

**İZMİR KATİP ÇELEBİ UNIVERSITY ★ GRADUATE SCHOOL OF NATURAL AND
APPLIED SCIENCES**

**IMPROVEMENT OF ENGINEERING PROPERTIES AND LIQUEFACTION
REDUCTION OF SANDY SOILS USING ELECTRIC ARC FURNACE SLAG
AND ROOF TILE POWDER**

M. Sc. THESIS

Drinela AGOLLI

Civil Engineering Programme

Thesis Advisor: Assist. Prof. Dr. Adem EREN

JULY 2016

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İZMİR KATİP ÇELEBİ ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**KUMLU ZEMİNLERİN MÜHENDİSLİK ÖZELLİKLERİ VE SIVILAŞMA
DİRENÇLERİNİN ELEKTRİK ARK FIRIN CÜRUFU VE KİREMİT TOZU
KULLANILARAK İYİLEŞTİRİLMESİ**

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To my family

FOREWORD

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ABBREVIATIONS

EAF	: Electric Arc Furnace Slag
H₂SO₄	: Sulphuric Acid
TEOS	: Tetraethyl Orthosilicate
HCl	: Hydrochloric Acid
PC	: Portland Cement
BFS	: Blast Furnace Slag
GGBFS	: Ground Granulated Blast Furnace Slag
XRF	: X-Ray Fluorescence
UCS	: Unified compressive strength
CH₃COOH	: Acetic acid
CaCO₃	: Lime

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IMPROVEMENT OF ENGINEERING PROPERTIES AND LIQUEFACTION REDUCTION OF SANDY SOILS USING ELECTRIC ARC FURNACE SLAG AND ROOF TILE POWDER

SUMMARY

The scarcity of suitable land for construction of engineering facilities and shortage of natural earth aggregates has highlighted the need for finding innovative way of construction. Nowadays problematic soils such as: soft clay, organic soils and liquefiable soils can be improved to the required civil engineering requirements by application of soil stabilization. Soil stabilization is a method intended to increase or preserve the stability of soil mass and chemical alteration of soil to improve engineering properties.

Generally, ground treatment techniques used are: densification, reinforcement, drainage and deep soil mixing. Using soil treatment, unbound materials can be stabilized with cementitious materials (lime, cement, fly ash, waste materials). Replacement of stabilizing agents with waste materials is becoming a need due to lack of natural resources and environmental concerns. Slag a by-product of metallurgical industry is being used to improve engineering properties of low bearing capacity soils.

In this study, mechanical properties of non-cohesive soils are improved using waste materials. Waste material used is: electric arc furnace slag (EAF slag). Natural materials diatomite and roof tile powder are mixed too. In order to activate slag, some chemical additives were added. Firstly, cylindrical samples with different proportions were prepared. They were tested for period of 7, 21 and 28 days under unconfined compressive strength (UCS) test. The optimum mixture was tested also under 1-D shaking table subject to different earthquake records. Photogrammetric approach was used to observe behaviour of soil under dynamic load and settlement.

It was seen that combination giving the highest compressive strength was mixture containing EAF slag, sand, lime and sulphuric acid (H_2SO_4). The highest compressive strength obtained was 7.736 MPa. Bonding capacity between EAF slag and sand is increased by addition of sulphuric acid. Liquefaction effect and settlement was reduced compared to control sample. Photogrammetric approach seems to be a valuable way to calculate settlement of a structure. Soil stabilization with EAF slag waste material with some deeper studies can be a useful method to treat non-cohesive soils.

KUMLU ZEMİNLERİN MÜHENDİSLİK ÖZELLİKLERİ VE SIVILAŞMA DİRENÇLERİNİN ELEKTRİK ARK FIRIN CÜRUFU VE KİREMIT TOZU KULLANILARAK İYİLEŞTİRİLMESİ

ÖZET

Mühendislik yapıları için uygun arazinin az bulunması ve doğal yeryüzü agregasının kıtlığı, yenilikçi yapım şekli bulma ihtiyacını doğurmuştur. Günümüzde yumuşak kil, organik ve sivilaşabilir zeminler gibi problemlili olan zeminlerin stabilizasyonu yapılarak inşaat mühendisliği için uygun projeler gerçekleştirilebilir. Zemin stabilizasyonu, zeminlerin kütleli ve kimyasal deęişikliğe uğramasını önlemek veya stabilitesini korumak için mühendislik özelliklerini iyileştiren bir tekniktir.

Genellikle kullanılan zemin iyileştirme teknikleri, yoğunlaştırma, güçlendirme, drenaj ve derin karıştırmadır. Bağlayıcısı olmayan malzemeler de zemin iyileştirmesi için kullanılan çimentolu malzemeler (kireç, çimento, uçucu kül, atık maddeler) ile zemin iyileştirmesi yapılabilir. Çevresel kaygılar ve doğal kaynakların eksikliği, dengeleyici malzemeler ile atık malzemelerin yer deęiştirmesi ihtiyacını doğurmaktadır. Metalurji sektörünün bir yan ürünü olan cüruf, düşük taşıma kapasitesine sahip zeminlerin, mühendislik özelliklerinin iyileştirilmesi için kullanılmaktadır.

Bu çalışmada, kohezyonsuz zeminlerin mekanik özellikleri, atık malzemeler kullanılarak iyileştirilmiştir. Kullanılan atık malzeme, elektrik ark fırın cürufudur (EAFC). Doğal malzeme olan diatomit ve kiremit tozu da karıştırılarak mühendislik özelliklerinin deęişimi incelenmiştir. Cürufu aktif hale getirmek için bazı kimyasal katkı maddeleri de ilave edilmiştir. Hazırlanan silindirik numuneler üzerinde 7, 21 ve 28 günlük periyotlarda bekletildikten sonra serbest basınç dayanım (SBD) testi yapılmıştır. Optimum karışımın sivilaşma direncinin deęerlendirilebilmesi için, laboratuvar ortamında farklı deprem kayıtları altında bir boyutlu (1-D) sarsma tablası deneyleri yapılmıştır. Dinamik yükleme altında zemin davranışı ve oturmaları deęerlendirmek için fotogrametrik yaklaşım kullanılmıştır.

İçerisinde EAFC, kum, kireç ve sülfürik asit (H_2SO_4) olan karışımın dayanımı 7,736 MPa ile en yüksek basınç dayanımına sahip olduęu görülmüştür. EAFC ve kum arasındaki bağ kapasitesi, sülfürik asit eklenmesi ile arttırılmıştır. 1-D sarsma tablası deneyleri incelendiğinde elde edilen karışımın sivilaşma direncinin arttığı ve oturmaların da etkisi azaltılmıştır. Yapıların oturmasını hesaplamak için fotogrametrik yaklaşımın kullanılabilirliği de böylece ortaya konmuştur. Yapılacak daha ayrıntılı çalışmalarla, EAFC atık malzemesinin zemin stabilizasyonun da kullanılması kohezyonsuz zeminlerin iyileştirilmesi için kullanışlı bir yöntem olduęu deęerlendirilmektedir.

1. INTRODUCTION

Ground treatment is quite an old technique and it has been stated that soil improvement is apparently the oldest of all common improvement methods in civil engineering discipline. Soil stabilization binds stabilizing agents in weak soils to improve geotechnical properties such as strength, permeability, compressibility and durability. Most of soil stabilization is applied into soft soils, but they are not the only problematic soils. Due to natural disasters, such as earthquakes, poor sandy soils lose their strength and carrying capacity. In addition, liquefaction starts to occur. Mogami and Kubo (1953) defined liquefaction as loss of shear strength due to seismically induced cyclic loading. Since soil after liquefaction occurrence is not able to safely transmit the loads that are imposed upon, it needs to be treated.

Many methods have been presented to increase liquefaction resistance. Generally, the main methods used to mitigate liquefaction are categorized as densification, reinforcement, drainage and deep soil mixing. These traditional methods generally have high energy-consumption needs and high costs, and some of them are unsuitable for use over large areas (Khodadadi and Bilsel, 2012). In addition, lack of natural resources, environmental concern and the need for reduction of construction cost has led to the use of industrial wastes as stabilizing agents. Slag can be used as a stabilizing agent. Slag is a waste material obtained from iron core and available material in many countries. It can be reusable and has low cost of usage. It has similar characteristics to natural crushed stone or sand. Slag has the characteristics of solidification and brittleness after curing. Generally, chemical composition of the slag consists of oxides of calcium, silica, alumina etc, and is an important parameter effecting the reaction with other soil chemical elements found in soil. It doesn't contain cementitious compound itself, but it has latent hydraulic properties which can be activated by addition of lime or alkaline material (Sherwood, 1993; Åhnberg et al., 2003).

For a notable stabilization, laboratory tests followed by field tests may be needed to estimate the engineering properties of treated soil. UCS test is used to identify maximum carrying capacity of treated soil and for liquefaction assessment are used

both laboratory and field tests. SPT and CPT tests are field test used to assess liquefaction. The laboratory methods include direct shear test, triaxial shear test, torsion shear test, centrifuge tests, ring shear test and shaking table test.

UCS tests and 1-D shaking table tests were carried out to investigate the behavior of sandy soils. Increase in carrying capacity and reduction of liquefaction was possible by involving waste materials in soil stabilization.

1.1 Purpose of Thesis

This study plans to use industrial waste material as soil stabilizer to improve the behavior of liquefiable sandy soils.

The aims are as listed below:

1. Investigation of the behavior of liquefiable sandy soils with particle size 0.250-0.425 mm improved with waste material such as: electric arc furnace slag, roof tile powder diatomite and chemical additives.
2. Conduction of UCS test and optimization of mixtures to be selected.
3. Testing of optimum mixture obtained under 1-D shaking table subject to well-known earthquake records (El Centro, 1940; Niigata, 1964; Loma Prieta, 1989; Northridge, 1994; Kobe, 1995; Kocaeli, 1999).

1.2 Organization of the Thesis

The thesis consists of six chapters. The first chapter presents an introduction of the study that is related to the entire work. Chapter 2 presents a literature review of existing ground improvements methods, liquefaction and adverse effects of it. The characteristics of the materials used for improvement of engineering properties of soil are presented in Chapter 3. Chapter 4 displays sample preparations, types of mixtures and the conduction of the required laboratory tests. Evaluations of test results are discussed in Chapter 5. In Chapter 6, summary and findings of this study are presented. The last chapter is followed by a list of references

2. REVIEW OF GROUND IMPROVEMENT METHODS AND LIQUEFACTION

2.1 Literature Review of Ground Improvement Techniques

Data and instructions how soil stabilization is implemented have been well documented. Many journal articles and textbooks are available. The first part of this review discusses literature cases about ground improvement techniques used against liquefaction. The second part briefly discusses liquefaction effect to soil.

Basic concepts of soil improvement, as introduced in ASCE (1978) report on soil improvement such as densification, cementation, reinforcement, drainage, drying and heating were developed hundreds or thousands of years ago and still continues to be unchanged. There have been a lack of space devoted to the soil improvement subject in early soil mechanics books and in journals. The first papers related to ground treatments were introduced in the First Geotechnique Conference held on 29 May 1975. Initially, ground treatment methods of that time were surrounded by mystery. All methods were at primitive state. Generally, ground improvement methods consisted of required ground behavior for particular use of the ground, identifying any deficiency in ground behavior (Burland et al., 1976).

Compaction stands for densification of soil by dynamic methods, which based on the method of conveying the energy to the soil, can be divided into two main groups, impact compaction and vibratory compaction. Massarsch (1991; 1999), Mitchell (1982) and Schlosser (1999) have extensively described the methods and their practical applications.

Dynamic compaction is a technique of subgrade strengthening consisting of non-cohesive sand soils. This method is used to strengthen weak soils up to the depth of 14 m (in practice up to 10 m high). Vibro compaction is likely the oldest deep compaction method existing. It was founded by Johann Keller Company in 1936, following the finding of the depth vibrator. Schneider (1938), Greenwood (1976) and Kirsch (1993) reported a detailed description of the method from its beginnings up to the pre-war

period. This technique is the most suitable for the stabilization of soils with limited amounts of fines. Mitchell (1981) reported that the best desirable soils for vibro compaction are when the soil's fines content is 18%. Woodward (2005) proposed that when fines content is less than 10% best results can be obtained.

Falkner et al., (2010) reported a theoretical investigations of the rapid impact compaction (RIC), which involves numerical computer simulations of the impulse type compaction effect, the energy transfer into the soil, and the wave propagation. Experimental tests in different soil conditions gave a verification of the theoretical analyses. They also gave the basis for an optimized and economical application of the compaction method in practice. Case studies of different construction projects showed a successful application of the RIC for middle-deep improvement and compaction of the ground.

Simpsons (2008) observed a case study on the use of the RIC at a reclaimed site (1.21 km²) in California, USA. Pre and post treatment Cone penetration test (CPT) results were given. The comparison of the state before and after liquefaction potential was also done. The results of vibration monitoring performed during conduct of the RIC method were examined. It was summarized that the RIC is a suitable and economical ground improvement method and liquefaction mitigation method as well.

Tarawneh and Matraji (2014) evaluated the usefulness of RIC technique in the Arabian Gulf Region. The RIC technique was used to improve an area of 29,000 m² on a project site near Dubai, UAE, where the groundwater level is shallow. Cone Penetration Tests (CPT) and settlement calculations were performed before and after soil improvement. Test results demonstrated improvement in the soil bearing capacity and decrease in expected settlements.

Sand compaction pile (SCP) is a soil stabilization technique that is used to improve stability, control liquefaction and reduce settlement of various structures. The behavior of SCP is similar to that of stone columns. These piles can significantly accelerate the pore water pressure dissipation process and the time for consolidation when built in soft soils. It combines fundamental principles of ground improvement, such as densification and drainage. SP were first constructed in Japan in 1930 (Ichimoto, 1981). SCP technique is most used in Japan as countermeasure against liquefaction (Harada, 2004).

Okamura et al., (2002) demonstrated that during the improvement of a site by SCP, where the compaction piles are put into the soil by pressurized air supplied from the top of the casing, some of the air percolated into the sand and some spouted from the ground surface. Based on this investigation, Okamura et al., (2002) observed another site treated 26 years ago by SCP and concluded that air bubbles survived for 26 years. Having this supportive evidence, the authors also studied whether or not air/gas will remain entrapped under groundwater flow at low and high gradients. Large scale constant head flow test setups were prepared.

