The Potential of Using Waste Tire as a Soil Stabilizer

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ABSTRACT

The amount of tire wastes, an unwanted urban-industry surplus, has been increasing every year throughout the world. One of the chances to dispose of this waste material is to use these refuses, as a stabilizer in soils, in order to increase the strength properties and the bearing capacity of the soil-stabilizer mixture. In this thesis, in order to study the influence of tire waste on shear strength and bearing capacity of sand, series of experiments have been performed on soil samples with different sand-tire ratios, water content, and size of tire waste. Two forms of tire waste: tire buffing and tire powder have been used in the study. Various sand-tire mixtures having 0 %, 10 %, 20 % and 30 %, waste tire particles by weight were chosen. To find the effect of tire waste on shear strength, direct shear test device has been used and California Bearing Ratio (CBR) test apparatus has been utilized to study the effect of tire waste on the bearing capacity of the stabilized soils. It was found that addition of up to 20% of tire buffing to sand noticeably increased the shear strength parameters: cohesion and the internal friction angle while it had a very small effect on bearing capacity. Decrease in bearing capacity has been obtained for a sand-tire buffing mixture of 30 percent. Also it was noticed that adding up to 10% of tire powder, slightly increased the shear strength parameters, although more percentage of it lead to a decrease on these parameters. Both sand-tire buffing and sand-tire powder treated soils created more plastic material and produced an apparent cohesion in the tire-waste treated sands. Plasticity of the treated soils increased because of the penetration of the sand particles into the tire grains. Addition of tire buffing into the sand did not improve the CBR value of the treated soils significantly. But since sand-

tire mixtures are lightweight materials and they apply less lateral earth pressures on retaining structures, application of tire buffing into the sand is still promising.

Keywords: California Bearing Ratio, Direct Shear Test, Internal Friction Angle, Tire Buffing, Tire Powder

ÖZ

İstenmeyen bir kent-sanayi artığı olan lastik atıklarının miktarı dünya çapında her yıl artmaktadır. Bu atık malzemelerinden kurtulma şansından biri de zeminin mukavemet özellikleri ve taşıma kapasitesini arttırmak amaçlı atık malzemenin zeminde toprak-stabilize malzemesi olarak kullanılmasıdır. Bu tezde, lastik atık malzemesinin zemin makaslama dayanımı ve kum taşıma kapasitesi üzerindeki etkisini araştırmak için farklı kum-lastik oranları, su içeriği, ve farklı lastik atık boyutlarında karıştırılmış kum örnekleri üzerinde deney serisi gerçekleştirilmiştir. Çalışmada lastik atıkları iki formda kullanılmıştır: polisaj lastiği ve lastik tozu. Ağırlığa göre değişik kum-lastik yüzdeleri 0%, 10%, 20% ve 30% seçilmiştir. Lastik atık malzemesinin makaslama dayanımı üzerindeki etkisini araştırmak için direk kesme deney aleti kullanılmış, iyileştirilmiş zeminde taşıma gücü kapasitesi üzerindeki etkisini çalışmak için ise Kaliforniya Taşıma Oranı (KTO) deney aleti kullanılmıştır. Kum malzemesine %20 polisaj lastiği eklendiğinde kayma direnci parametreleri: kohezyon ve içsel sürtünme açısı değerlerinde belirgin bir artış gösterdiği, taşıma gücü değerlerinde ise çok az bir etkisinin olduğunu göstermiştir. Yüzde 30'luk kum- polisaj lastiği karışımında, taşıma kapasitesi değerinde azalma elde edilmiştir. Ayrıca 10% kadar eklenen lastik tozu, kumdaki kayma direnci parametrelerini biraz arttırdığı, daha yüksek yüzdeliklerde ise bu parametrelerde düşüşe neden olduğunu göstermiştir. Hem kum- polisaj lastiği, hem de kum-lastik tozu stabilize edilmiş zemin daha yüksek plastisiteli malzeme meydana getirmiş ve görünen bir kohezyon değeri ortaya çıkarmıştır. Kum daneciklerinin lastik daneler içerisine penetrasyon neticesinde stabilize edilmiş zeminin plastisitesi artmıştır.

Polisaj lastiği iyileştirme yönteminde, kuma eklenen polisaj lastiği KTO değerinde önemli bir iyileştirme meydana getirmemiştir. Ancak kum-lastik karışımı hafif malzeme olması nedeni ile ve istinat yapılarına uyguladıkları daha düşük yanal basınç değerinden dolayı , kum içine polisaj lastiği uygulaması hala umut vericidir.

Anahtar kelimeler: Direk Kesme Deneyi, İçsel Sürtünme Açısı, Kaliforniya Taşıma Oranı, Lastik Tozu, Polisaj Lastiği,

To my parents

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C_c	Coefficient of curvature
C_u	Coefficient of uniformity
Dr	Relative density
G_s	Specific gravity
Φ	Internal friction angle
C	Cohesion
e	vid ratio
CBR	California bearing ratio
ASTM	American society for testing and materials
EPA	Environmental Protection Agency
ρ_{min}	Minimum Density
ρ_{max}	Maximum Density

Chapter 1

INTRODUCTION

1.1 Introduction

Soil is the smallest natural element which exists on the earth's crust and it is one the oldest natural mortars that has been used in the construction industries during time (Das, 2009). The world's architecture and the ruins of its work are indebted to this element and its attributes. Despite all the new materials we have now a day, large amount of soil is still being used directly or indirectly in the construction industries. As of the creation view, soil is the final production of weathering, result of physical destruction and chemical degradation of stones along with aggregation of leftovers of the organisms in decay by nature (biodegrades) (Das, 2009). All along the history, mankind has been trying to find a better use of soil in different matters. We can find the origin of this idea in natural models and examples. Lots of species specially birds, they mix soil and tiny branches to build their nests or the hillsides will be stabilized by the plant growth and their roots. The idea of mixing straw and clay to build thatch mortar or recently the use of shredded tires and polymer fibers to reinforce the materials and soil structures are the samples of this idea (Das, 2009).

