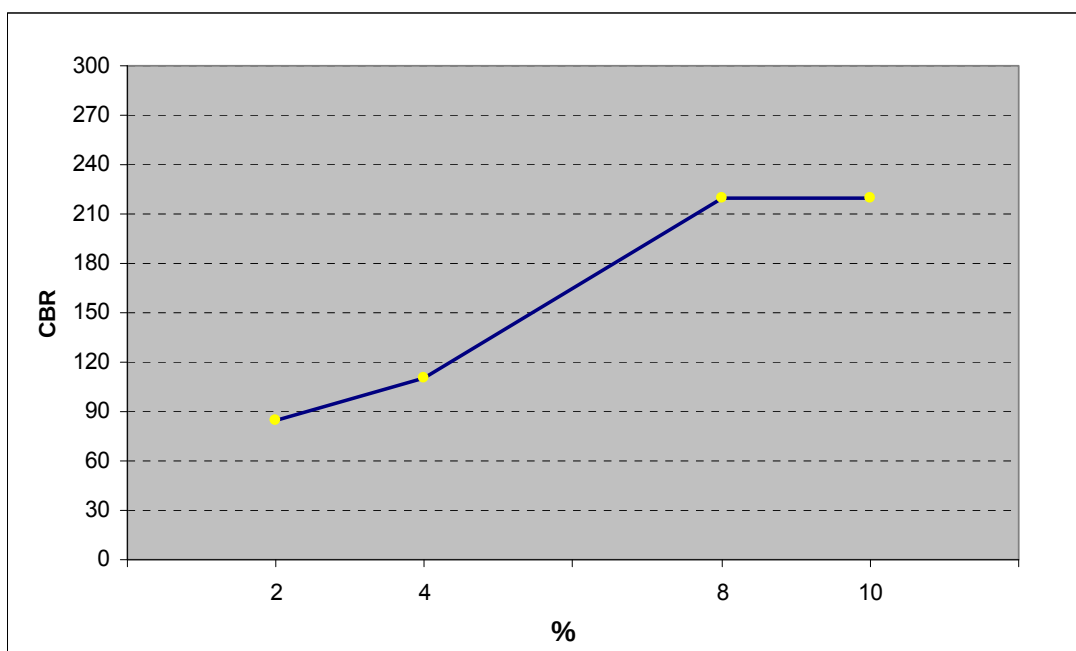


**Figure D.1 :** CBR Values of Cement Stabilized and 7-day Cured Samples.

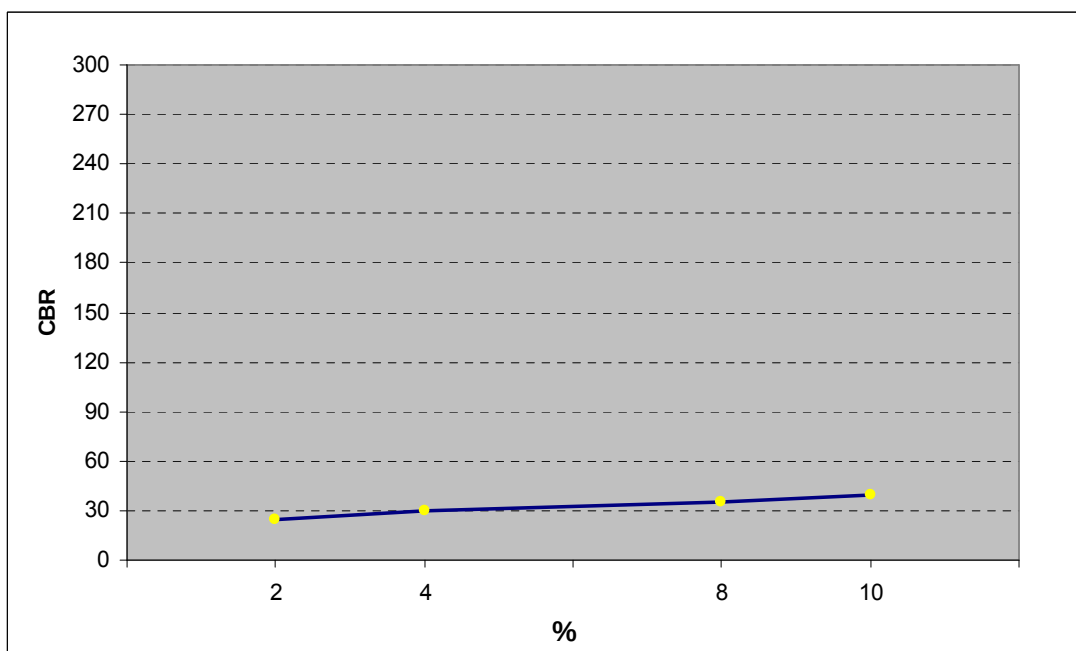


**Figure D.2 :** CBR Values of Lime Stabilized and 7-day Cured Samples.

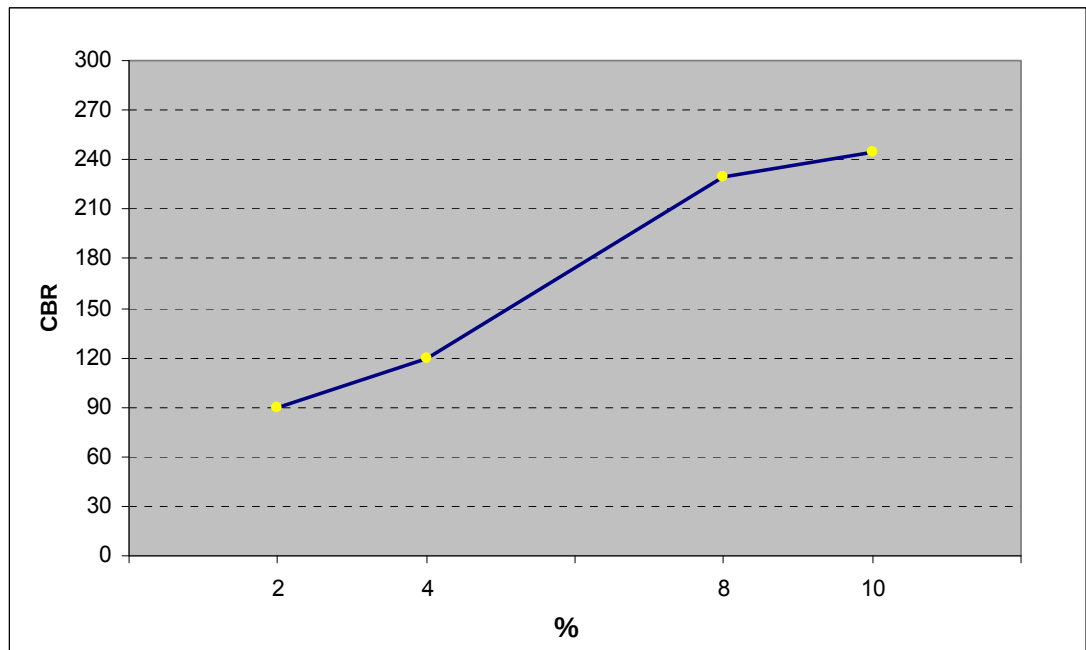


**Figure D.3 :** CBR Values of Cement Stabilized and 14-day Cured Samples.

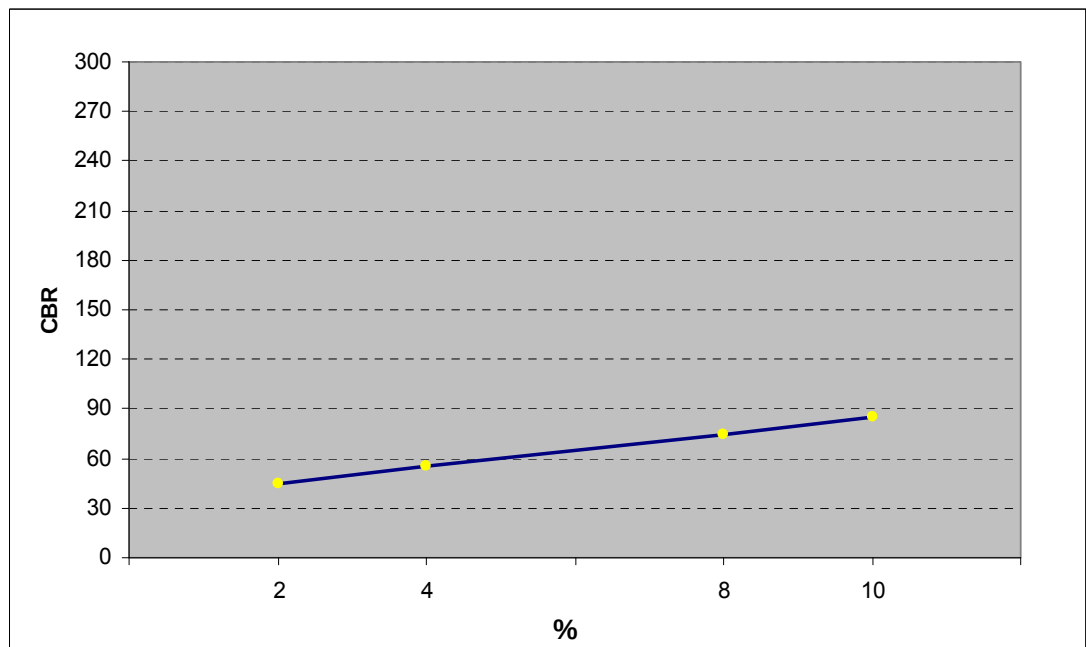