Stone columns are a ground improvement technique that used to increase the load-bearing capacity of shallow foundation on soft clay layers. Adalier et al.,(2003) found that when trying to stabilize nonplasticsilty soils, only the third benefit can be expected primarily to mitigate liquefaction. This method has been applied since late 1950s. Gnieal and Bouazza (2008), Shenthan et al., (2004), Mitra and Chathpadhyay (1999) have presented that during an earthquake, stone columns can behave as a gravel drain column to discharge pore water pressure and the liquefaction potential of a ground can be reduced. Gniel and Bouazza, (2008) suggested that conventional stone columns in soft soil deposits was found to be beneficial for foundations in many respects. Reinforced short pile method can be applied to improve the stability of the structure and avoid the liquefaction damages to the structures. Cernica (1995) found that the length and diameter of the reinforced short pile are important in application.

Arman et al., (2009) in their study proposed the application of modified dry bottom feed stone column as dominant ground improvement method in the region of Adapazari city in Turkey. A numerical analysis was performed to check performance with respect to displacement. Results showed that significant improvements were achieved in terms of displacement.

Jet grouting is a soil stabilization technique, in which cement slurry is injected into the soil at high velocity to create a soil-concrete matrix. The process of jet grouting was first developed in 1960s. Most of the research work was implemented in Japan, (Ohata and Shaibzaki, 1982). Later on, it was spread in Europe in 1970s.

Jet grouting technique can be used to treat a whole range of soils, from silty sands to cohesive deposits, by using cement grouts. It can be applied to soils with a wide range of granulometries and permeability.

Yasuda (1993) reported that, in Japan during the period 1985-1990, deep densification by different methods was implemented at 175 sites, partial improvement or hardening was used at 16 sites, drainage to decrease saturation was carried out on 22 sites, and drains to prevent large buildup of excess pore pressures were executed at 101 sites.

Deep mixing stabilization is one of the methods used to mitigate liquefaction. It was first developed in 1954 in USA. Later it was spreaded in Japan (1960), Sweden and it is nowadays worldwide known. At the beginning, this method used lime as binder material for treatment of soft-clay soils. Later in 1975, cement was used as fluid cement grouting for treatment of soft marine soils (Bruce, 2000).

Deep mixing as a soil stabilization technique which enhances the engineering characteristics of soil, consisting in increased strength, low compressibility, permeability and erodability, liquefaction mitigation, reduction of water content and increased durability in dynamic or cyclic actions (Nicholson & Peter, 2014).

In deep mixing method, different admixtures are used as binder, such as lime, cement, fly ash, and waste materials.

Lime stabilization is a ground stabilization method in which soil is mixed with lime used to modify the soil, improve the strength and durability. Lime is the first binder used to enhance the geotechnical characteristics of the ground. The quantity of lime used to improve most soils varies from 5 to 10%.

Sherwood, (1993) reported that soil stabilization using lime provided an increase in strength by cation exchange capacity rather than by cementing effect of pozzolanic reaction.

The types of lime used for mixing are high calcium lime, calcitic quicklime and monohydrated dolomitic lime. Rogers et al., (1996) presented that quicklime is the most commonly used lime for soil stabilization.

Tran (2014) noted that lime soil treatment can be used in various applications such as roads, highways, embankments, dams, airfields, etc. to enhance the shear strength, reduce the deformations and decrease water content.

Cement is being extensively used as a stabilizing material for soil, generally for construction of highways and earth dams. It is used to stabilize sandy and clayey soils. When liquid limit (LL) is less than 45 to 50 and plasticity index (PI) is less than about

25, cement stabilization is effective for clayey soils. The reaction that occurs between cement and water is a hydration reaction. Sherwood, (1993) reported that the hydration reaction is slow process starting from the surface of the cement grains and the center of the grains may remain unhydrated. MacLaren and White (2003) found that cement hydration is a complex mechanism with a complex series of unknown chemical reactions.

Generally used cement content according to soil type is shown in Table 2.1 below:

Table 2.1: Cement ratio ranges for stabilization (Das, 2011)

AASHTO Classification	Cement Ratio Ranges for Stabilization (%)
A-1-a	3-5
A-1-b	5-8
A-2	5-9
A-3	7-10

Sherwood (1993) stated that cement can be considered as primary stabilizing agent or hydraulic binder because it can be used alone to achieve the required stabilizing action. Maher et al., (2004) reported that soils treated using cement binder are susceptible to frequent dry-wet cycles due to diurnal changes in temperature.

Nicholson (2014) found that for the ground with a high degree of moisture and high organic content, using cement as a hardening agent is not the most economical way.

Anagnostopoulos & Chatziangelou, (2008) reported that the strength of cement-stabilized soil is influenced by sand and fines content, the mineralogy, the particle packing, density, the liquid limit (LL), the water content, the pH and the amount of added cement and curing time.

Saroglou (2009) investigated the compressive strength of five type of soils mixed with different proportion of cement, for curing period of 7 and 28 days. It was observed that the soil type is a important factor on the rate of increase of compressive strength with increasing of cement content.

Blast furnace slag can be a suitable option to replace traditional stabilizing agents. Generally, it is used to improve the engineering properties of clay soils and increase the unconfined compressive strength (UCS).

Kodikara and Yeo (2005) reported in situ stabilization technique as an applicable method of rehabilitation of degraded granular road pavements. The method involves

adding of certain percentage of a binder to treat ground soil. The main binder types used for in situ stabilization are cementitious and/or bituminous. As stabilization binders, they introduced the use of alkali activating slag. After this study it was concluded that more research is needed to be done to advance this technique.

Poh et al., (2006) investigated the behavior of English China clay and Mercia mudstone stabilized with three Basic Oxygen Steel (BOS) slag fines from three different steel production sites. A mixture of BOS slag fines and two different activators, quicklime and sodium met silicate, were also tested. In the end of the experiment, it was concluded that the use of BOS slag fines improves in strength and durability, and also reduces the expansion. In order to achieve significant improvements in strength, soils required a high percentage, 15–20% of BOS slag fines, and a long curing period.

Manjunath et al., (2011) studied the behavior of typical black cotton soil stabilized with granulated blast furnace slag (an industrial waste) along with hydrated lime. The specimens were tested for UCS after different time periods. It was found that undrained shear strength (S_u) of black cotton soil improved phenomenally after curing for 28 days with 4% lime and 40 % ground granulated blast furnace slag. Also it was found that when 20% slag and 4 % lime are added to soil, S_u increased almost 16 times; and with 40% slag & 4 % lime mixing proportions S_u increased 18 times.

In the study of Takahashi et al., (2014), the deformation behavior of improved ground using slag was investigated. Test results showed that slag could be a viable alternative to natural sand as an improvement material.

Veith (2000) suggested that environment must be taken into consideration, regarding the selection of an appropriate stabilizer for soils. Therefore, sustainable environmental binders can be used. Utilization of slag (a by-product and waste material) in soil stabilization is introduced as a choice for engineers in addition to lime and cement.

Slag has the characteristics of solidification and brittleness after curing. At the same time, it has useful geotechnical properties such as lightweight, high internal friction angle and high permeability. Therefore, the use of this product in soil stability related problems seems to be acceptable. Emil Langen (1862) was the first who discovered the cementitious properties of granulated blast furnace slag (GBFS). In recent years,

the production of pig iron has increased progressively in the world. Escalante, (2001) reported that approximately 300 kg of slag is produced per ton of iron.

Oner (2000) presented that annually in Turkey are produced around 35 million tons of cement and 13 million tons of crude steel. In 1996 and 1998, the production of GBFS was about 0.75% and 2.2% of total Turkish cement production respectively. Now the production is increasing.

Generally slag is used for stabilization of roads, highways, pavements, etc., in clayey soils. In literature, studies related to soil stabilization with slag exist. Slag has shown promising results in increasing the UCS values of the reactive soils and decreasing the swelling potential. (Yadu & Tripathi, 2013) investigated the increase of UCS values of soft soils treated with granulated blast furnace slag (GBS). They reported that, addition of slag in stabilized specimens resulted in increased UCS values. An increase of 28% of UCS values compared with untreated ones was obtained when 9% of slag was added in the mix.

Ortega-López et al., (2014) observed the behavior of clayey soils stabilized with five different types of ladle furnace slag at a proportion of 5%. They noticed positive results such as reduction in the swelling potential of soil, strength and volumetric stability and higher CBR indices as compared with the untreated soil.

In literature there is limited information regarding to engineering properties of blast furnace slag. Emery (1980) found that loose dry unit weight values for palletized BFS range from 8.2 to 10.4 kN/m³. It is a glassy material, typically with sand-to-gravel-size particles.

According to the method used to cool the molten slag, different forms of slag product are produced. Other available product can be air-cooled blast furnace slag and pelletized slag expanded or foamed slag (TFHRC, 2004).

There are many application of steel slag in concrete production, as asphalt aggregate, as road bases and sub-base aggregates, and there are few studies for soil stabilization applications. Electric arc furnace slag (EAF slag) has a high specific gravity. Due to that, if used as an aggregate for structural concrete, we can produce heavy weight concrete.

Kim et al., (2012) investigated the characteristics of concrete with EAF oxidizing slag as an aggregate and evaluated the usability of slag for concrete in RC members. The

study conducted bond performance tests between the steel bar and the concrete with EAF oxidizing slag aggregates, which were checked in order to use this new material in RC members.

Sekaran et al., (2015) reported the contribution of EAF oxidizing slag as coarse aggregate to the compressive strength of concrete, and as an environmental friendly solution. The aim of study was to define and analyze the physical, mechanical and durability properties of eco-friendly concrete containing 50% EAF oxidizing slag aggregate and 30% of fly ash. Based on the overall results, it could be recommended that EAF oxidizing slag and fly ash could be effectively used as coarse aggregate replacement and cement replacement in all concrete applications.

Manso and Gonzalez (2004) studied durability of concrete made of EAF slag as an aggregate and the results were acceptable. The concrete mixes using conditioned EAF slag provided good fresh and hardened properties and showed acceptable behavior against aggressive environmental conditions. It was seen that the compressive strength was comparable to that of traditional concrete. The durability was slightly lower compare to conventional concrete. The concrete had 21 good physical and mechanical properties, but results showed that special attention should be given to the gradation and crushing process. It was observed that the high porosity of EAF slag aggregates affects concrete resistance to freezing and thawing but improvements in the field could be possibly done by adding air-entraining admixtures.

Maslehuddin et al., (2003) investigated the mechanical properties and durability characteristics of concrete containing steel slag as an aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag showed better physical properties, durability characteristics and compressive strength, whilst similar results were obtained for the flexural strength.

Ducman et al., (2011) evaluated the utility of the refractory concrete production using EAFS as aggregates and the results indicated that when slag was heated up to a temperature of 1000 ° C prior to its use for refractory concrete, the final products exhibited mechanical properties which are similar to concrete with conventional refractory aggregate, e.g. bauxite.

The study by Altun et al., (2002) showed that the cement with 30% steel slag fine powder addition satisfied the Turkish standard requirements for Portland cement

Pellegrino et al., (2013) investigated the possibility of partially substituting natural aggregates with Black/Oxidizing (EAF) slag in concrete production. In order to identify a convenient substitution ratio for concrete, five recycled and one traditional mixes were prepared. Results provided that high substitution ratios of coarse natural aggregates are possible without decreasing mechanical properties of concrete. It was seen that presence of calcium and magnesium oxides is not a limit for durability of concrete, due to their stabilization in crystalline lattice.

Ahmedzadea et al., (2009) investigated the effect of implementation of steel slag as a coarse aggregate on the properties of hot mix asphalt. The results provided that steel slag used as a coarse aggregate enhanced the mechanical properties of asphalt mixtures. Moreover, volume resistivity results confirmed that limestone asphalt mixtures showed lower electrical conductivity compared to steel slag asphalt mixtures.

Asi (2007) concluded that asphalt concrete mixes made up of 30% steel slag had the highest skid number followed by Superpave, Stone Mastic Asphalt (SMA), and Marshall mixes, respectively.

Ameri et al., (2012) investigated the performance of steel slag as a substitute for virgin aggregates on mechanical properties of cold mix recycling asphalt pavement. The results showed that the utilization of steel slag could improve Marshall Stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to permanent deformation of CIR (Cold in Place Recycling) mixes.

Abdalla (2011) observed the behavior of diatomite to improve the effect of salinity on clovers. He described that the use of different diatomite mix ratios, 0, 1.5, 3 and 4.5 g/kg soil, decreased the negative effects of salinity on two varieties of clover.

Karatepe et al., (2004) by investigating the factorial design, studied the effect of diatomite and modified diatomite on lead available in soil, and stated that manganese diatomite compared to crude diatomite had more effective on decreasing the lead concentration and increasing the soil pH as well.

From the review presented in this chapter, it can be concluded that soil improvement is an old technique to improve engineering properties of different types of soil and prevent structure failure against natural hazards. Increasing the shear strength, durability and permeability of cohesive soils is an important searching area of researchers. Waste materials such as slag are generally used to enhance engineering

properties of cohesive soil but not to mitigate liquefaction hazard and improve engineering properties of cohesion less soils.

2.3 Literature review for liquefaction

After it was firstly highlighted in Niigata (Japan) Earthquake (1964), soil liquefaction has been the main concern of researchers. Many studies regarding the effect of liquefaction phenomena, its evaluation and prevention of destructive damages have been conducted. Different researchers have defined liquefaction term differently. Terzaghi and Peck (1948) were the first that used the term “liquefaction” to describe loss of shear strength of very loose sands causing flow failures due to slight disturbance (Kramer, 1996).

Yang et al., (2003) have stated that the potential influence of partial saturation on pore pressure builds up. Also, Xia and Hu et al., (1991), Ishihara et al., (2002) have reported that partially saturated sands exhibit larger cyclic strength against liquefaction than fully saturated sands at the same density.

There are two main types of liquefaction phenomena: flow liquefaction and cyclic mobility. Both of them are very important. Cyclic mobility occurs more frequently than flow liquefaction but the last one has more severe effects. Cyclic mobility can be observed in much broader range of soil and site conditions. (Kramer, 1996).

Bartlett and Youd (1992) reported that liquefaction-induced ground deformations were mainly destructive to highway and railway bridges during the 1964 Alaska Earthquake. Also, Shinozuka (1995), Matsui and Oda (1996), Tokimatsu et al., (1998) reported many bridge failures that occurred during Hyogo-Ken Nanbu (Kobe) earthquake (1995).

The National Research Council (1985) lists eight types of ground failure commonly associated with soil liquefaction in earthquakes:

- 1.** Sand boils, resulting in land subsidence accompanied by relatively minor changes.
- 2.** Failure of retaining walls due to increased lateral loads from liquefied backfill or loss of support from the liquefied foundation soils.
- 3.** Ground settlement, generally linked with some other failure mechanism.
- 4.** Flow failures of slopes resulting in large down slope movements of a soil mass.
- 5.** Buoyant rise of buried structures such as tanks.