Soil reinforcement is one of the geotechnical branches which has been reinforcing and improving the soil engineering specifications and mechanical properties like strength, plasticity, bearing capacity and elasticity modules by the use of new technologies and suitable materials (Craig, 2004). Soil reinforcement is a reliable and effective method to improve the soil strength and stabilization which has always been the human interest. Around 3000 years ago Babylonian used reinforced soil with thatch to build their temples (Mwasha, 2009).

At the present times, the elements which are used in soil reinforcement are made of metal or polymeric materials or even herbal like jute and Coir fiber geotextiles (Galán-Marín et al. 2012). Friction phenomena between the soil and its reinforcement materials play an important role in mechanism of action and behavior in soil.

One the methods of soil reinforcement is, integration of soil with fibers like natural, glass, polymer or other synthetic materials. Mixture of these elements with soil creates a complex environment in which the involvement of the elastic parts (reinforcement elements) and soil particles improves the soil strength and plasticity in many ways like increase in peak strength, reduction in post-peak loss of strength and axial strain at failure (Haeri et al., 2000). There have been many elements like metal fibers or fiber glass or polymeric fibers and etc., which have been applied to soils as soil reinforcement (Haeri et. al., 2000) and (Jewell & Greenwood, 1988) studied the mechanical effects of geotextile reinforcement (Prabakar & Sridhar, 2000) investigated addition of sisal fiber (Yeung et. al., 2007) studied the glass-fiber reinforcement. We can categorize the methods of soil reinforcements into three categories of mechanical, physical and chemical processes (Al-khanbashi & Abdalla, 2006). For example, as mechanical processes we can name compaction, consolidation and drainage and as chemical processes, addition of natural or industrial cementite’s materials and after all as physical processes applying the reinforcing elements like geotextiles and fibers, heating or freezing (Al-khanbashi & Abdalla, 2006). According to (Billong et. Al., 2009) “chemical stabilization consists in adding to the soil, other materials or chemicals which modify its properties either by a physicochemical reaction, or by creating a matrix which binds or coats soil particles together”. The physical stabilization involve the physical condition of soil and mechanically stabilization leads to increase in density of soil through subjecting the soil to mechanical forces like surface compaction (Al-khanbashi & Abdalla, 2006).

Population growth, industries, increasing developments, changing consumption patterns and environmental protection on one hand and material and energy constraints on the other hand have rendered the efficient use of natural resources and protection of them by the industries a priority (Neville, 2012). Considering the annual production of tire around the globe and the raising issue of old cars that increases the worn tires disposal, the management of this kind of waste become more important. Obviously, the best solution in this area is to recycle the worn tires.

1.2 Objective of This Research

Rubber products are such substances that return to the nature too late, for example it takes centuries for a tire to perish in nature. (Ahmed et. al., 1996) Most important issues with disposal of worn tires as a waste are its very long disintegration time; its shape witch is capable of infestation by parasites and insects; fire hazards, resurfacing of covered tires etc. (Kemkar, 2000).

Tires are made of polymeric materials which do not decay in the nature easily (Ahmed et. al., 1996). In many cases, old tires are accumulated like waste hill and create ugly scenery which always carries out a fire risk (Kemkar, 2000). Fighting the fires made by dense masses of rubber if not impossible yet it is very hard to quench, sometimes it takes months till all the rubbers burn and this may produce a toxic liquid and thick smokes that can pollute the surface and ground water and if we use water or foam to extinguish the fire, it will cause more pollution, so sometimes they let the fire to burn the whole tires (EPA, 2006).

Figure 1: Burning tires
www.epa.gov/osw/conserve/materials/tires/fires.htm

According to (EPA, 2006) burning tires creates black, harmful smokes which will pollute the environment. By considering the rapid increase in the use of vehicles, it seems that we will soon face many serious problems in this field.

Unlike other wastes, we cannot bury tires without any basic operations. On the other hand, leaving worn tires in the nature have serious risks to the environment and human health, also accumulated and buried tires have great potential for fires in a way that its fire is associated with thick smoke and hard to control (Kemkar, 2000). These smokes are burned carbon and will leave toxic gases into the environment. Tires have sulfur, iron and other metal objects in them which can free dangerous gases like polyaromatic hydrocarbons, S02, CO, HC1, and N02 into the air (Pillsbury, 1991).

The series of activities by which materials that are no longer useful to the generator are collected, sorted, processed, and converted into raw materials and used in the production of new products (EPA, 2012). As the result of recycling process, the amount of wastes and therefore their pollution will be decreased and the need of production by using imported materials will be reduced and thus the national production will be increased.

There are quite extensive literature investigating the properties waste tire and how to use the tires in civil engineering applications. The aim of these studies is to use the high volume of worn tires to reinforce soils in a project.

It should be noted that the natural soil at the project site is not always perfectly useful and sometimes it is essential to do some improvements to reach the required soils characterization. Soil reinforcement with modern technology was first introduced in the 60's by Vidal which used the steel belts to reinforce retaining wall (Prabakar & Sridhar, 2002). In fact, the duty of the reinforcing materials was to transfer tensile stress from soil into the reinforcement, generated by friction between the soil and reinforcement. Reinforcement and soil surface roughness were two essential factors.

In the history of building materials technology, soil has been known as masses with good compressive and shear strength but low resistance against tensile stress.

Reinforced soil is a combination of two different materials which their combined performance is limited to the minimum possible weaknesses of each. Sometimes, the soil amendment is to fight the potential inflation in swelling soils and sometimes to increase the shear and tensile strength of the soil mass by the reinforcement to increase the soil bearing capacity or reduce the adverse impact and height the earthen walls may be reasons of soil amendments.

The aim of this study is to investigate the use of waste tire materials in geotechnical applications and to evaluate the effects of tire rubber on the shear strength parameters and the California Bearing Ratio (CBR). Geotechnical properties of tire-chip and its mixture (10, 20, and 30%) with a sandy soil will be investigated through a series of soil mechanical tests such as grain size, compaction, relative density, direct shear box and CBR.