**Figure D.4 :** CBR Values of Lime Stabilized and 14-day Cured Samples.

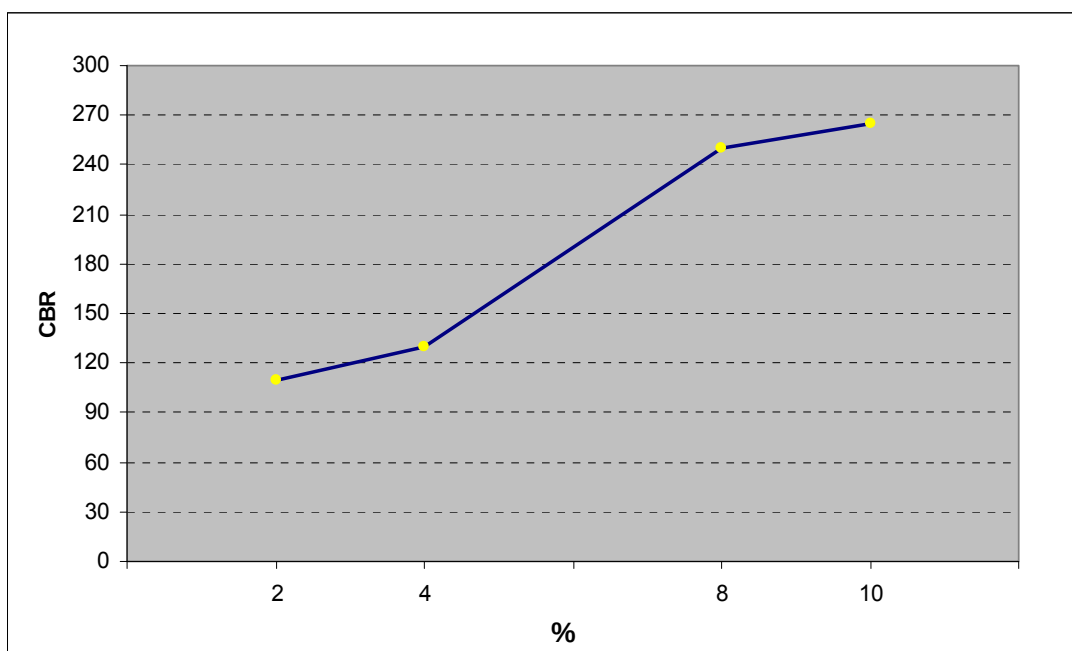


**Figure D.5 :** CBR Values of Cement Stabilized and 28-day Cured Samples.

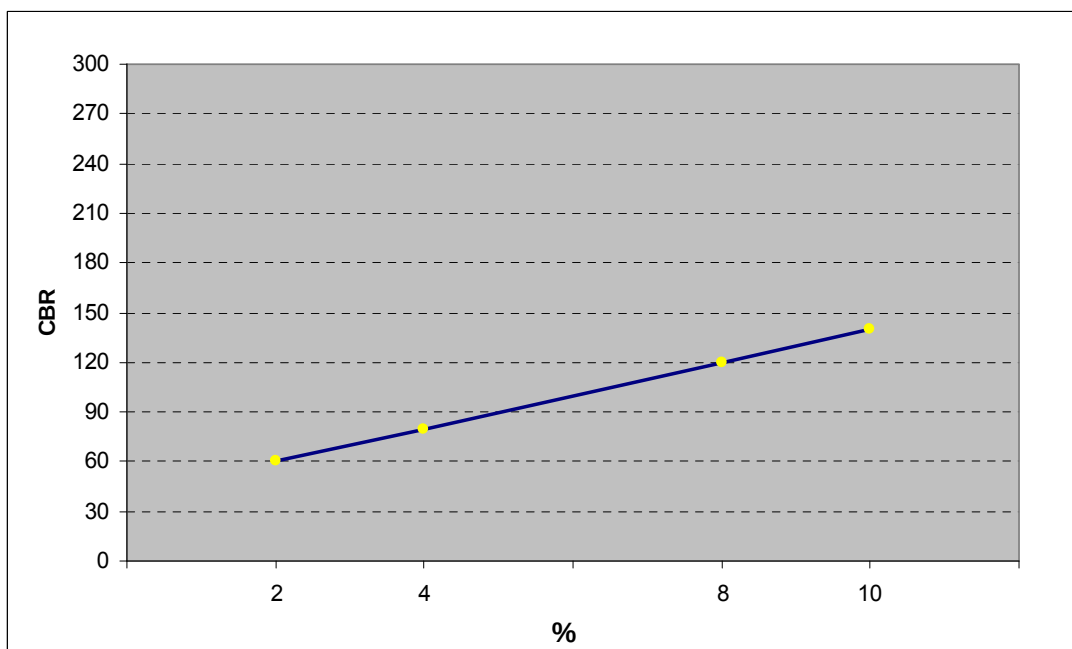


**Figure D.6 :** CBR Values of Lime Stabilized and 28-day Cured Samples.

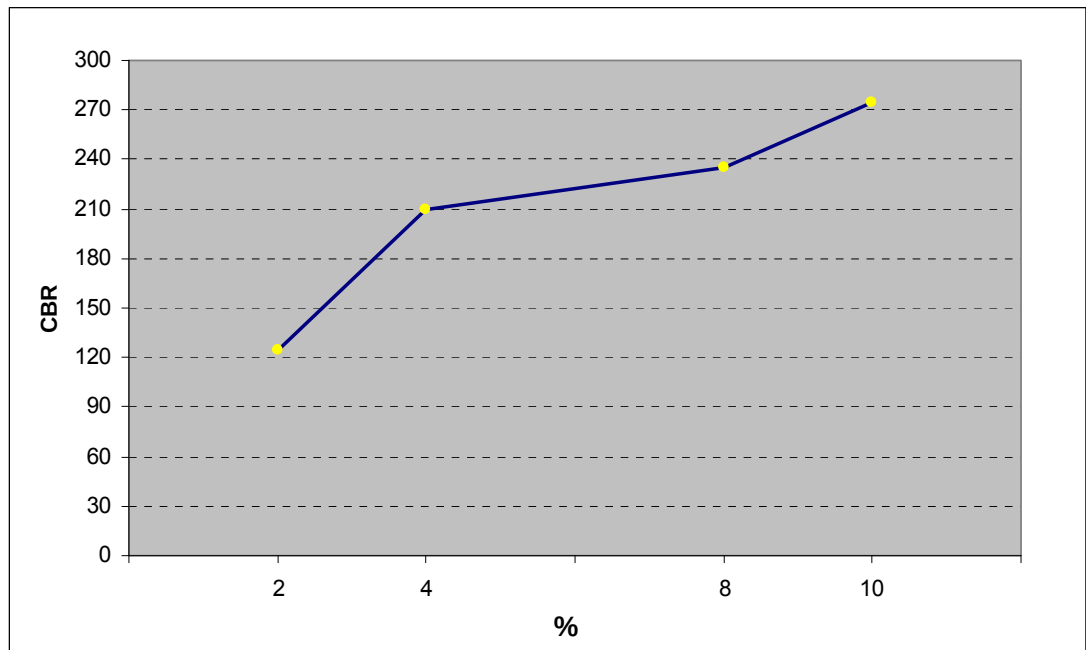