6. Lateral spreads resulting from the lateral movements of gently sloping ground.
7. Loss of bearing capacity resulting in foundation failures, uplifting of lighter structures, subsidence of heavier structures.
8. Ground oscillation involving back and forth displacements of intact blocks of surface soil.

Lateral spreading is permanent ground displacement caused by flow slides or cyclic mobility on very gently sloping ground or on nearly flat ground adjacent to drainage or stream channels or bodies of water. It may cause conspicuous surface manifestations of ground failure. Displacement occurs in response to combination of gravitational and inertial forces generated by an earthquake. Youd (1993) stated that lateral soil deformations (lateral spreading) have been the most pervasive type of liquefaction-induced ground failure

Hamada et al., (1986), Rauch and Martin (2000) presented pioneering studies of lateral spreading following earthquakes in Japan. Lateral spread displacement has been evaluated based on two parameters, the thickness of the liquefiable layer and the slope angle.

Soil stiffness is reduced during an earthquake due to development of positive excess pore pressure. At the beginning of the earthquake, a deposit of liquefiable soil is stiffer than that in the end of the motion. Large, transient ground oscillations and decoupling of the liquefied soils from the surficial soils are caused due to liquefaction at depth beneath a flat ground surface. Surficial soils are broken into blocks, separated by fissures that can be open and close during the earthquake. During ground oscillation, ground waves with amplitudes of up to several meters are observed, but permanent displacements are usually small.

An example of alternation ground motion is Marmara Earthquake (August 17, 1999). Many buildings sank into the soil and collapsed by the shaking. Ground oscillation has been attribute of most ground movements that have occurred in San Francisco during Loma Prieta Earthquake.

In their studies, Seed et al., (1975), Baziar and Dobry (1995); Moriwaki et al. (1998) reported that the failure of the upstream slope of the Lower San Fernando Dam during the 1971 San Fernando earthquake is a well-studied example of a flow failure.

Sasaki et al., (1996), and Naesgaard et al., (1998) have reported that the loss of soil strength can result in potential foundation bearing failure and large foundation settlements. The assessment of these potential hazards requires estimation of liquefaction potential and the factor of safety with respect to bearing failure.

Several field test are used to evaluate liquefaction resistance such as standard penetration test (SPT), cone penetration test (CPT), shear-wave velocity measurements (V_s) and Becker penetration test (BPT). Analytically, liquefaction resistance is evaluated by the estimation of two variables: **1) Cyclic stress ratio (CSR)** and **2) cyclic resistance ratio (CRR)**. If the ratio between CSR and CRR is less than 1, liquefaction occurs.

There are many factors that control soil liquefaction such as soil type, grain size distribution, grain shape, depositional environment, age of deposits, relative density and void ratio of soil, initial confining pressure, drainage conditions and earthquake magnitude and duration. Each of these factors has different effect on the influence of liquefaction potential.

Wellgraded soils are less susceptible to liquefaction than poorly graded soils. Particle shape has influence on liquefaction susceptibility as well, rounded particle shapes are more susceptible to liquefaction than angular-grained soils since they densify more easily. Ground water is a factor that affects liquefaction, with increase of ground water depth, liquefaction susceptibility decreases. New soils deposits are more susceptible to liquefaction than old deposits (Kramer 1996).

2.4 Photogrammetric approach

Photogrammetric approach was used to measure settlements during shaking. Photogrammetry integrate the optic – sensing and surveying technologies allowing to get geometric measurements by taking photos on site and interpreting data in lab, to provide a relationship between the photos and the three-dimensional (3D) object space. (Blachut and Burkhardt, 1989) approach makes measurement using 2-D photos.

In contrast with conventional surveying methods, photogrammetry has some advantages such as: 1) interprets data directly on photos without directly measurement; 2) collects data easily by using digital camera. Preliminary, in construction it has been used to model component provision for; visualization (Dai and Lu, 2008); progress

assessment (Golparvar-Fard et al., 2009) quantity take-off (Gomez-Lahoz, 2009) and dispute resolution (Luhmann and Tecklemburg, 2001).

3. CHARACTERISTICS OF MATERIALS USED

In this study, some different waste materials and chemicals additives were used to enhance engineering properties of soil. The main component was electric arc furnace slag and sandy soil. The other constituents as roof tile powder, diatomite, sulfuric acid, hydrochloric acid, acetic acid and lime makes the minor part of composition.

3.1 Slag

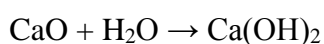
Slag is a by-product of metallurgical industry, obtained by transformation or purification of metals such as iron, copper, lead or aluminum. The main slags are classified in various types: ferrous slag, iron slag generated in blast furnace process, steel slags, non-ferrous slag generated by production non-ferrous metals (Cu, Zn, Pb, Ni) boiler slag obtained by coal combustion. Steel slag have greater soluble salt content than limestone because of the content of CaO and MgO, which react with water to form Ca(OH)_2 and Mg(OH)_2 . These hydroxides contain water solubilities of 1.20 g/L and 0.009 g/L, respectively, compared to 0.014 g/L for CaCO_3 and 0.013 g/L for MgCO_3 (National Lime Association, 1990). Contain of high bulk density of 3.2g/cm^3 qualifies steel slags as a construction material for hydraulic engineering purpose. In the field of hydraulic structures, steel slags are mostly applied for:

1. Dams and dikes
2. Stabilization of river bottoms
3. Refilling of erosion areas on river bottoms and stabilization of rivers banks.

When steel slag is mixed with soils, it undergoes some reactions which are listed below:

1. Hydration reaction

When f-CaO react with water hydration occurs as shown:



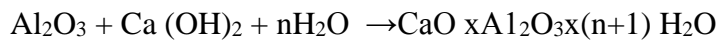
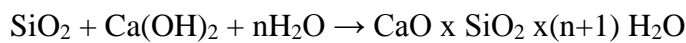
Due to this, the water in soil will be reduced; because of the hydration heat evolution, the water in soil is partly vaporized; the consolidation of soil will be accelerated and finished

2. Ion Exchange

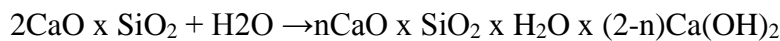
The content of C_3S and $\beta-C_2S$ in steel slag mixed with soil, will produce $Ca(OH)_2$, $CaSiO_3$. A large number of Ca^{2+} and soil particles mutual exchange adsorption, speed up the soil consolidation.

3. Cementation and Agglomeration

The redundant Ca^{2+} in soil, when meeting the chemical content SiO_2 , Al_2O_3 and CaO ,



As for the existence of $\beta-C_2S$ in steel slag,



The procedure and the created compound will provide harden effects and the soil will be agglomerated. The steel slag can be likely usable in the application of soil improvement. A comparison of the formation process of various slags is shown in the form of flow chart in Figure 3.1.

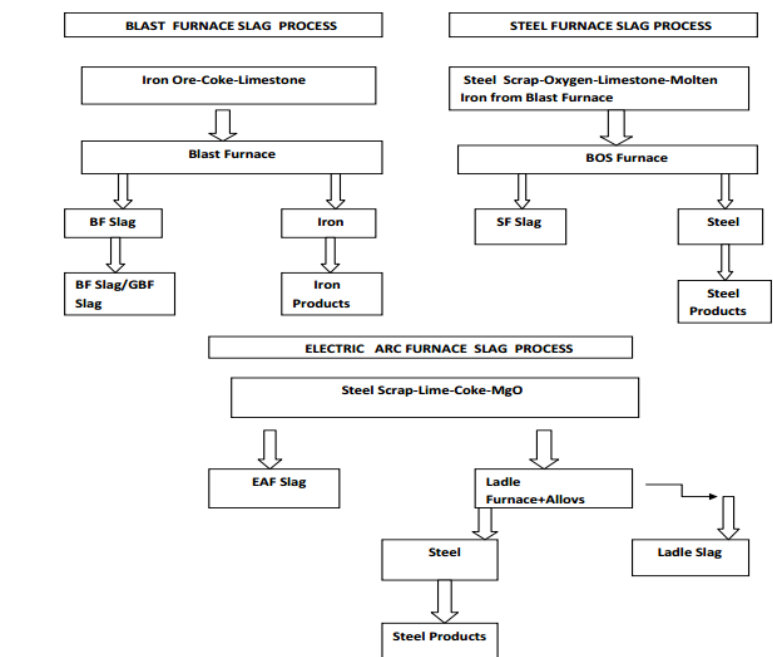


Figure 3.1 : Flow chart showing the processes of various slag (ASA, 2002)

3.2 Blast furnace slag

Rapid growth of industrialization has increase the pressure all over the world on available land, not only for housing and industrial complexes, but also for landfilling as means of disposing huge quantities of waste generated form industrial and mining-mineral processing operations. Waste disposal has reached at an amount where lots of land is required. Taking in consideration this concerning issue there should be some broad-base action to use waste materials in effective way (Rai, 2002).

Ground granulated blast furnace slag (GGBFS) is a nonmetallic by-product of the steel industry. Generally, it is classified into two types: granulated blast furnace slag and air-cooled blast furnace slag. Blast furnace slag (BFS) is an amorphous glassy material which consist of SiO_2 , Al_2O_3 and CaO chemical components (Seggani, 2003). The molten slag, which absorbs much of the sulfur from the charge, comprises about 20% by mass of iron production (Monshi, 1999). Production process is schematically presented below:

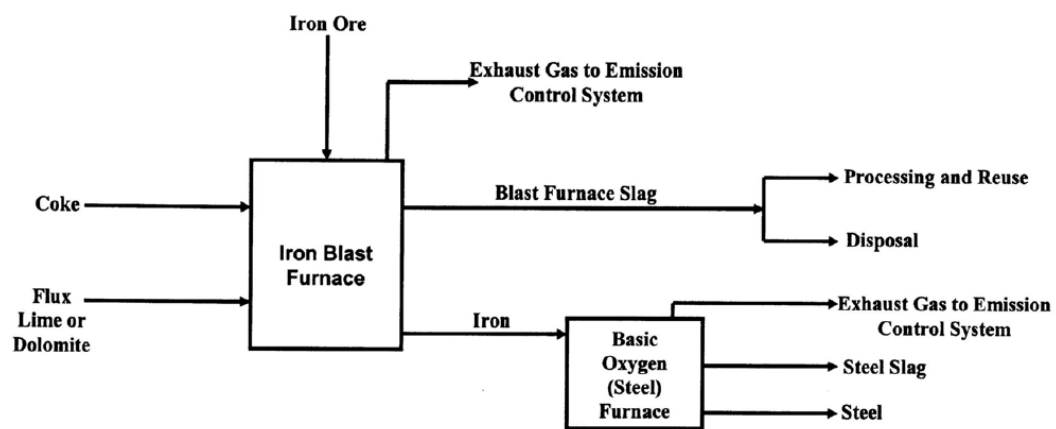


Figure 3.2 : General schematic of blast furnace operation and blast furnace slag production (TFHR, 2004)

BFS can replace Portland cement (PC) as binder by reacting with the alkali product of hydrated PC $\text{Ca}(\text{OH})_2$ in alkali activations or pozzolanic reactions. By using blast furnace slag instead of PC CO_2 emissions can be decreased. It has cementitious properties After that manufacture of GBFSC has substantially increased due to greater emphasis on energy conservation, utilization of waste materials and certain technical advantages over ordinary PC such as higher resistance to aggressive conditions.

Blast furnace slag has been widely used as a successful replacement material for PC, improving some properties and bringing economic benefits.

3.2.1 Air-cooled blast furnace slag

If the liquid slag is poured into beds and slowly cooled under ambient conditions, a crystalline structure is formed and a hard lump slag is produced, which can subsequently be crushed and screened. It has angular, roughly cubical, and has textures ranging from rough, vesicular (porous) surfaces to glassy (smooth) surfaces with conchoidal fractures.

3.2.2 Expanded or foamed blast furnace slag

If the molten slag is cooled and solidified by adding controlled quantities of water, air, or steam, the process of cooling and solidification can be accelerated, increasing the cellular nature of the slag and producing a lightweight expanded or foamed product. Foamed slag is distinguishable from air-cooled blast furnace slag by its relatively high porosity and low bulk density. Expanded blast furnace slag (EBFS) has angular, roughly cubical shape, and has a texture that is rougher than that of air-cooled slag. The porosity of expanded blast furnace slag aggregates is higher than air cooled slag aggregates. The bulk relative density of expanded slag is difficult to determine accurately, but it is approximately 70 percent of that of air-cooled slag. Typical compacted unit weights for expanded blast furnace slag aggregates range from 800 kg/m³ (50 lb/ft³) to 1040 kg/m³ (65 lb/ft³).

3.2.3 Pelletized blast furnace slag

This product is formed by cooling the molten slag using water to produce a lightweight aggregate that can be used for high fire-rated concrete masonry and lightweight fill applications over marginal soils. It is perfectly suited for aggregate in lightweight concrete masonry, lightweight ready-mix concrete and lightweight precast concrete due to its reduced-weight. Types of blast furnace slag are shown in Figure 3.3



Figure 3.3 : a) Blast furnace slag b) Air-cooled blast furnace slag c) Pelletized blast furnace slag

3.3 Electric arc furnace slag

EAF slags are a by-product of the steel-making process. They are obtained by a treatment process based on controlled solidification and subsequent crushing of slags from scrap melting in the electric arc furnace. After every crushing step, magnetic belts extracted the newly freed iron particles and the slags were screened in different grain sizes, becoming artificial aggregates. The main chemical constituents of EAF slags are FeO (22-60%), CaO (6-48%), SiO₂ (9-32%), Al₂O₃ (3-14%) and MgO (3-15%). The oxide composition values in literature are given in table below Table 3.1.

Table 3.1: The oxide composition values in literature (Autelitano and Giuliani, 2015)

Parameters	Literature Values
Calcium Oxide (CaO) %	6-48
Silica Dioxide (SiO ₂)%	9-32
Aluminum Oxide (Al ₂ O ₃)%	3-14
Magnesium Oxide (MgO)%	3-15
Iron (II) Oxide (FeO)%	21-48
Manganese (II) Oxide (MnO)%	1-16
Titanium Dioxide (TiO ₂)%	0-1
Phosphorus Pentoxide	0-2
Chromium (III) Oxide (Cr ₂ O ₅)%	0-2
Sulfur (S)%	-
Chromium (Cr)%	-

The oxide composition of EAF slag was determined using X-ray fluorescence (XRF) analysis. Table 3.2 shows the oxide composition of EAF slag used in our experiments. Major oxide found are FeO, CaO and SiO₂.