1.3 Materials and Methods

Soil samples were prepared by mixing a uniform sand with 10, 20, 30% fine grained tire-chips. The grain size distribution of the sand used in the study is given in Figure 16. Fine tire-buffing were between 2 mm (No. 10 sieve) and 0.85 mm (No. 20 sieve) and the tire powder passing from 0.85mm (No. 20 sieve). The sand was locally obtained from the Silver Beach in Famagusta, North Cyprus. The physical properties of the sand used in the study are given in Table 1.

Table 1: The uniformity coefficient, C_u and, coefficient of curvature, C_c of natural Silver Beach sand

Soil	D_{10}(mm)	D_{30}(mm)	D_{60}(mm)	C_u	C_c	Sand Type
Silver sand	0.16	0.183	0.222	1.39	0.95	SP

Waste tire buffing and tire powder used in this study are shown in Figure 2.

Figure 2: Tire powder and tire buffing

The specific gravity of the sand and the tire-chips were determined according to the procedure described by ASTM D854-83 (1989). The specific gravity of the sand was 2.69 and an average value for the specific gravity of the tire buffing 0.86 and tire powder 0.98 tested several times.

The minimum and maximum values of unit weights of the sand and sand-tire chips were obtained according to the procedure described by ASTM D698-78 (1989).

In the present study, using both the direct shear box test and the California bearing ratio (CBR), the bearing capacity and shear strength of the tire reinforced soils will be investigated.

1.4 California Bearing Ratio Test (CBR)

In this study, the CBR test was performed in the laboratory by using the CBR machine. The test was done according to ASTM D1883-07 standard.

CBR test results were used to compare the bearing capacity of reinforced soil and the untreated soil. And the test results of both soils were compared and discussed and investigated the effects of tire buffing based on changing other effective parameters like unit weight of sand mixture and rubber chips or the percentage of tire mixed in the mixture. This test conducted using the CBR testing maching.

1.5 Direct Shear Test

The most common and most accessible means of laboratory test to find the shear strength of sand is the direct shear box. Direct shear test accuracy is less than the triaxial tests but its cost is lower and for general engineering proposes accurate results of direct shear test is acceptable. Even in critical and major projects, as a result of high costs and its problems, fewer samples will be tested by the triaxial tests and more samples by the direct shear test. In the present study, the direct shear box test was performed at different moisture content and density values on the treated and untreated soils and the test results were compared and discussed. The direct shear box test was performed according to ASTM D 3080 standard.

Chapter 2

HISTORY OF RECYCLING

2.1 Introduction

Reuse or generation of energy from materials that would otherwise been thrown away, is called recycling. Recycling has many merits like natural resource preservation, reduction of energy consumed for production and transportation, reduction of pollution risk, need and reliance for new resources, costs of production and decrease in the transportation and landfilling cost.

Tires that cannot serve its intended purpose anymore are defined as scrap tire by Rubber Manufacturers Association (Irevna, 2012). Rubber recycling is almost as old as its production. It goes back to 1820, only one year after starting the production of rubber rain-coats, when Charles Macintosh faced shortage of rubber that he couldn't afford to import. (Weinstein, 1983). His colleague Tomas Lee Hancock devised a new machine that grounds the rubber waste of rain-coat production process then turned them into block to be used in the production process. He called this machine "Grinder" because it grinds the rubber into little pieces, but it is commonly called Pickle. (Kalia & Avérous, 2011).

In short term rubber waste may not cause any problems but in the long run it has the capability of inflicting many serious damages. One instance of such a problem occurred when the dumping sites of US filled with used tires. In 1999 a black cloud was observable from 60 miles away over the dumping sites of Columbus. This black cloud had two causes, one was the smoke of the burnt tires and the other was the mosquitoes infesting the site. This incident left no other choice for Ohio state authorities other than intervention (EPA, 2006).

Recycling intuitively reminds everyone, of a concept relating to environment protection, but in their own way. State authorities, industries, trade organizations and scientific research centers have their own understanding and definition of Recycling that indicates the necessity of a commonly accepted body of knowledge for recycling. In this research we accepted the following definition of recycling:

The series of activities by which materials that are no longer useful to the generator are collected, sorted, processed, and converted into raw materials and used in the production of new products. (EPA, 2012)

According to a generally accepted rule of thumb, there is one tire for each person that is thrown away annually in industrial countries (Reisman et. al., 1997). These numbers should be adjusted for conditions of underdeveloped countries and progresses achieved with regards to mileage of tires which have increased almost five folds. In the late 90s recycling industry in industrial countries was regarded as the most lucrative industry and won the gold medal.

Used tires are divided into two main categories. One is category are reclaimable and the other is non-usable. The reclaimable category are renovated through grooving or retreading (grooving is not applicable to passenger car tires duo to its thin lining). The other category that none of above methods is applicable is dealt through four methods (Ahmed et. al., 1996):

1. Recovery of rubber for reproduction of tires
2. Recovery of rubber for other purposes
3. Energy production
4. Landfilling

Most of these studies deal with the processes of dissociative adsorption and desporption of small molecules chemisorbed on metal surfaces; these processes are governed by formation and rupture of covalent adsorbate-metal chemical bonds. The processes of physical adsorption and desorption on non-metallic surfaces have received less attention (Figure 3).

Figure 3: Tire landfill
(Source: http://www.cbc.ca)

In other literature these application are further divided like (Essex, 2012) that sets forth the following classification:

1. Retreading

2. Reuse
3. Engineering uses
4. TDA production
5. De-Vulcanization
6. Pyrolysis
7. Incineration

2.2 Recycling Techniques

There are three scrap tire recovery methods which are ambient mechanical grinding, Cryogenic grinding and Pyrolysis. In ambient mechanical grinding the shredding happens in ambient temperature. Other method is the cryogenic grinding in which, the grinding happens in the -80 degree centigrade to make the rubber more brittle. In pyrolysis method the tire is thermally decomposed to its constituting parts like scrap steel, carbon black, hydrocarbon gases and oil (Irevna, 2012). In Table 2, a comparison between ambient and cryogenic methods is provided.