**Figure D.7 :** CBR Values of Cement Stabilized and 3-month Cured Samples.

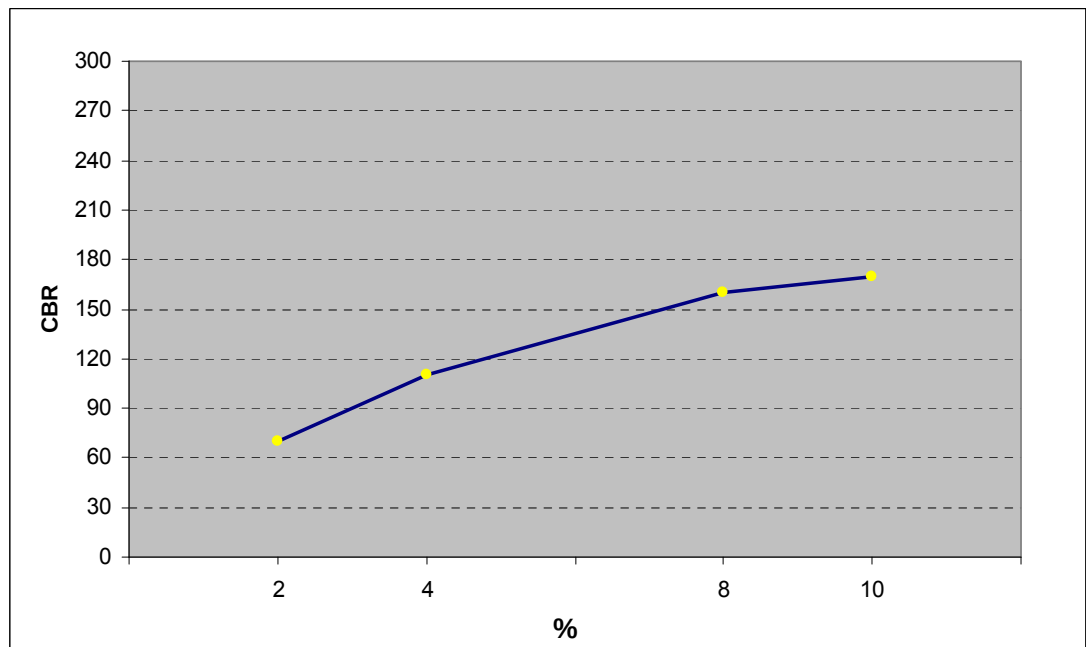


**Figure D.8 :** CBR Values of Lime Stabilized and 3-month Cured Samples.

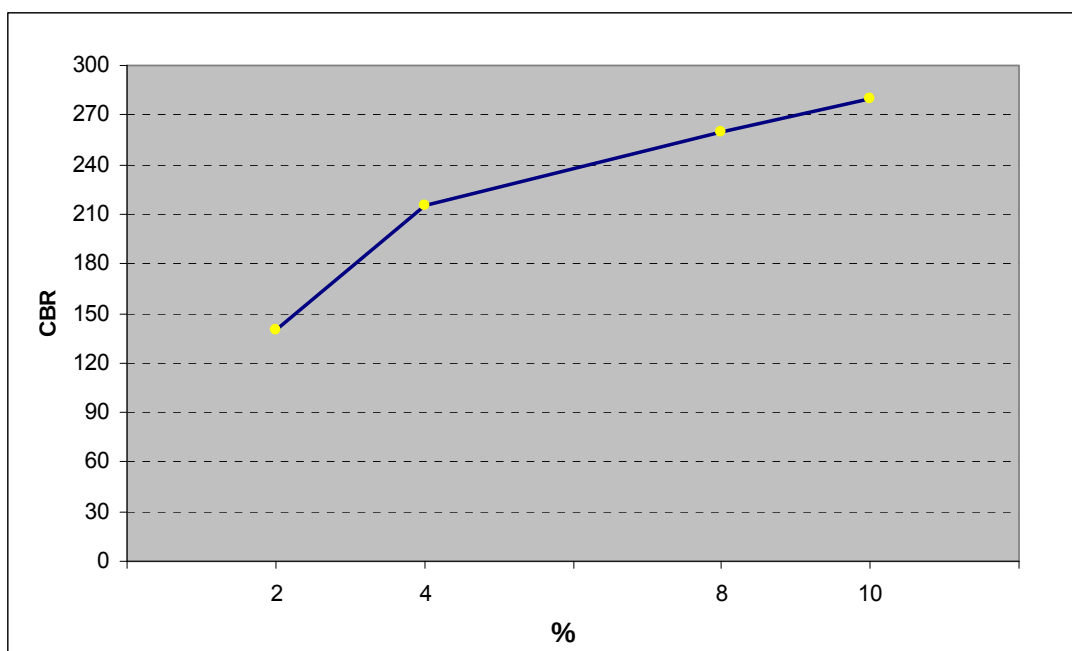


**Figure D.9 :** CBR Values of Cement Stabilized and 6-month Cured Samples.

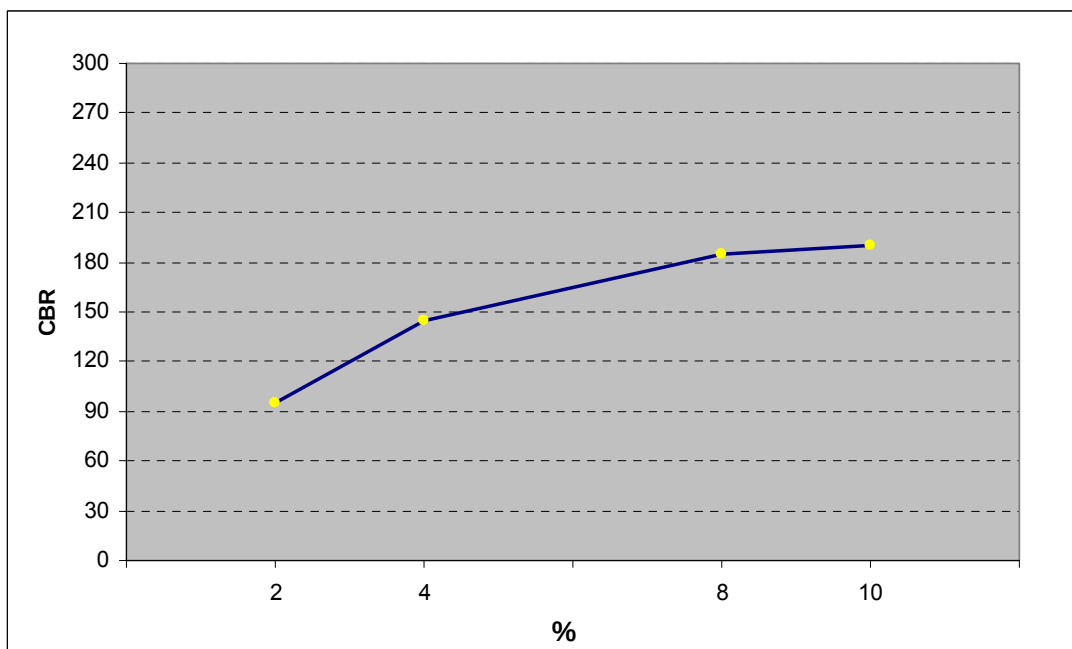


**Figure D.10 :** CBR Values of Lime Stabilized and 6-month Cured Samples.

## **CURRICULUM VITAE**

Abdulgazi Gedik was born in 1982 in Elazig. He completed his high school education at Balakgazi High School in Elazig. In 2000, he started to study civil engineering program in Istanbul Technical University (ITU). He graduated in June 2005, and then he started to study Transportation Engineering Graduate program at ITU in September 2005. He has been working as a control engineer at First Region (Istanbul) of Turkey General Directorate of Highways (KGM).

### **List of Publications:**

- Gedik A.G, Lav M.A., Lav A.H. (2008). "Utilization of Waste Foundry Sand as Pavement Sub-base and Fill Material". 1st ISSMGE International Conference on Transportation Geotechnics, The University of Nottingham, United Kingdom, 25–27 August 2008
- Solmaz P., Gedik A.G, Lav M. A., Lav A.H. (2008). "Utilization of Waste Foundry Sand as Impermeable Layer for Pavement Structures". 1st ISSMGE International Conference on Transportation Geotechnics, The University of Nottingham, United Kingdom, 25–27 August 2008