Table 3.2 : EAF oxide composition

Parameters	EAF oxide composition
Calcium Oxide (CaO) %	27.1125%
Silica Dioxide (SiO ₂)%	22.4373%
Aluminum Oxide (Al ₂ O ₃)%	6.8397%
Magnesium Oxide (MgO)%	3.3343%
Iron (II) Oxide (FeO)%	34.6857%
Manganese (II) Oxide (MnO)%	5.2908
Titanium Dioxide (TiO ₂)%	0.4956%
Phosphorus Pentoxide	0.5126
Chromium (III) Oxide (Cr ₂ O ₃)%	1.2236%
Sulfur (S)%	0.692%
Chromium (Cr)%	

3.4 Sand

The sandy soil used in experiments belongs to boundaries of most liquefiable soil shown in Figure 3.4. Physical properties of soil were estimated by some laboratory test done in our laboratory. For determination of friction angle and cohesion coefficient direct shear test was conducted. Specific gravity and unit weight were determined by specific gravity test and unit weight test. Physical properties are shown in Table 3.3.

Table 3.3 : Physical properties of sand

Physical Properties	Values
Unit Weight	14kN/m ³
Cohesion Coefficient	0
Specific Gravity	2.65
Friction Angle	33°
Particle Size	0.425 mm

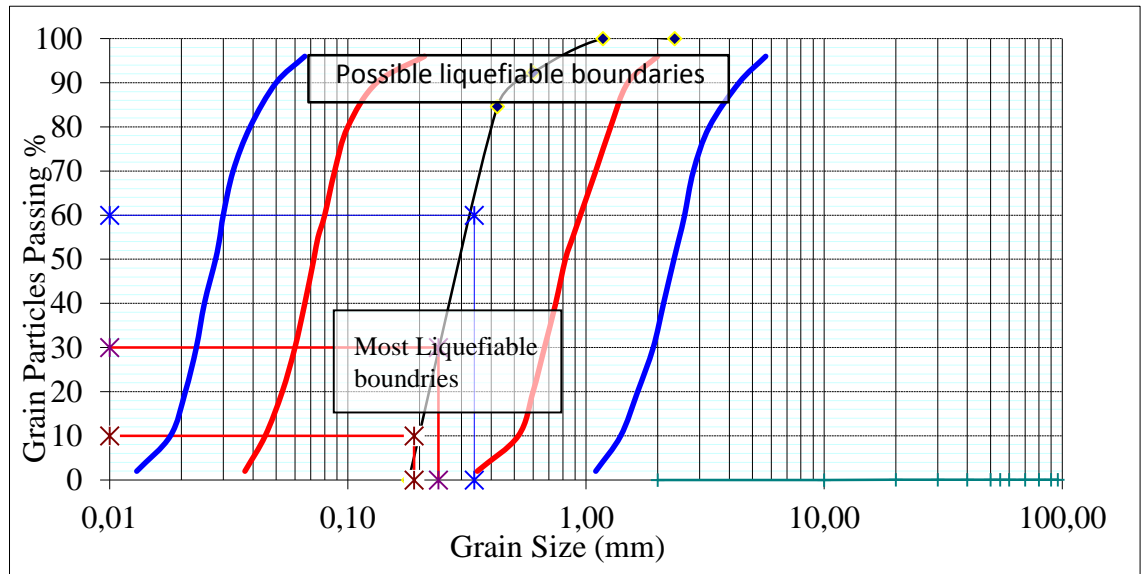


Figure 3.4 : Limits in the gradation curve separating liquefiable soils (modified from Tsuchida, 1970)

3.5 Roof tile powder

The major constituents of roof tile powder are SiO_2 , Fe_2O_3 , Al_2O_3 and MgO . Roof tile powder has pozzolanic activity. A pozzolano material is rich in silica and alumina which itself possesses little or no cementitious properties but in presence of moisture, chemically react with CaOH at ordinary temperatures and form compounds having cementitious properties. It is natural, smooth and ductile. It is used also for agriculture purpose and to give color to roof. It has a unit weight of 11 kN/m^3 and it has grain size of 1- 4 mm in ranges.

3.6 Diatomite

Diatomite is a near pure sedimentary deposit made up almost of silica. The Greeks first used diatomite over 2000 years ago in pottery and brick. Exists many diatomite deposits throughout the world. Diatomite has high porosity, high permeability, small particle-size, large surface area, low thermal conductivity, for this that makes it suitable for a wide range of industrial applications (Inglethorpe, 1993). Typical chemical analyses of pure diatomite's generally is composed of 70-80% silica (SiO_2), porosity 85%, unit weight $2\text{-}4 \text{ kN/m}^3$, and contain other elements like TiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5 . The four main usages of diatomite in the

United States during 2013 were filter media (56%), cement additive (15%), fillers (14%), absorbents (13%) and other (2%). Literature values of chemical composition are given in Table 3.4. Physical characteristics of pure diatomite are like chalk and usually white gray. Particle size of diatomite varies from 5 to 1000 μm , but the dominant size is between 50 to 100 μm .

Table 3.4 : Literature values of chemical composition (URL 1)

Parameters	Literature Values
Calcium Oxide (CaO) %	1-2
Silica Dioxide (SiO ₂)%	80-90
Aluminum Oxide (Al ₂ O ₃)%	1-6
Magnesium Oxide (MgO)%	0-1
Iron (II) Oxide (FeO)%	1-5
Titanium Dioxide (TiO ₂)%	0-1
Phosphorus Pentoxide	0-1
Sulfur (S)%	0-1
Sodium Oxide (Na ₂ O)%	-

3.7 Sulfuric acid

It is soluble in water in all preparations with the evolution of a large amount of heat. It is drying and dehydrating agent, it can extract water from compounds. Sulfuric acid is very reactive and corrosive. It can react with water, alkalies, with carbonates and bicarbonates and metals. Moreover, it is a moderately strong oxidizing agent. Sulfuric acid is the world's major volume industrial chemical. It is mainly used in the production of phosphate fertilizers. Furthermore, it is used to manufacture explosives, other acids, dyes, glue, wood preservatives, automobile batteries, in the purification of petroleum, the pickling of metal, copper smelting, electroplating, metal work, and the production of rayon and film. In Table 3.5 are given physical properties of H₂SO₄.

Table 3.5 : Physical properties of sulfuric acid (URL 2)

Physical Properties of Sulfuric Acid	
Melting Point	10.35°C
Boiling Point	315-338°C
Vapor Density	3.4
Specific Gravity	1.84
Molecular Formula	H ₂ SO ₄

3.8 Environmental impact

Reuse of slag is turning on to a core content of sustainable development. Much more efforts must be done in order to increase the recycling attitudes of society and to cut down the waste landfill disposal. Industrial waste management is one of the major environmental problems in Turkey and all over the world. Therefore, recycling and reuse of industrial wastes play vital role both in solving industrial waste problem and in getting benefit from it. The use of slag in cement manufacturing considerably reduces CO₂ emission and the energy needed. The use of slag as aggregate decrease the need for virgin material and the energy use and emission produced during the mining, processing and transportation of those materials fit from it. Usage of waste material as admixtures such as electric arc furnace slag, brick dust, fly ash, silica fume can reduce environmental impact. We can save natural resources and protect the human health by using industrial co-products. In fact, the scrap steel slag does not only take up a lot of land but also causes environmental pollution without treatment. Increase in steel slag production seems to be a serious problem also in the future.

4. SOIL PREPARATION & EXPERIMENTS

For unconfined compressive tests, waste materials (electric arc furnace slag, roof tile powder, diatomite) are mixed at different proportions with sand and chemical additives. Optimum mixing proportion will be tested under 1-D shaking table to investigate liquefaction resistance which is the most phenomena occurring at sandy soils. Firstly, physical properties of sandy soil were determined. Sieve analysis, direct shear test and specific gravity tests were conducted. In order to determine chemical composition of electric arc furnace slag, XRF analysis was done and results were given in Chapter 3.

4.1 Sieve analysis

Particle size distribution of coarse-grained soils is obtained by conduction of sieve analysis. The test used to define particle size distribution was done based on ASTM D422 standards. A stack of sieves was placed on sieve shaker and shaken for 10 minutes. (Fig 4.1). Sieve analysis was done for sand and EAF slag in order to obtain the required particle size that will be used in experiments.



Figure 4.1: Stack of sieves

Sand particles retained on sieve number 60 and 120 are used in our experiments. Sand used has a particle size varies from (250 μm - 425 μm). Electric arc furnace slag has a particle size of 150 μm .

4.2 Specific gravity test

Specific gravity (G_s) is a physical parameter of soil calculated by the ratio of weight of soil solids to the weight of water of equal volume. The specific gravity of coarse grained soils ranges from 2.6-2.8 but fine grain soils have less G_s . The test is conducted based on ASTM D854.

Value of specific gravity obtained is: $G_s=2.63$

Figure 4.2 illustrates desiccator and pycnometer.



Figure 4.2 : Dessicator and pycnometer

4.3 Wet sieve analysis

The ASTM D1140 standard test method was used to obtain clean sand. The sand obtained after shaking on sieve shaker will be washed through sieve with diameter $74\ \mu\text{m}$. The soil was washed through sieve with diameter $74\ \mu\text{m}$ under tap until the effluent is clear (Figure 4.3). After that, it was dried in the oven, at 105°C for 24 hours.



Figure 4.3 : Washing of sandy soil through sieve with diameter $74\ \mu\text{m}$

4.4 Direct shear test

Direct shear testing (ASTM D3080) is performed to get shear strength properties of soils under drain loading conditions cohesion (c') and friction angle (ϕ). Generally is used to test cohesionless soils. Results are expressed in terms of Mohr-Coulomb failure envelope (Figure 4.4), shear strength (τ_f) and normal stress (σ_f). Since the test is performed for cohesionless soils, cohesion (c') is nearly equal to zero.

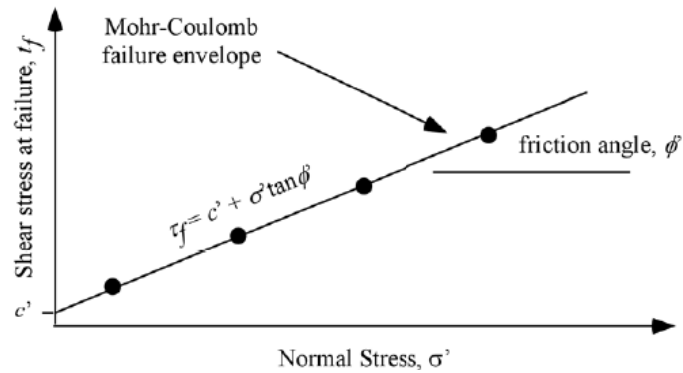


Figure 4.4 : Mohr-Coulomb failure envelope

Friction angle and cohesion coefficient of used sandy soil were 33° and 0 respectively. Figure 4.5 shows stress-strain curve obtained from direct shear test.

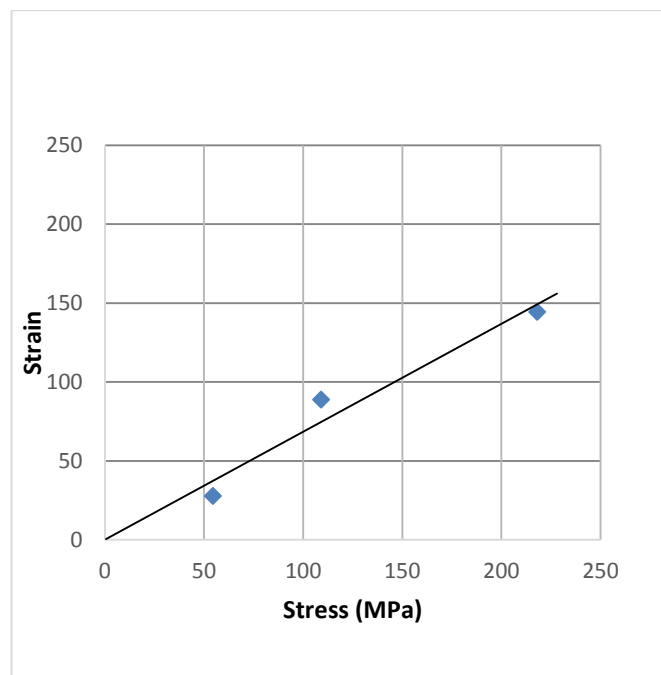


Figure 4.5 : Direct shear test

4.5 Unconfined compressive strength test

Unconfined compressive strength test is done to determine strength of soil. Each mixture is tested under axial load and maximum load, and stress strain curve is obtained for each combination. Figure 4.6 illustrates unconfined compression machine.

Unconfined compression test was carried out separately for each mixture. Cylindrical samples with dimension height and diameter 100 mm x 50 mm were prepared in laboratory conditions. After one day, samples were unmolded and cured in air conditions for 7, 21 and 28 days. Tests results and failure type will be discussed in Chapter 5.



Figure 4.6 : Unconfined compressive strength test machine

4.6 1-D shaking table test

Optimum mixing proportion obtained will be tested on 1-D shaking table. The shaking table test is done to investigate the response of sandy soils under dynamic loads. A specimen is set up on the table which can be driven by actuators as shown in In order to hold the physical model, a rigid box was used. Figure 4.7 shows the plan view of physical model. Ground motion records used are most known earthquakes (El Centro, 1940; Niigata, 1964; Loma Prieta, 1989; Northridge, 1994; Kobe, 1995; Kocaeli, 1999). 1-D shaking table has a capacity of 35 kg and 1-g acceleration.

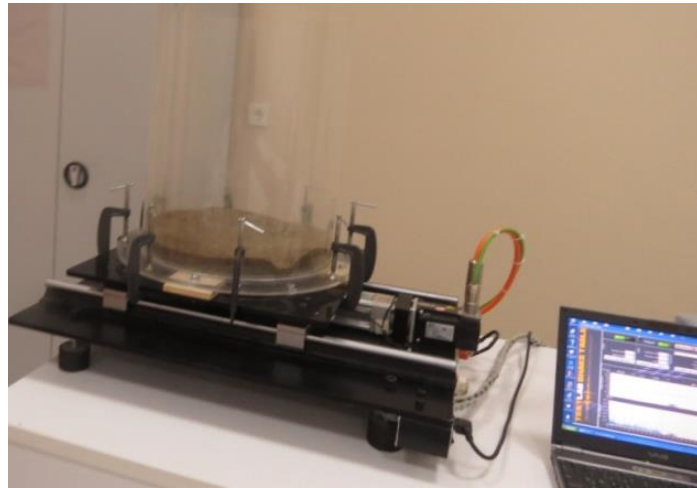


Figure 4.7 : 1-D shaking table

4.7 Methodology steps

Firstly, EAF slag was mixed in different proportions with water. Cylindrical molds were prepared. After, unmolded samples were cured in the air. Behavior of EAF slag mixtures was investigated under tensile loads. Samples contained 5, 10, 15% amount of water. Low bonding capacity was observed. After observation of this effect it was proposed usage of chemical additives to provide a better connection between components. As chemical additive, H_2SO_4 was added to mixtures prepared. After that, instead of H_2SO_4 , acetic acid was added to decrease the cost of materials. Addition of H_2SO_4 activated the slag that's why it is used in all type of mixtures. Besides that, in order to increase the strength of sandy soils, waste material roof tile powder and natural material diatomite was added to prepare the mixtures. Reddy et al., (2006) reported that cementitious properties of steel slag tend to increase with an increase in their basicity. Based on this, in some of mixtures prepared Na_2SO_4 and Na_2S salts were added. Compressive strength of all the mixtures were investigated. In Table 4.1 are given all mixture type and mixing proportions of constituents used.