Table 2: Ambient vs. Cryogenic technologies (Irevna, 2012)

Parameter temperature	**Ambient**	**Cryogenic**
Operating Temperature	Ambient, maximum of 120^0C	Below-80^0C
Size reduction principle	Cutting shearing, tearing	Breaking cryogenically embrittled rubber pieces
Particle morphology	Spongy and rough, high specific surface	Even and smooth, how specific surface
Particle size distribution	Relatively narrow particle size reduction per grinding step	Wide range particle distribution(ranging from 10mm to 0.2mm)
Maintenance cost	Higher	Lower
Electricity consumption	Higher	Lower
Liquid nitrogen consumption	-	0.5-1.0 kg liquid nitrogen per kg of tire

2.3 Grounded Tire Uses and Applications

The best method for managing non-useable tires is recycling. There are many applications of this material and an abundant number of products are made of recycled rubber available in the market. Tire shreds are used as fillings in the construction projects and as floor covering for children playground in park. It is also used in combination with polyurethane as covering of the running tracks or in the production of asphalt (Humphry, 2012).

Tire shredding requires sophisticated technology. It starts with grinding of tire into coarse pieces of 2 inch dimensions then they are grinded into finer bits by another granulizing machine (1/3 inches). Usually these processes are carried out in the big disposal sites. It leads to up to 75% reduction in the size of the tire and also the plastic or steel fibers inside the tire are removed by magnets or blowing (Cecich et. al., 1996).

2.3.1 An Overview of the Tire Shred Market of US & Canada for Pavement in 2001

From the 60s the use of rubber-enhanced asphalt in the sidewalks started in Arizona and in the early 90s an increase in the demand for tire shreds was evident, especially in North America. This demand almost doubled between 1995 till 1999.

Adding tire shreds to asphalt results in better performance of asphalt and it is verified throughout thousands of kilometers of US highways. Advantages of rubber-enhanced asphalt are less corrosion, lower heat and light refraction, anti-freezing property and lower noise pollution. Also lower maintenance cost and higher durability and serviceability leads to reduction in life cycle cost of pavement (Figure 4).

Figure 4: Tire shredding plant for pavement
(http://www.shredderhotline.com)

2.3.2 Molded Products of Recycled Rubber

The increasing amount of annually produced recycled rubber and invention of high quality and strength glues resulted in abundant number of product of recycled rubber. This method of production is generally used in production of high volume molded pieces like mats, seamers, speed bumps, sport field mats, flooring and even ballistic absorption walls (Irevna, 2012).

Figure 5: Rubber running track
(www.industrialrubbergoods.com)

Playgrounds, sport halls and running tracks flooring is made of a mixture of rubber and urethane which acts like mortar but with a much less injury risk for participants and safer places for children (Figure 5).

Grinded rubber is also used as soil admixture in agriculture for decreasing the soil compact ability, better water absorption and reduction of need for pesticide.

2.3.3 Applications in Tire Industry

The tire industry consumes almost 68% of the total natural latex produced globally and the rest is consumed by latex, food storage, tech. and adhesive industries. Geographically Asia/Oceania account for 61% and Europe and North America 32% of total global demand and the remaining is consumed by South America and Africa together (Prüfer et. al., 2012). The use of recycled rubber is not suitable option, given the high performance, speed and security concerns of cars. Hence mainly they made of new latex but a maximum 10 percent of recycled rubber mixed with fresh material leads to higher efficiency of production procedure duo to reduced processing time. Some tire producers use tire shreds as fillers to improve the surface of municipal vehicles, agricultural cars and other equipment that need to have stiffer lining e.g. construction equipment.

2.3.4 Applications in Construction and Other Applications

There is wide spread use of scrap tire in construction industry. It is mainly used for replacing other material like polystyrene insulation, drainage aggregate or soil fill. For construction related application tire shreds are used instead of tire buffing or crumbs, because of their coarseness and being less process intensive (i.e. its process demands less energy duo to coarser product size). Other application of scrap tire in civil engineering are subgrade fill and embankment, backfill for walls and bridge abutments, subgrade insulation for roads, landfill construction and septic system drain fields. It has many advantages compared to other fillings like lightness, better drainage, ease of application and better insulation performance (Humphry, 2012).

2.4 Problems Associated with Tire Dumping

Even before the collapse of tire recycling industry in 60's the over accumulation of scrap tires in legal and illegal landfills of the US had been started. According to Rubber Manufacturers Association there are 2 to 3 billion tires in US scrap yards (EPA, 2012).

Even those scrap tire that are properly disposed in the legal landfill cause problem. When used as lining of the municipal landfill, it may resurface and get mixed with surface water or lose its insulating property and let the leachate get mixed with ground water. According to Rubber Manufacturers Association, Environmenrtal Protection Agency, EPA 2012 whole tire landfilling is prohibited in 38 states, only 35 states allow shredded tire to be landfilled and 11 states ban all forms of scrap tire from landfills but there are 8 other states that allow all forms of tire to be disposed of.

Illegaly disposed scrap tires pose a higher environmental risks, one of which is the tire fire risk. Extinguishing such fire is very difficult job if not impossible. Some times it takes several months to all tire to be burnt out and it causes huge of thick black smoke and also big amounts of toxic substances to be emitted into atmosphere. Such fires can also contaminate the ground and surface waters and this problem is exacerbated if the fire is put out by water or foam (EPA, 2012).

One incident happened in Kirby Ohio in 21 August 1991. In this accident over 21 million tires burnt during 5 days. The fire caused an oily substance to leak to a river in the vicinity leading to death of thousands of fish. Over 250 firefighters from 21 local fire stations together with many federal, local and state agencies and heavy equipment were involved in this accident which finally was put out by covering it with soil. The Ohio EPA has spent $13.8 million for surface removal of tires and a $6.6 million for treating contaminated surface water (EPA, 2006). From 1966 an additional 50 cent tax has been levied on the tire sold on Ohio state which is earmarked for EPA to be spent on investigation, control and cleaning of tire dumping sites.