Table 4.1 : Mixing proportions of components by weight

Number	Sand (%)	Slag (%)	Water (%)	H ₂ SO ₄ (%)	Roof tile Powder (%)	Diatomite (%)	CaCO ₃ (%)	(Na ₃ PO) ₆ (%)	CH ₃ COOH (%)	Na ₂ SO ₄ (%)	Si(OC ₂ H) ₄ (%)	HCl (%)
1	31	38	15	12	0	4	0	0	0	0	0	0
2	42	33	8	13	4	0	0	0	0	0	0	0
3	33	25	25	13	0	0	4	0	0	0	0	0
4	33	33	8	17	0	0	8	0	0	0	0	0
5	42	25	13	13	0	0	4	4	0	0	0	0
6	50	25	21	4	0	0	0	0	0	0	0	0
7	38	38	19	3	0	0	3	0	0	0	0	0
8	42	25	18	0	0	0	2	0	0	0	11	3
9	42	25	14	13	0	0	4	0	0	3	0	0

5. ANALYSIS OF THE TEST RESULTS

In this study some different mixtures were carried out and for each of them UCS tests was performed. Specimens were moulded by standard cylindrical shape with diameter 50 mm and high of 100 mm size. For each different mixture, at least 3 specimens were prepared and compressive strength for 7, 21 and 28 days were determined. Mixture having the highest compressive strength was tested under dynamic load on 1-D shaking table and liquefaction resistance and settlement behaviour was observed using photogrammetric approach. Three different 1-D shaking table tests were carried out. In the following section tests results of each mixture are explained in detail.

5.1 Test results of mixture EAF slag+ Water

Firstly, EAF slag was mixed with water in different proportions of 15, 20, 25 % of total mass. During unmolding some of specimens were spread due to low bonding capacity between water and EAF slag. Some of specimens could not be unmolded (Figure 5.2). Beside that, specimens failure mode didn't have a 45° angle of failure. Figure 5.3 gives failure mode of specimens. Maximum carrying force of three specimens was 266 N and with increase of slag content strength is increased too. Figure 5.1 shows maximum carrying force of EAF slag + water mixture.

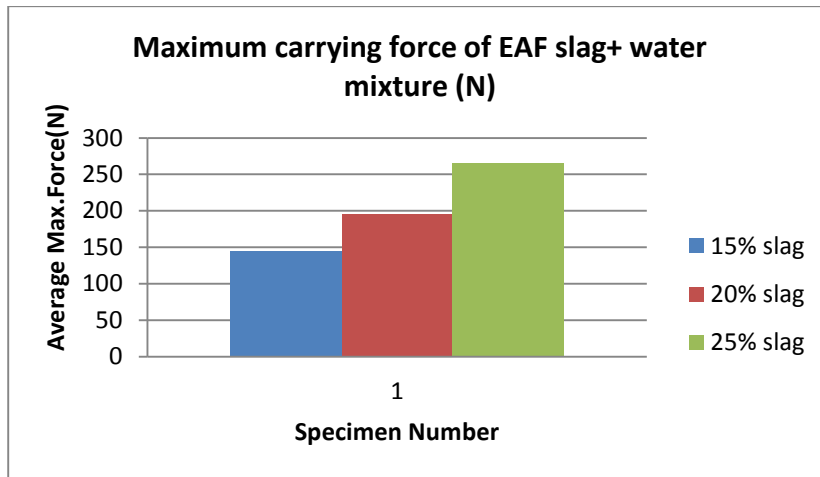


Figure 5.1 : Maximum carrying force (N) of EAF slag + water mixture



Figure 5.2 : Unmolded specimens or spread during unmolding

Low bonding capacity of EAF slag results from its chemical compositions. All oxides that EAF slag is composed are insoluble in water. After a detailed XRF chemical analysis, it was decided to use chemical additive to activate EAF slag. In second step of research was aimed to increase the bonding capacity of slag and later to increase the strength.

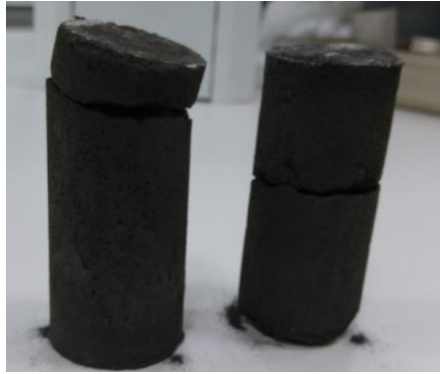


Figure 5.3 : Failure mode of specimens

Two different specimens were prepared. Lime and sulfuric acid was used as bonding additives. Table 5.1 gives mixing proportions ratio of this two specimens. Specimens were cured in air for a period of 7 days. Maximum carrying capacity obtained was 0.118 MPa and 0.125 MPa respectively. Figure 5.4 and Figure 5.5 gives view before and after failure of specimens containing sulphuric acid and lime respectively. It is seen that addition of sulphuric acid has activated EAF slag and bonding capacity between sand and slag is increased. Sulfuric acid can act as an oxidizing agents. Addition of lime has caused some increase in strength compare to other specimen. Positively results push the study in further steps, increasing the strength of sandy soil was the purpose. In the following sections results of other mixtures when different additives were tried are given. Waste material roof tile powder, chemical slats and diatomite was mixed with sand and slag to increase load carrying capacity.

Table 5.1 : Mixing proportions of additives (%)

Nr.	Sand	Slag	Water	H ₂ SO ₄	Lime	NaCl
1	50	25	21.25	3.75	0	0
2	37.5	37.5	18.75	2.5	3.125	0.6



Figure 5.4 : Specimen with sulphuric acid a) before and b)after test.



Figure 5.5 : Specimen with lime a) before and b) after test

5.2 Test results of EAF slag+ sand+ lime+ H₂SO₄ mixture

9 different specimens by mixing (EAF slag+ sand+ lime+ H₂SO₄) were prepared and cured in the air for 7, 21 and 28 days. In this mixture, comparing with the other mixture with same contents, ratio of sulphuric acid used is greater. Increasing sulphuric acid has increased the strength of the specimen. It is seen that strength is increased by time as it is shown in Figure 5.6. This combination gave better results compared to other combinations. At the same time, this combination was tested at 1-D shaking table to observe liquefaction resistance. Lowest compressive strength obtained was 0.413 MPa (after 7 days curing) and highest one 7.736 MPa (after 28 days curing) by 1800%. Maximum compressive strength of mixtures with H₂SO₄ for 7, 21 and 28 days of curing are given in Figure 5.6. Failure modes of specimens are given in Figure 5.7. Expected angle of failure is clearly seen in these specimens.

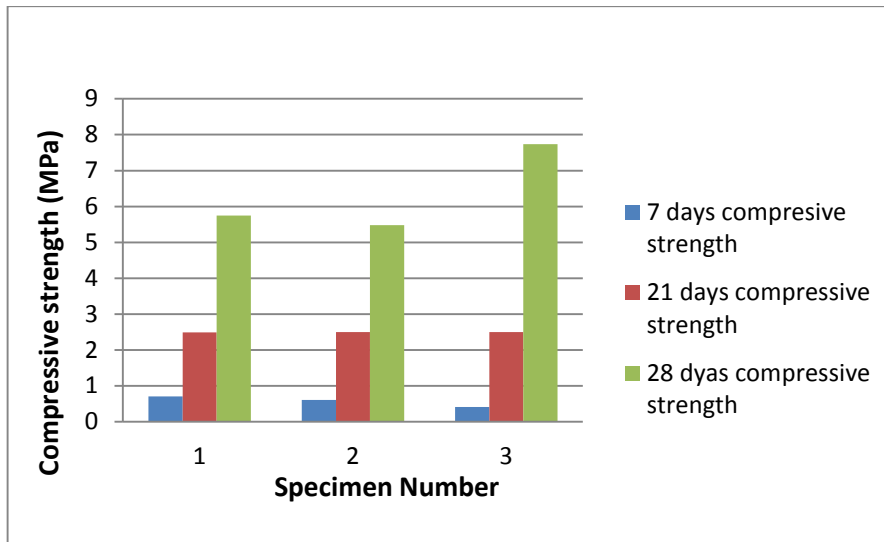


Figure 5.6 : Maximum compressive strength of mixture with H₂SO₄ (MPa)

While choosing additives, also cost of them should be taken in consideration. In order to increase the strength with low cost instead of sulphuric acid acetic acid is added. In other mixtures content of sulphuric acid is decreased and was substituted by roof tile powder, diatomite and two different salts (Na₂SO₄& Na₂S). UCS test was observed for each mixture.



Figure 5.7 : Failure mode of specimens

5.3 Test results of eaf slag+ sand+ lime+ acetic acid mixture

Acetic acid, sand, lime and EAF slag were mixed with each other. In this mixture, acetic acid is used instead of sulphuric acid to decrease the cost of mixture. Acetic acid can react with oxides found in the EAF slag. Specimens were cured in the air for 21

days but one of them couldn't be unmolded. Maximum carrying capacity obtained was 0,262 MPa. Figure 5.8 shows specimens before and after failure.

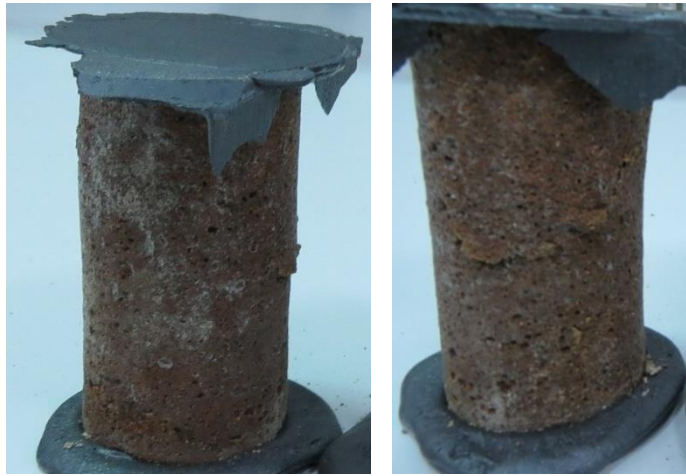


Figure 5.8 : Specimes view a) before and b) after failure

It can be said that substituting sulfuric acid with acetic acid didn't affect the change in strength positively. Behaviour of specimens for different curing days can be investigated. This may require some extra additives or different proportions to achieve better results.

5.4 Test results of EAF slag+ sand+ H₂SO₄+ Roof tile powder mixture

6 different specimens by mixing (EAF slag+ sand+ H₂SO₄+ roof tile powder) were prepared and cured in the air for a period of 7 and 21 days. Maximum compressive strength obtained was 2.496 MPa and was gained for a period of 7 days. Maximum compressive strength of mixtures with roof tile powder for 7 and 21 days of curing are given in Figure 5.9. It is seen that specimens gain high strength in short period and strength is decreased by time. Excepted behavior was not achieved. Non-linear behavior was observed. Reason for this non-linear behavior may be occurrence of some different chemical reaction when roof tile powder, H₂SO₄ and EAF slag are combined with each other. Volume instability caused by presence of EAF slag may have caused different void ratio in each specimen which indirectly have affect the strength. In Figure 5.10 failure mode of specimens are presented.

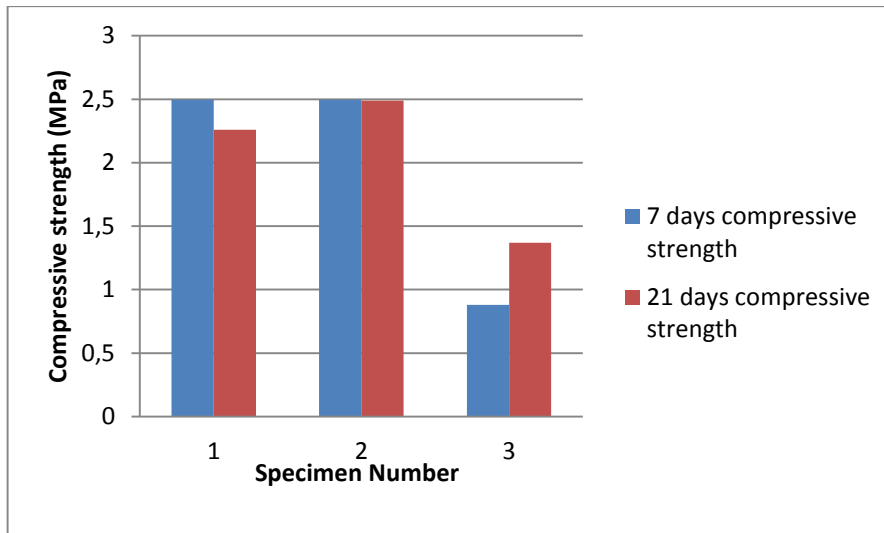


Figure 5.9 : Maximum compressive strength of mixture with roof tile powder (MPa)



Figure 5.10 : Failure mode of specimens

5.5 Test results of EAF slag+ sand+ HCl+ TEOS mixture

Tetraethyl orthosilicate (TEOS) with chemical compound of $(\text{Si}(\text{OC}_2\text{H}_5)_4)$ easily converts to silicon dioxide in presence of water. For this mixtures, 2 different samples were prepared and cured in air for 21 days. Maximum compressive strength obtained was 0.202 MPa. It can be said that addition of TEOS chemical to EAF slag + sand mixture doesn't affect the strength positively. Reasons for this low compressive strength are experimental error. Firstly, TEOS compound alone with hydrochloric acid (HCl) was not mixed in specified time. TEOS compound must be mixed with HCl for 24 hours than added to mixture. Laboratory conditions were not appropriate to obtain the required mixing conditions Secondly, EAF slag may have not been totally activated since sulphuric acid was not added. Further, researches need to be conducted using

this material. This mixture showed more plastic behavior than other combinations. Figure 5.11 shows relationship force-displacement and in Figure 5.12 failure mode of specimen is shown.

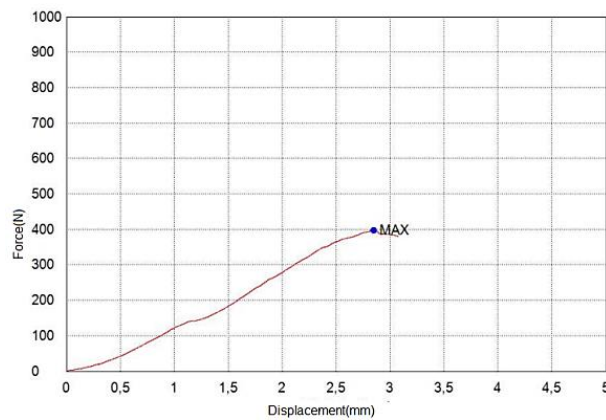


Figure 5.11 : Relationship between force & displacement of mixtue with EAF slag+ sand+ HCl+ TEOS



Figure 5.12 : Failure mode of specimen

5.6 Test results of EAF slag+ sand+ lime+ H_2SO_4 + $(NaPO_3)_6$ mixture

Six different specimens were prepared by mixing (.EAF slag + sand + lime+ H_2SO_4 + $(NaPO_3)_6$ at proprtions given in Table 5.2. $(NaPO_3)_6$ was used to increase basicity. Only in five of specimens were carried out compressive strength test. They were cured for 7, and 28 days. Results showed that with time increase more strength is gained. Maximum compressive strength obtained was 4.39 MPa (28 days curing) and for 7 days curing was obtained a maximum compressive strength of 2.7 MPa it is increased nearly 4MPa. In Figure 5.13 are given maximum compressive strengths of mixtures for 7 and 28 days of curing. Failure mode of specimens are shown in Figure 5.14.

Table 5.2 : Mixing proportions ratio of components (%)

Nr.	Sand	Slag	Water	H ₂ SO ₄	Lime	(NaPO ₃) ₆
1	42	25	13	13	4	4

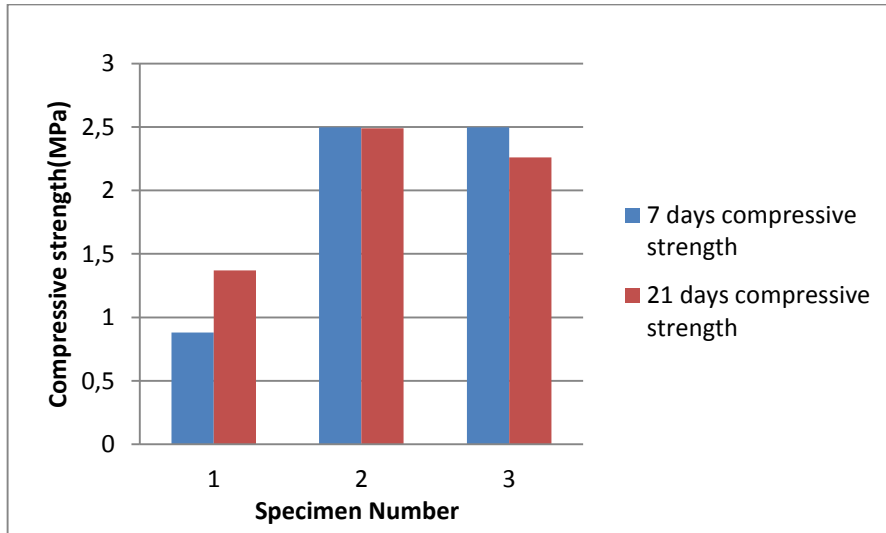


Figure 5.13 : Maximum compressive strength of mixture with (NaPO₃)₆ salt (MPa)



Figure 5.14 : Failure mode of specimens

5.7 Test results of EAF slag+ sand+H₂SO₄+Diatomite mixture

Besides waste materials, natural material diatomite was used. Six different specimens were prepared and compressive strength test were carried on. Specimens were cured for 7 and 28 days. After 28 days of curing maximum compressive strength obtained was 4.13 MPa and lowest compressive strength was less than 1MPa after 7 days of curing. Maximum compressive strength of mixtures with diatomite for 7 and 21 days of curing are given in Figure 5.15 and failure mode in Figure 5.16. It is seen that

compressive strength is increased by time. Comparison done between compressive strength values of EAF slag+ sand + lime+ H₂SO₄ mixture after 7 days of curing has shown that replacement of lime with diatomite has increased the strength more. Table 5.4 gives compressive strength values of EAF slag+ sand + lime+ H₂SO₄ mixture and EAF slag+ sand + diatomite+ H₂SO₄ mixture after 7 days of curing.

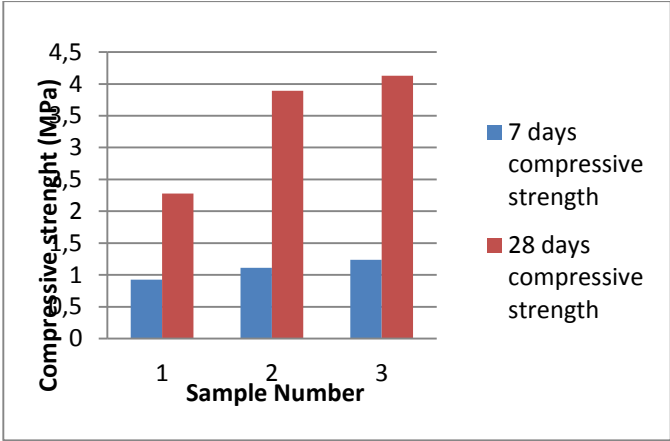


Figure 5.15 : Maximum compressive strength of mixture with diatomite (MPa)



Figure 5.16 : Failure mode of specimens

Table 5.3 : Compressive strength 7 days curing (MPa)

Mixture type	Compressive strength 7 days curing (MPa)		
EAF slag+ sand + lime+ H ₂ SO ₄	0.4137	0.602	0.707
EAF slag+ sand + diatomite+ H ₂ SO ₄	0.926	1.11	1.24

5.8 Test results of EAF slag+ sand+ lime+ H₂SO₄+Na₂SO₄ mixture

Salt (Na₂SO₄) was added in 3 different specimens and cured for 21 days. After 21 days of curing maximum carrying capacity was 0.96 MPa. Since both (NaPO₃)₆ and Na₂SO₄

salt are used to increase the basicity of mixture a comparison of results is done Reddy et al., (2006). Mixture with Na_2SO_4 for a period of 21 days showed more carrying capacity. Figure 5.17 gives the comparison between maximum forces of two different mixtures.

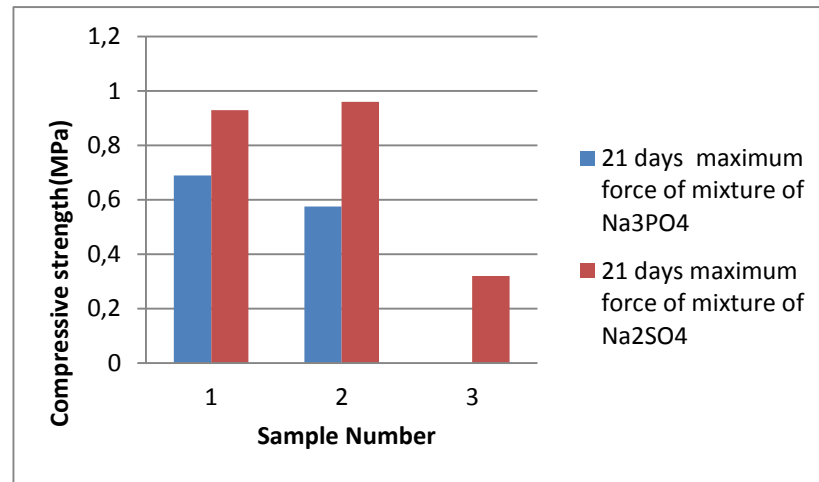


Figure 5.17 : Comparison of maximum compressive strength between two different mixtures



Figure 5.18 : Failure mode of specimen

5.9 1-D shaking Table tests

Three different 1-D shaking table tests were carried on to investigate liquefaction behaviour and settlements. Measurements were done using photogrametric approach technique. Three different mixtures were prepared. The first mixture consists of 20% water+ 80% poorly graded sand. The second mixtures consist of 15% water+ 15% electric arc furnace slag + 70% poorly graded sand. In the third mixture sulphuric acid was added since combination with sulphuric acid obtained the highest compressive strength. Experiment setup as it is shown in Figure 5.19.

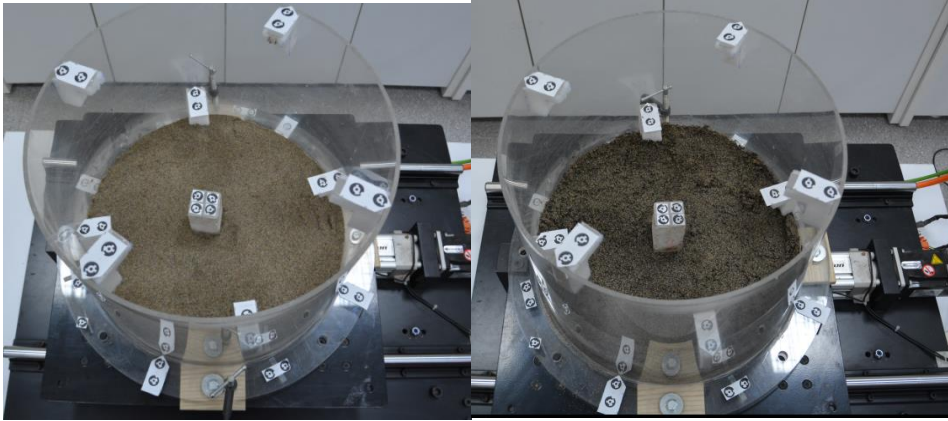


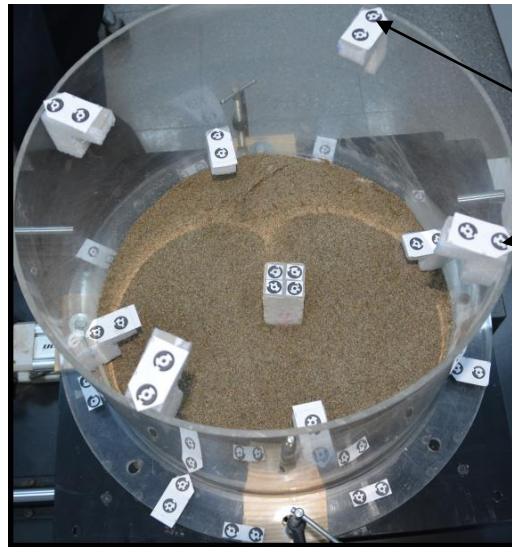
Figure 5.19 : Experiment Setup a) water + sand mixture b) water + steel slag+ sand mixtures c) water + steel slag+ sand + H_2SO_4

A concrete block was selected as “scale down building” to measure the settlement under shaking. Four markers were installed on upper face of selected “scale down building” (Fig 5.21).



Figure 5.20 : Markers to be surveyed.

Eight groups of photos were taken to infer on the coordinates from a referenced local point of cards. Soil mixtures were shaken using Kocaeli, (1999) earthquake with 7.4 magnitude. Photos were taken from each corner where the markers were placed (Fig 5.22).



The Mark. Point where photos were taken. Same procedure for 4 sides

Figure 5.21 : Place where markers are placed

Using photogrammetric approach the behavior of referenced building before and after shaking was obtained. In unmixed soil sample referenced, building indicted more tilt and displacement, compared to original position due to liquefaction occurrence. Post-processing of photos which give the displacement results, are shown detailed in Table 5.4.

Table 5.4 : Displacement results

	Displacement		
	Sand+ Water Mixture	Sand+ Water+ EAF Slag Mixture	Sand + water + EAF Slag + H ₂ SO ₄
X	4.85 mm	0	0.74 mm
Y	52.48 mm	1.08 mm	0.84 mm
Z	4.23 mm	0	0
θ	44°	1°	0°

The structure behavior before and after shaking for unmixed and mixed soil is shown in (Fig.5-23). The yellow object represents referenced building before shaking and red object represents building after shaking, respectively for each cases.

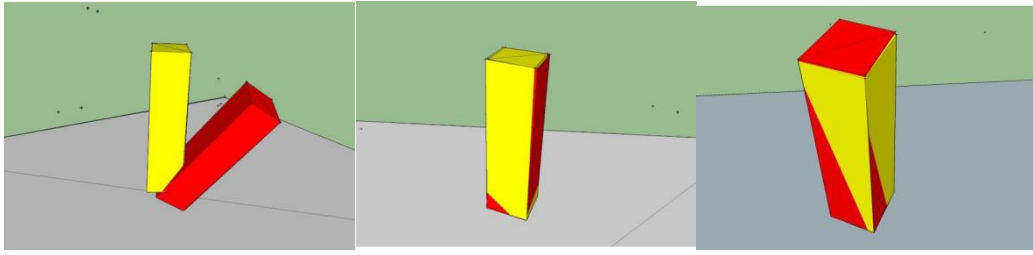


Figure 5.22 : Behavior of structure before and after shaking. a) unmixed soil sample
 b) mixed soil sample EAF slag c) mixed with EAF slag + H₂SO₄

An analytic calculation of settlement under dynamic load was conducted using method introduced by (Seed et al., 1984). In order to calculate settlement $(N_1)_{60}$ and $CSR_{M=7.5}$ values must be determined first. Then based on correlation between $(N_1)_{60}$ and $CSR_{M=7.5}$ volumetric strain (ϵ) saturated sands is estimated. $(N_1)_{60}$ was calculated based on correlation between $(N_1)_{60}$ and relative density. Relative density of used soil was 40%. $(N_1)_{60}$ was estimated as 10. Volumetric strain (ϵ) in saturated sands is estimated from chart giving correlation between CSR and $(N_1)_{60}$ shown in (Fig.5-24). (After Tokimatsu and Seed, 1987). Settlement calculation is given in Table 5.5.