2.5 Rationale for Recycling

As mentioned in previous parts the scrap tires were recycled till late 1960's but, cheap oil and difficulty of shredding steel belt tires left no economic justification for scrap tire recycling and simply dumping them become a much cheaper option (Turer, 2003). However, such a response to scrap tire problem entail many adverse effects such as increased pollution, higher energy consumption and waste of valuable resources.

Recycling constitutes only a part of what could have done by society, industry and individuals to reduce the adverse effect of scrap tire dumping. The other supportive point of view recommending recycling is economic point of view according to which energy recovery and recycling are considered profitable. In production of some goods use of rubber recovered from scrap tire may less expensive than the new rubber.

In the recent decade, the research about scrap tire recycling and search for finding new applications for recovered rubber, fiber, steel and energy from recycling is increasing but reduction of disposal from the first step look the best approach form both economic and environmental point of view.

2.6 Structure of Industry

Scrap tire is created when old tires are replaces with new ones or when old cars are disposed of. The scrap tire of existing stockpiles is another source. These tires which are usually gathered in places like dealers or retailers are transported via haulers. This structure is generally same in different countries, however, there are some slight differences like free of charge hauling or paid hauling systems.

In the Table 3, a cross-country comparison of market structure has been presented:

Table 3: Scrap tire recycling industry status in various countries

	United States	Canada	Japan	France	Germany	United Kingdom	Italy	Spain
Scrap Tire Generation[1]	4,139,100	317,520	1,004,000	372,330	600,000	450,000	388,389	301,000
Existing stockpiles[2]	271	34	Minimal	NA	NA	NA	NA	NA
Recycling rates	80%		86%	52%	78%	59%	70%	25%
Main end-markets	Tire-derived fuel, Civil engineering products	Vary across states, mostly molded products	Tire-derived fuel	Tire-derived products	Tire-derived fuel	Tire-derived products	Tire-derived fuel	Tire-derived fuel
Regulation	At state level; almost all states have laws dealing with scrap tire management	At state level; almost all states have laws dealing with scrap tire management	Regulated as part of solid waste	Manufacturers and importers responsible for scrap tire management	No specific regulation for scrap tires	Whole and shredded tires banned from landfills, voluntary approach by industry preferred	Regulatory framework still evolving	Regulation exists at provincial level
Stewardship programs	Yes; At state level	Yes; At state level	None	None, but Aliapur co-ordinates the scrap tire management program	None	None, but Tyre Recovery Association co-ordinates the program	None	None
Competition	Intense	High	-	-	-	-	-	-
Other comments	Highly advanced market	-	Well established industry	-	-	-	-	-

(Irevna, 2012)

2.7 Recycling in Different Countries

In the following section an overview of the scrap tire recycling in different countries is presented.

2.7.1 Canada

According to latest available data provided by Canadian Association of Tire Recycling Agency, around twenty million scrap tires is generated throughout Canada that grows by 2% annually.

2.7.1.1 Industry Structure

The generated scrap tier by consumers or collected from stockpiles are entered enter the recycling chain from tire retailers or vehicle recyclers. The collected tires are picked up by haulers and transported to processors. Sometimes municipalities also take part in collection and hauling process (Irevna, 2012). Figure 6 illustrates the structure of industry (Irevna, 2012):

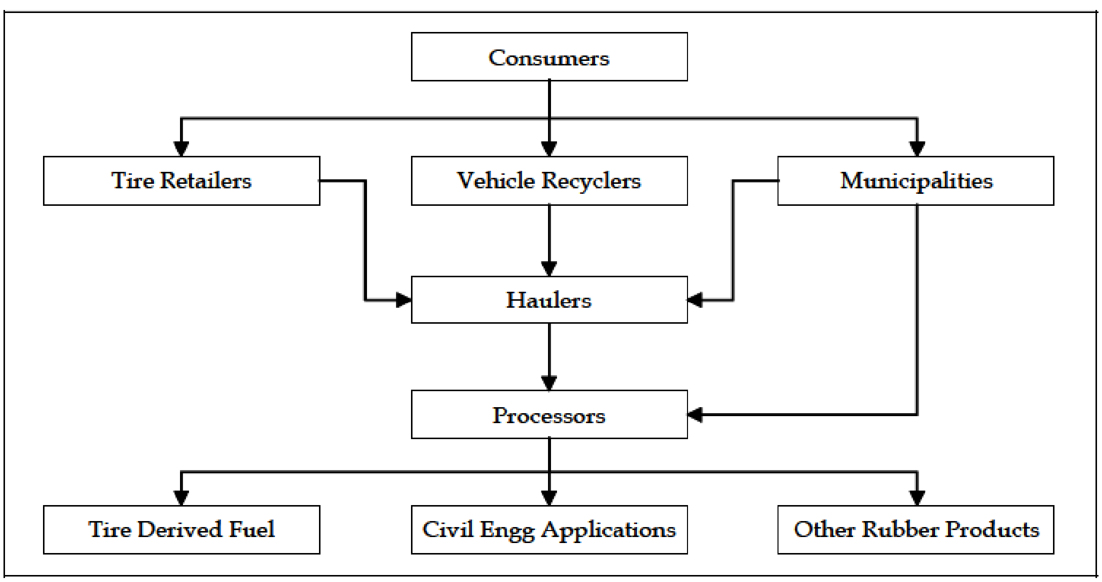


Figure 6: Industry structure in Canada (Irevna, 2012)

2.7.1.1.1 Generators

The point at which scrap tire enters the recycling chain is called generator. Vehicle recycling centers, tire retailers and landfill are examples of generators

2.7.1.1.2 Haulers

The link between generators and processing centers is defined as haulers. In Canada the stewardship authorities pay a fixed per tire to haulers depending upon the size and type of the tire and distance.