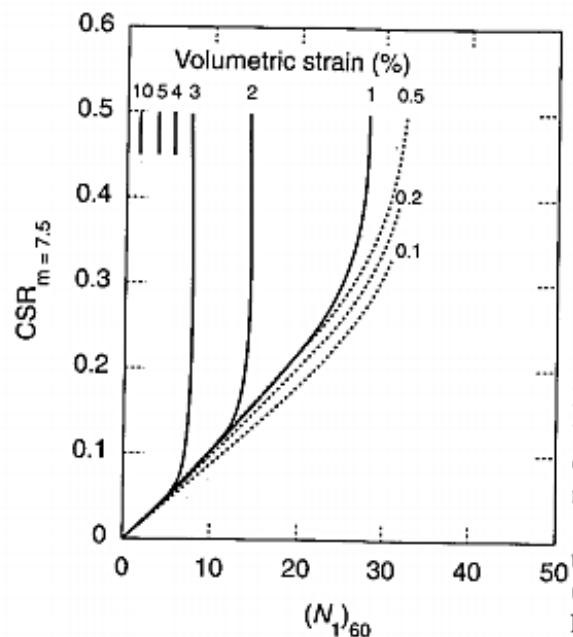


Figure 5.23 : Chart for estimation of volumetric strain in saturated sands from cyclic stress ratio and standard penetration resistance (After Tokimatsu and Seed, 1987)

Table 5.5 : Settlement calculation

Layer No	Depth (mm)	(N ₁) ₆₀	CSR _{M=7.5}	Volumetric Strain ε%	ΔH (mm)
1	600	10	0.1	3	1.8

$$\Delta H = \varepsilon\% \times \text{Depth (mm)} = 3\% \times 600 \text{ mm} = \mathbf{1.8 \text{ mm}}$$

In treated soil sample with EAF Slag, scale down building has tilted 1.08 mm in y-direction with an angle of distortion of 1° related to original position, compared to untreated one in which building has moved in x, y, z- direction. Tilting of building was caused by occurrence of soil liquefaction. When H₂SO₄ is mixed with EAF slag and sand a tilt of 0.84 mm and 0.74 mm is seen in y and x direction respectively. Based on calculation results settlement is reduced by using EAFslag and chemical additives. Using photogrammetric approach settlements of structure are not over estimated, a smaller value compare to analytic solution is achieved which mean a lower cost of construction.

5.10 Volume expansion effect

In all mixtures, during preparation volume expansion was observed. Different volume expansion occurred in all mixtures. EAF slag shows volume instability. EAF slag contains free CaO and MgO. When hydration reaction occurs, unbound lime and magnesia can cause volumetric expansion of EAF slag. Volumetric instability of slag can be treated using additives, steam treatment and aging (adequate exposure to moisture). Emery (1974) used H₂SO₄ to pre-moisture steel slag. The hydration of expansive components is accelerated using H₂SO₄. Due to environmental concerns, this treatment method is not widely used today. Volume expansion that was observed during mixture preparation may be because of gases formed when acids reacts. In this study volume expansion effect wasn't studied in details. Figure 5.24 gives volume expansion observed in one of mixtures.



Figure 5.24 : Volume expansion

5.11 Cost analysis

Cost of specimens providing good compressive strength was calculated. Table 5.6 : **Cost analysis** presents the cost of each mixture from cheap to expensive one. Mixture name corresponds to mixture name given in Table 4.1. Addition of $(\text{NaPO}_3)_6$ to increase strength was the cheapest combination and addition of H_2SO_4 increase the strength more than other chemical additives but it directly increase the cost. In order, to produce a specimen (Volume, 196.25 cm^3) by addition of sulfuric acid 31.13\$ is required.

Table 5.6 : Cost analysis

Material	Price TL/Unit	Mixture 5	Mixture 1	Mixture 2	Mixture 3
Roof tile powder	0.13			0.05	
Diatomite	20		0.05		
Slag	4.24	0.3	0.5	0.4	0.4
H_2SO_4	150	0.15	0.15	0.15	0.2
Lime	2.5	0.05			0.1
$(\text{NaPO}_3)_6$	1.17	0.1			
Sand	18	0.0005	0.0004	0.0005	0.0004
Total(\$)		70	74.9	79.4	93.4
According to exchange date: 26.06.2016					

6. CONCLUSIONS AND RECOMMENDATIONS

The main aim of this research was to study the behaviour of non-cohesive soils treated with waste material EAF slag, roof tile powder and natural material diatomite using chemical additives. Lack of suitable land for construction has led to finding of suitable alternatives for soil stabilization. Electric arc furnace slag is a by-product and using it as stabilizing agent for soil stabilization might be an economical and environmentally friendly solution.

A thorough literature review was conducted to study and investigate usage of electric arc furnace slag as soil stabilizer. The results showed that it is generally used to replace natural aggregates for concrete production, in road construction but there are few studies related to usage of EAF slag for soil stabilization for non-cohesive soils.

The results of this study were encouraging, since they show that EAF slag can be used as stabilizing agents for ground treatment of non-cohesive soils but addition of some chemical additives are required. Chemical additives are needed to increase cementitious properties of EAF slag.

The results obtained from this study can be concluded as follows:

1. Maximum compressive strength obtained was 7.736 MPa corresponding to mixture where EAF slag was mixed with sulfuric acid. Compressive strength was increased by time. An increase of 1800% from 7-28 days of curing was observed.
2. Besides all mixtures tried four of combinations gave better results. Addition of roof tile powder waste, diatomite, $(\text{NaPO}_3)_6$ chemical additives increased compressive strength apparently at a lower cost.
3. Cost analysis showed that usage of $(\text{NaPO}_3)_6$ chemical additives decreased the cost of production, but usage of chemical additives sulfuric acid increased compressive strength more. It also observed that replacement of sand with EAF slag has decrease the cost.

4. Liquefaction effect and settlement was reduced by mixing sand with EAF slag and H_2SO_4 . Measurement of settlement using photogrammetric approach seem to be a cost effective method for settlement estimation.

It should be kept in mind that experiments were conducted in the laboratory environment. Tests results are affected by experimental errors. Improper and not homogenous mixing of compounds, rate of loading, temperature of curing, geometry of specimens are all factors that will affect strength of specimens. Results taken from experiments are only comparative data; they don't particularly represent soil strength in field.

Some suggestions are listed for further researches.

1. Much more detailed field study on soil stabilization with electric arc furnace slag and chemical additives should be conducted; strength should be investigated and correlated to laboratory results.

2. The long term (6 month, 1 year) behaviour of non cohesive soils treated with waste material must be analysed.

3. A comprehensive chemical analysis of electric arc furnace slag should be carried out before application.

4. Behaviour of specimens underwater circumstances.

5. Implementation

4. Due to presence of chemical additives environmental impact during application must be taken in consideration.

5. Reduce errors of photogrammetric approach by using better camera calibration.

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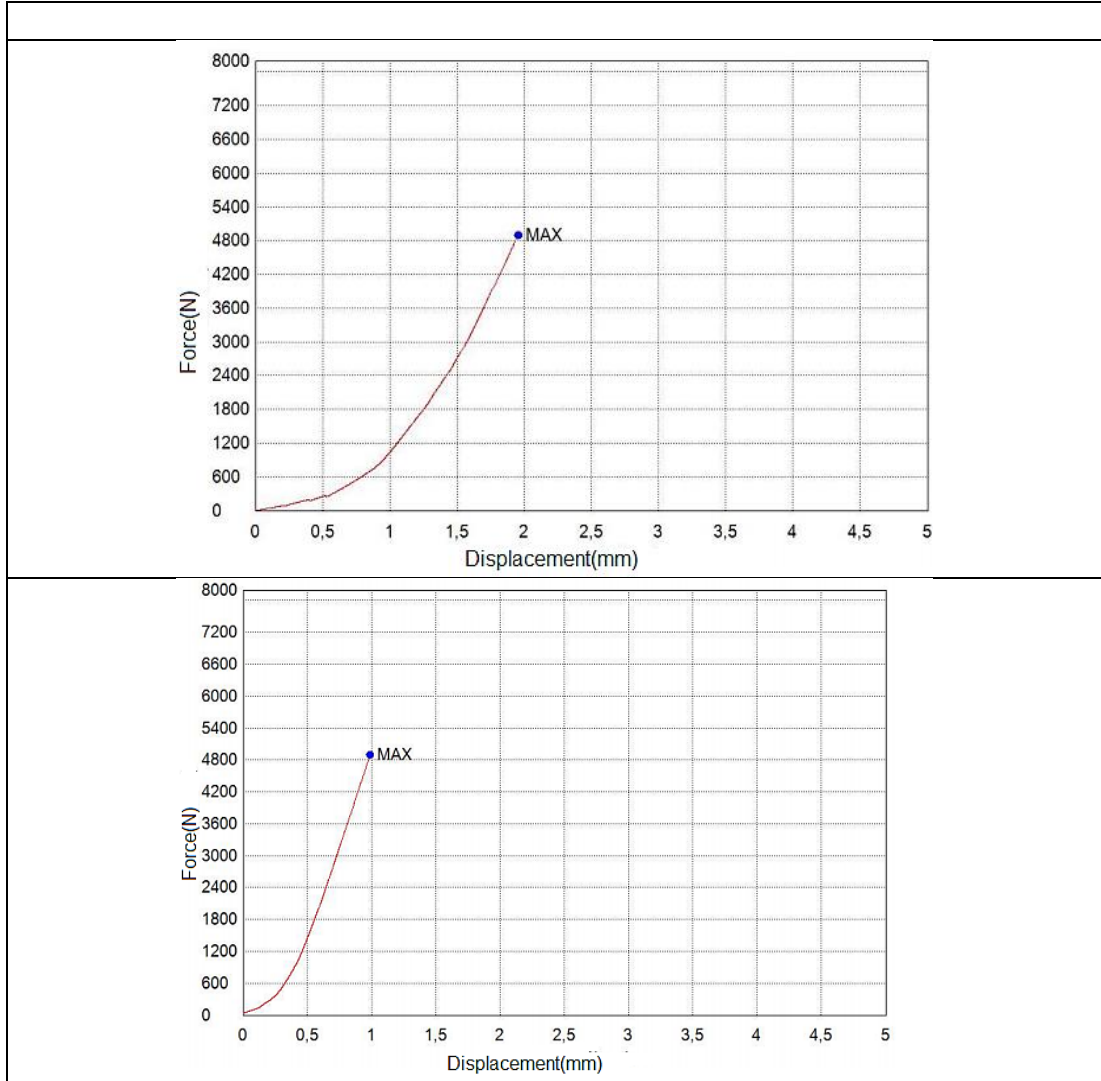
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APPENDIX

Force versus displacement curves of mixtures provided high compressive strength values are give. For all cases displacement is increased when fore is increased. Mixtures number corresponds to mixture number given in Table 5.1.



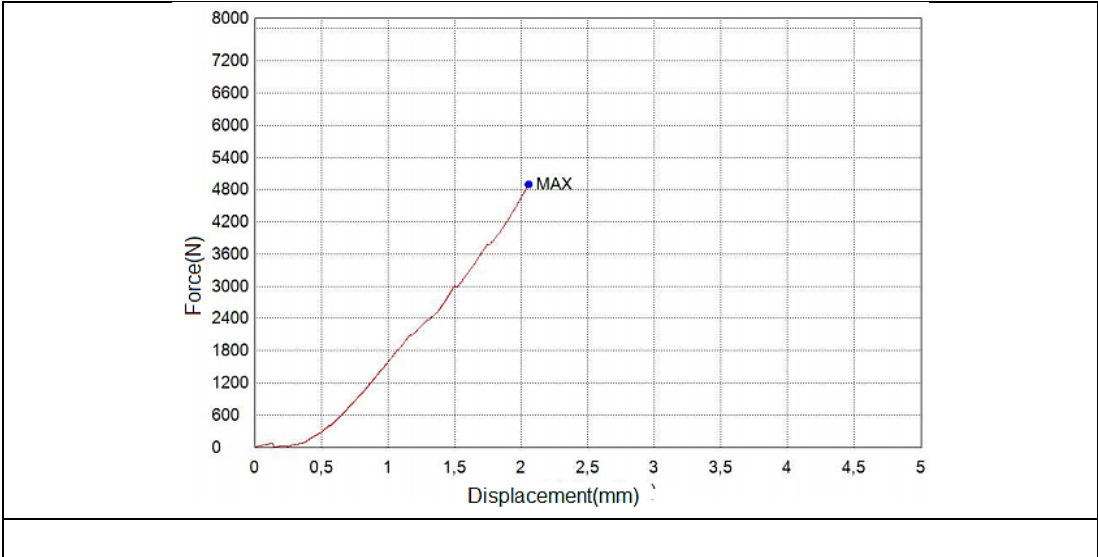
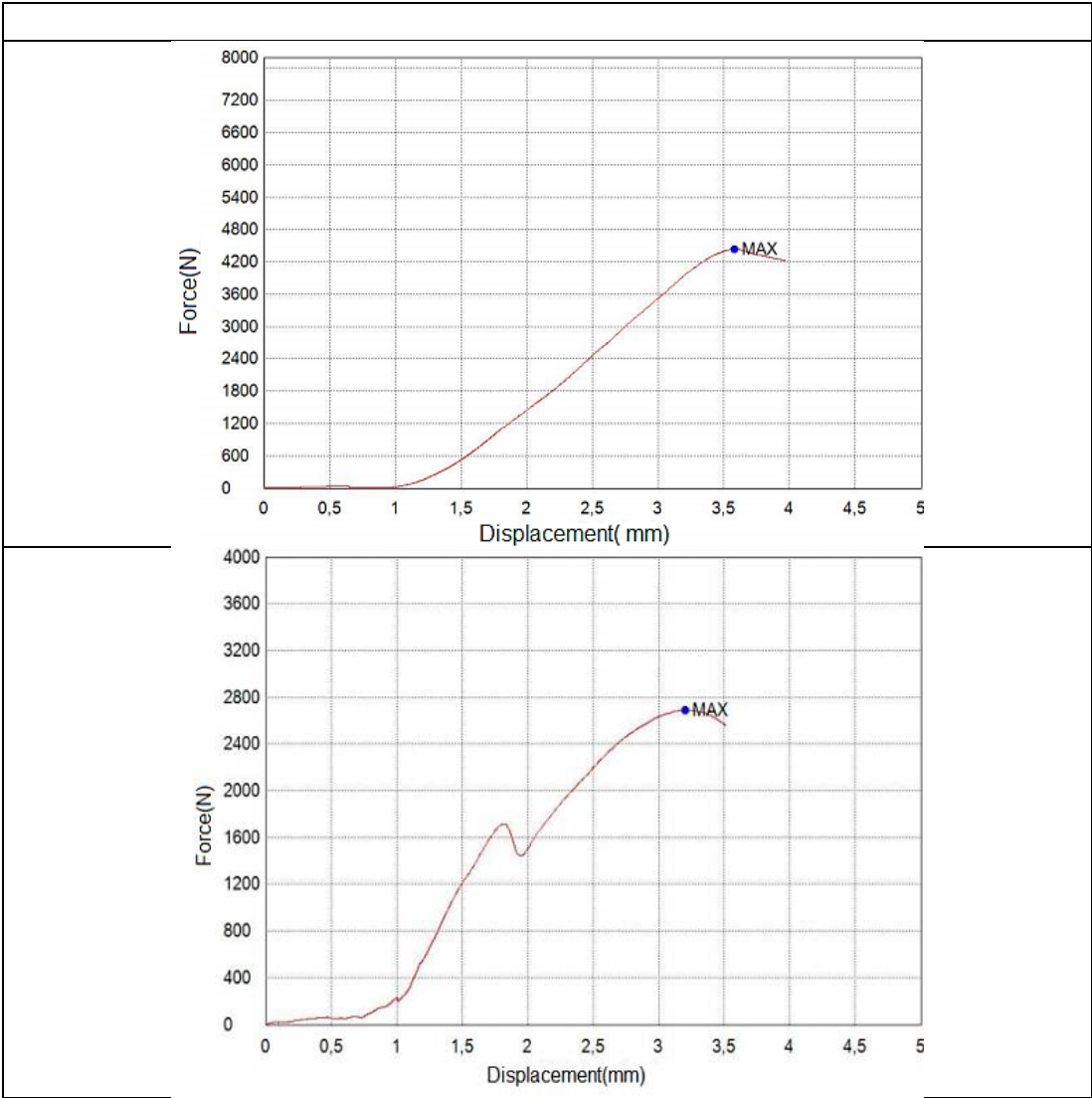