2.7.1.1.3 Processors

Processors transform scrap tires to suitable material for end-market. These processors produce shredded, crumb or fine rubber and scrap steel. In Canada stewardship boards pays them on grounds of scrap tire recycling (Figure 7). The choice regarding technology depends on the demanded quality by end-market (Irevna, 2012).

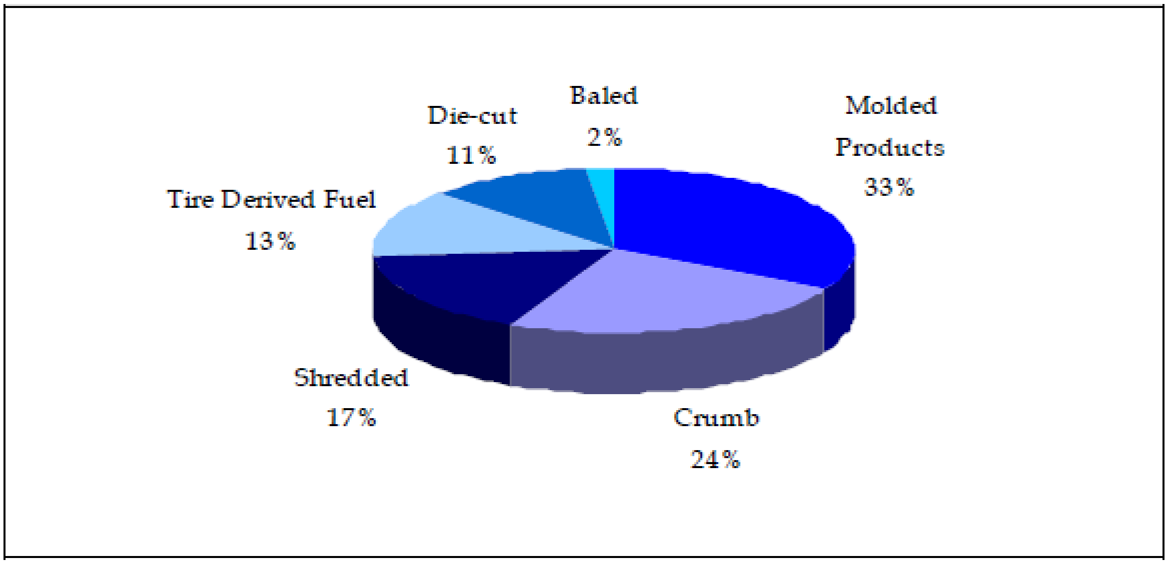


Figure 7: Usage of scrap tire in Canada (Irevna, 2012)

2.7.1.1.4 End-markets

There are three major end-market types for recycled scrap tire material which are fuel production, rubber products and civil engineering applications.

2.7.1.2 Stock Piles and Generation of Scrap Tires

Generated scrap tire in Canada from 1999 till 2003 is depicted in Figure 8. These numbers show an annual increase equal to 2%. Around 70% of them are recycled and the remaining amount is exported.

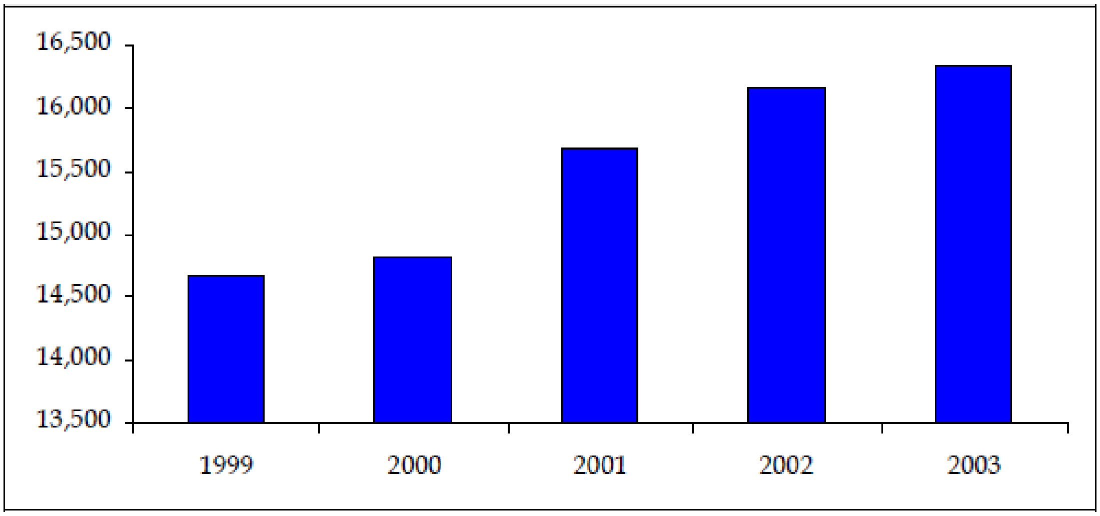


Figure 8: Used tire generation in thousands (Irevna, 2012)

2.7.2 United States

Possessing the largest scrap tire recycling industry, US have much more developed end-markets for tire-derived products and tire-derived fuel.

2.7.2.1 Industry Structure

The scrap tire industry of US is similar to Canada. In US the generators are the first actor in the industry that collects the tires and then haulers transport the tires to processors. The final link in this structure is between processors and end-market users. This structure is also shown in Figure 9.

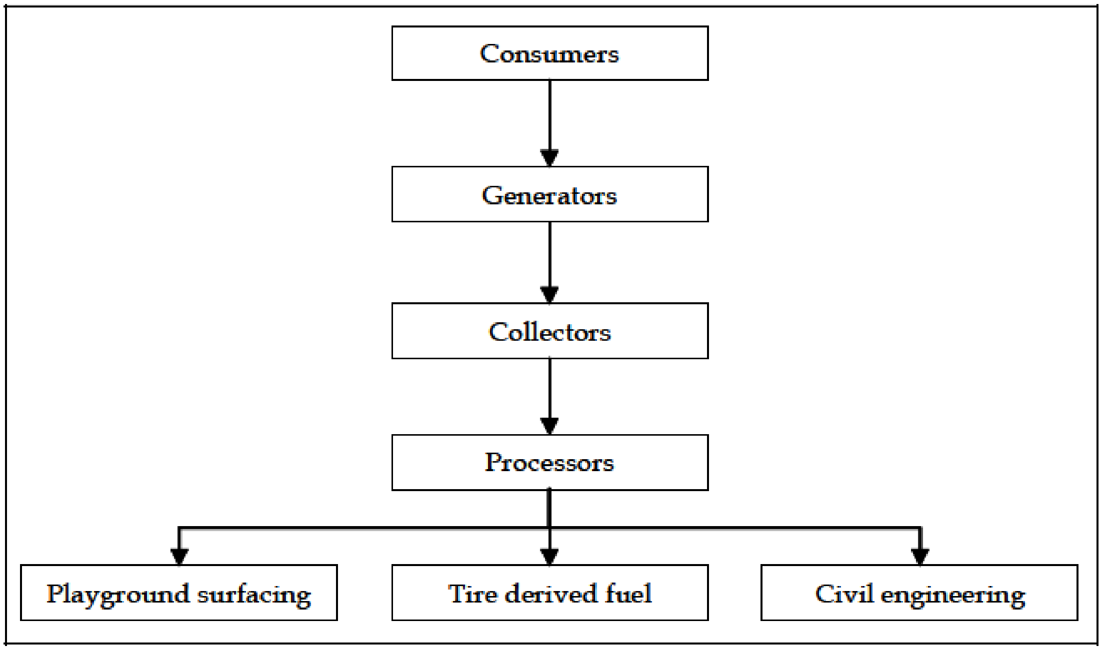


Figure 9: Industry structure in US (Irevna, 2012)

2.7.2.2 Stock Piles and Generation of Scrap Tires

From 1999 till 2003 an increase equal to approximately 10% is experienced in generation of scrap tires in US, but at the same time the percentage of recycled tire is considerably increased. The recycling rate increased from 11% in 1999 to about 80% in 2003 and these rates are expected to grow in following years. The Figure 10 shows the growth in the recycling and generation of scrap tire.

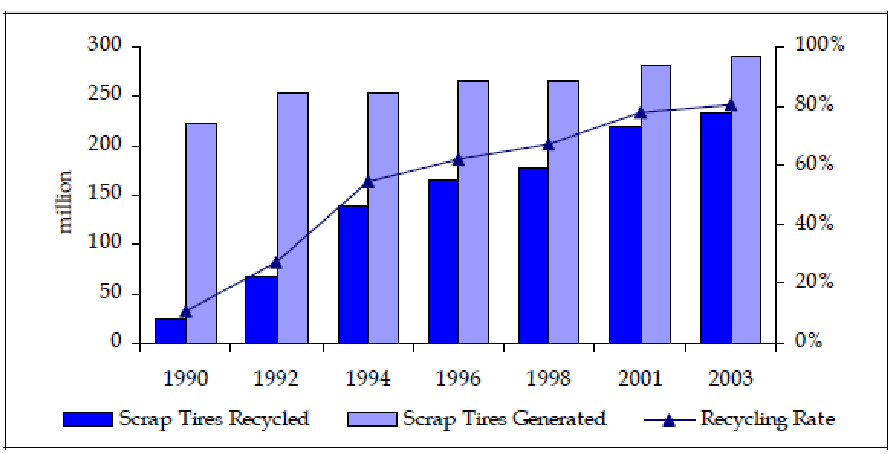


Figure 10: Scrap tire industry growth (Irevna, 2012)

2.7.2.3 Technology Trends of US

The most prevalent technology in the US market is ambient processing and cryogenic processing is applied by bigger players of industry. Those technologies that enable processors to produce smaller, uniform and steel free shreds are preferred in US markets.

2.7.2.4 Industry Drivers

Even though this industry pretty much relies on government growth, but it has the most developed end-markets. These end-markets are composed of civil engineering applications, tire-derived fuel, and ground rubber, punched and stamped products. The uses and application of US end-market is depicted in Figure 11.

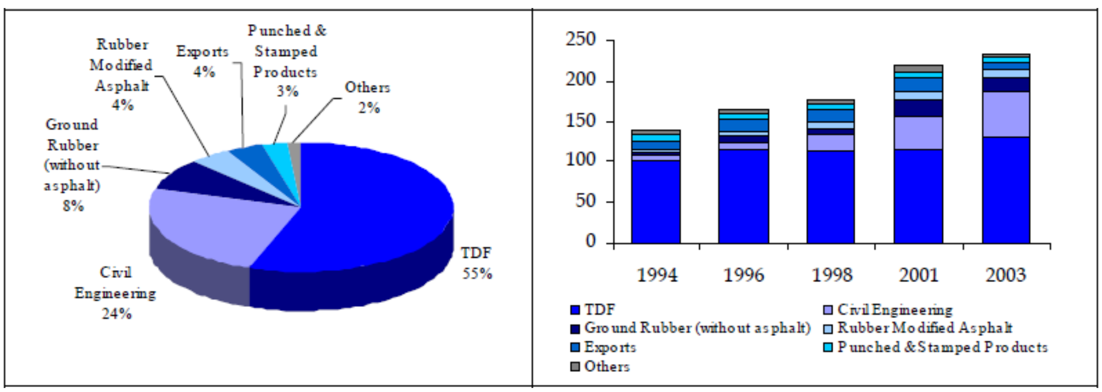


Figure 11: Uses of scrap tire in US (Irevna, 2012)

2.7.2.5 Tire-derived Fuel

As the widest end-use tire-derived fuel makes up to 58% of recycled tire during 2003. The major demand was from utilities and cement industries. The structure of tire-derived fuel is shown in Figure 12.