Figure A.1: Force- Displacement Curves of Mixture 3



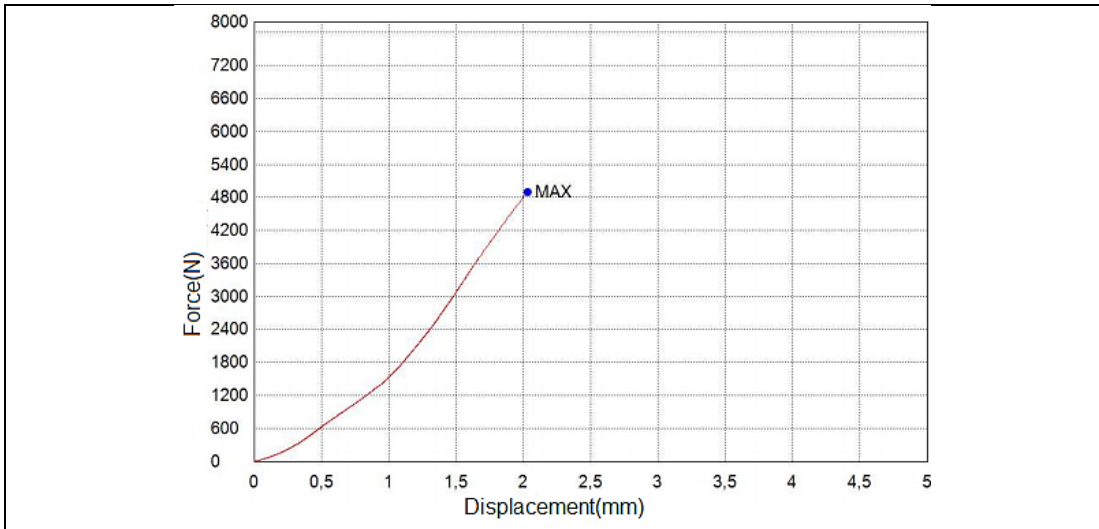
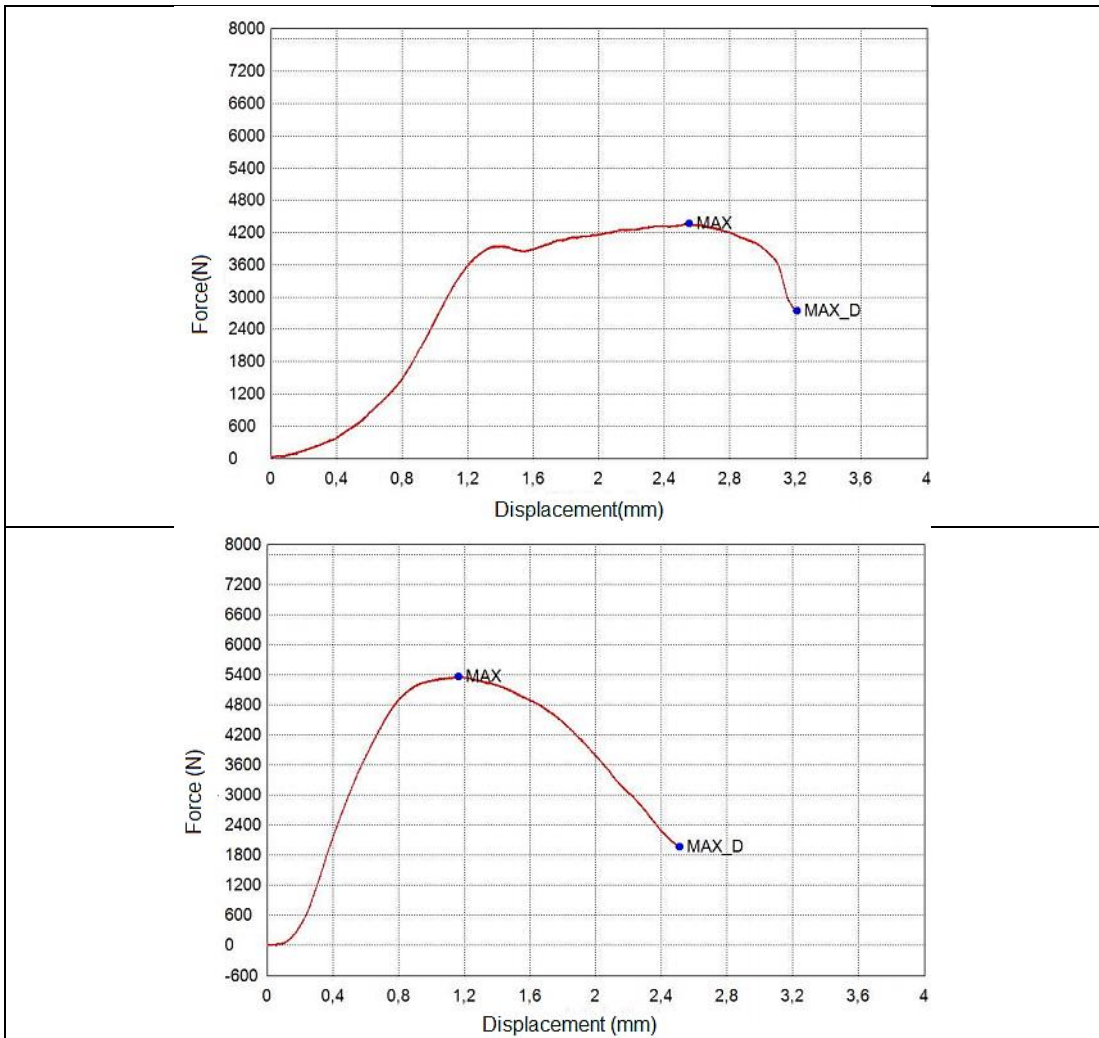


Figure A.2 : Force- Displacement Curves of Mixture 2



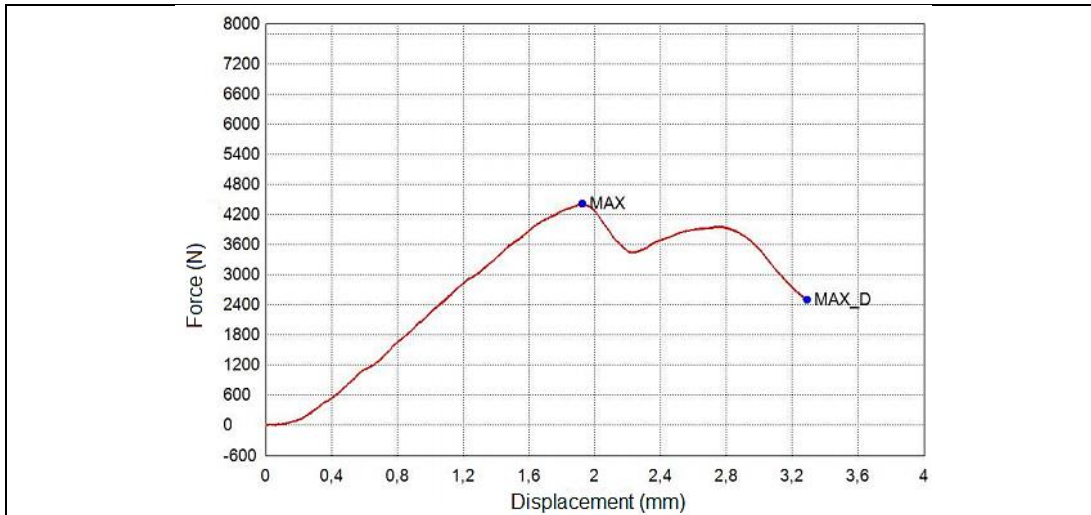
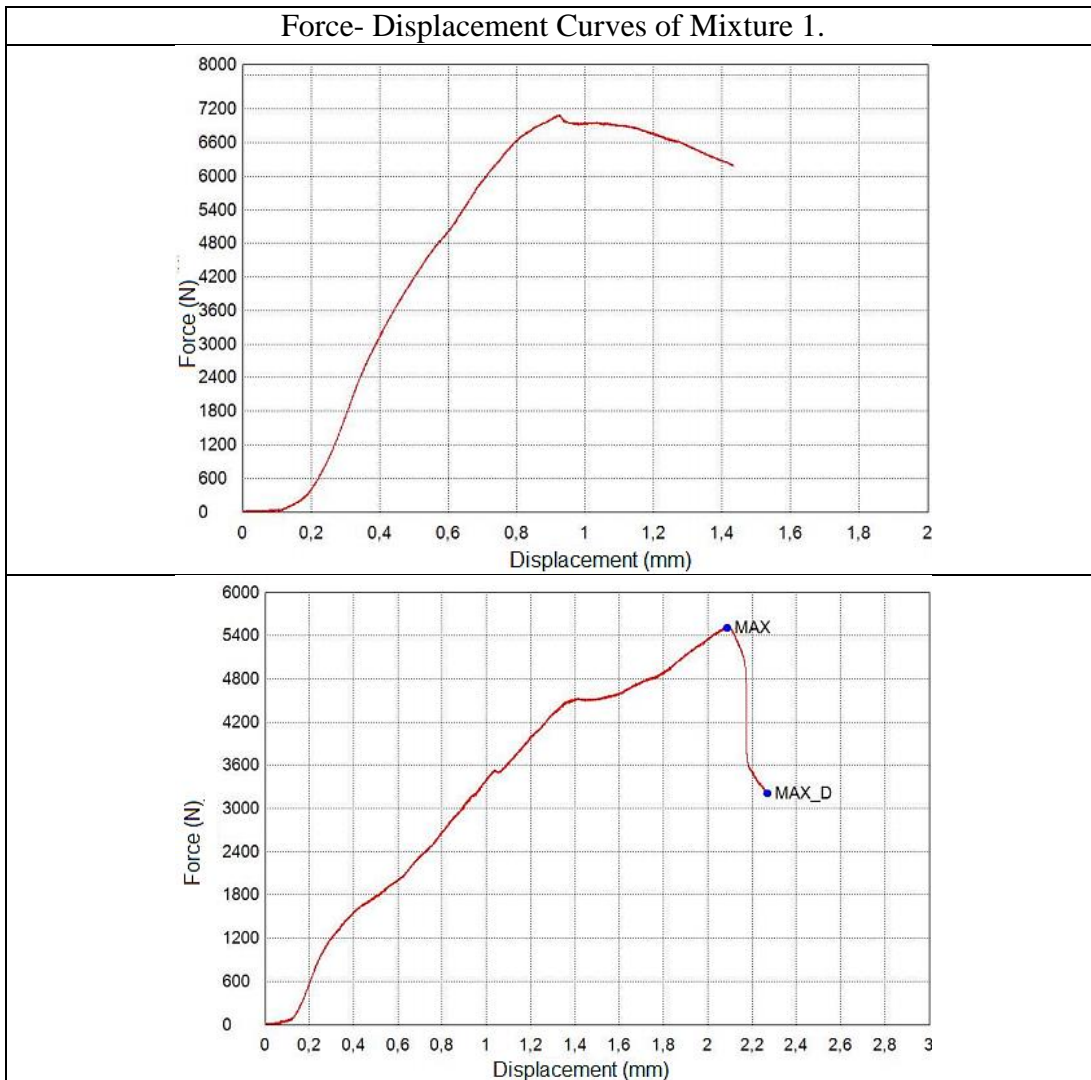


Figure A.3 : Force- Displacement Curves of Mixture 5



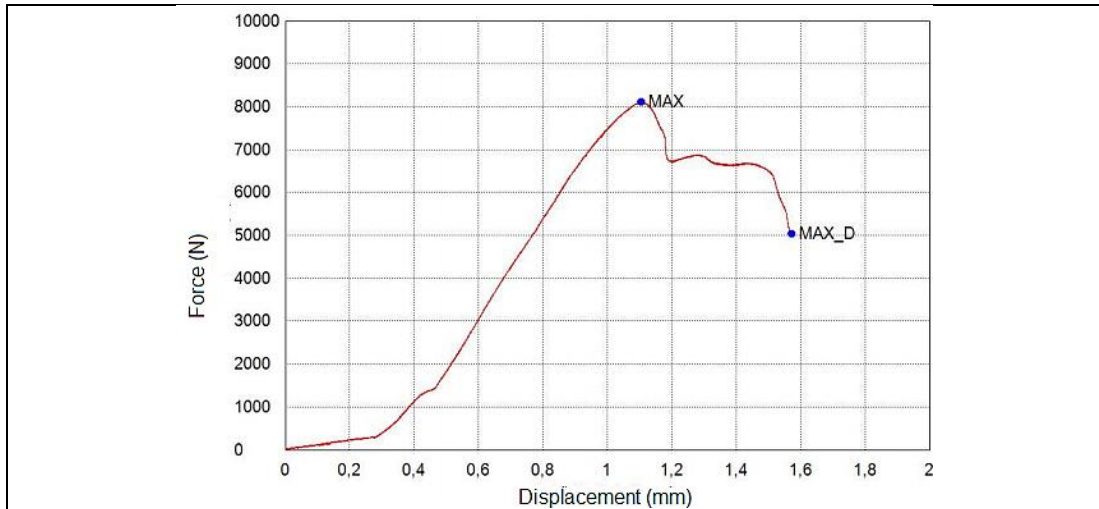


Figure A. 4: Force- Displacement Curves of Mixture 1

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