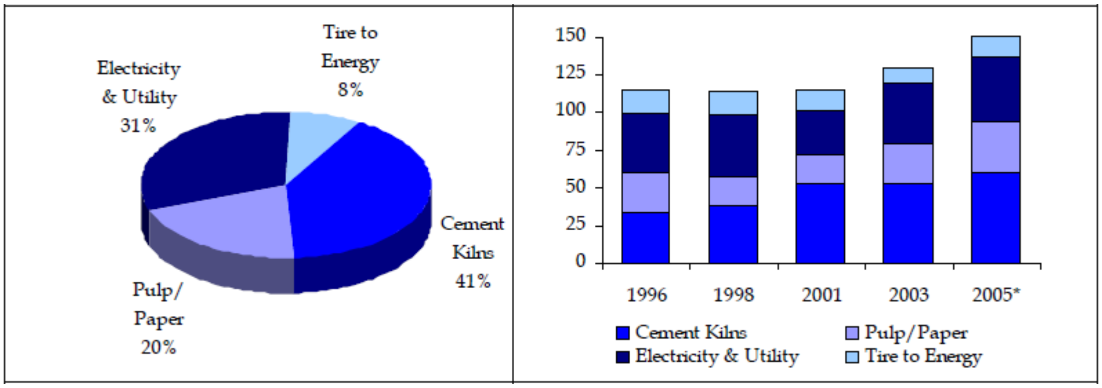


Figure 12: Fuel production from scrap tire in US (Irevna, 2012)

2.7.2.6 Civil Engineering Application

The applications in this field are landfill drainage layer, septic aggregate and lightweight fill. Even though this application is the fastest growing application but the hindering factor is the processors inability for producing products according to specifications.

2.7.2.7 Ground Rubber

The ground rubber is mostly used for production of molded and extruded products, asphalts, tire manufacturing, surface modification and animal bedding. Molded products and surfacing accounts for 61% of total demand and asphalt comprises 20% of it.

Chapter 3

LITERATURE REVIEW

3.1 Introduction

Being the most available material, soil has always been used in construction of different structure like buildings, roads and dams. Due to weak mechanical properties, the structures made of soil are much bulkier, heavier and dimensionally larger. Because of these weaknesses, there many researches aimed at enhancing the mechanical properties of soil and increasing its strength via adding different materials.

Reinforced earth is one type of enhanced soil that its tensile strength is increased. Although the addition of tensile resistant fibers to soil have been practiced by ancient civilizations but, the new technologies and advances in this field made the use of soil economically and technically much more justified and feasible.

There many method and technologies in used for increasing the tensile strength of the soil through mixing various additive or fibers to soil. Since the introduction of these methods, comprehensive theoretical and practical researches have been under way and some codes and standards developed for these methods.

The reinforcement of the soil is not new concept and its first applications goes back to 4 to 5 thousand years B.S when, hey or straw were used to reinforce the clay or bricks.

There are other evidences indicating use of reinforced soil in china wall and also ancient African and South Asian people used bamboo sheets, straw and date leaf in their buildings.

One of the materials used for enhancing the properties of soil is tire derived products like tire shreds, crumbs or powder. For this study a comprehensive literature review has been carried out that is summarized in this chapter. It covers the material properties of recycled tire, related tests and geotechnical applications of this material.

3.2 Tire

Although natural rubber is still used in the production of tire but, in modern tires manufacturing methods oil and gas derived synthetic rubber comprises considerable portion of consumed material for production of tires. According to Amari et al, (1999) vulcanized rubber and reinforcement constitutes the most of tire bulk and the generally used rubber is co-polymer styrene-butadiene (SBR) or a combination of SBR with natural rubber.

The categories of materials used in tire along with rubber are as below:

1. Reinforcing fillers like carbon black for strengthening and enhancing the abrasion resistance property of tire;
2. Reinforcing fiber for like steel or textile cords for increasing the tensile strength of rubber;
3. Extenders are petroleum derived oils that facilitates the production process. (Amari et. al., 1999)

The table 4 depicts the percentage of different ingredients of tire:

Table 4: Rubber compounding composition -Source: (US Environmenrtal Protection Agency, 2012)

Component	Weight (%)
SBR	62.1
Carbon black	31.0
Extender oil	1.9
Zinz oxide	1.9
Stearic acid	1.2
Sulfur	1.1
Accelerator	0.7
Total	99.9

3.3 Recycled rubber properties

3.3.1 Grading and Sizes

There are different definitions and notions used in literature for categorization of tire-derived aggregate (TDA) in terms of size. For example (Humphry, 2012) defines the following categories:

1. Rubber fines: ground rubber particles as by product of tire shredding process
2. Tire chips: pieces of tire between 12-50 mm in size and without wires
3. Tire shreds: pieces of tire with 50-305 mm dimensions
4. Rough shred: pieces bigger than 50*50*50 mm but smaller than 50*100*762 mm

As another example CEN Workshop Agreement (CWA) 14243-2002 (CWA, 2002) (as cited by (Oikonomou et. al., 2000) summarizes different sizes of TDA in the table 5:

Table 5: Different sizes of TDA (Oikonomou,2009)

Mterial	Size
Cuts	>300mm
Shred	50-300mm
Chips	10-50mm
Granulate	1-10mm
Powder	<1mm
Fine powder	<500
Buffing	0-40mm
Reclaim	Depends on input
Devulcanisate	Depends on powder
Pyrolitic char	<10mm
Carbon products	<500µm

Given this diversity of notation of different sizes in this research we define the range of tire buffing 3-10 mm and reinforcing wires are completely removed.

The grading test comprise passing of material through decreasing array of sieves. The ASTM D 422 is one of standards for this purpose. The only issue in this test is determination of sample size that ASTM D 422 calculates based on weight. In the case of TDA the minimum sample size is appropriate (Humphry, 2012).

3.3.2 Specific Gravity

The ratio of unit weight of the material to unit weight of water is the specific gravity of the material. Different test methods for obtaining the specific gravity of TDA have been used by several researchers. Kershaw and Pamukcu used the ASTM D 854 whereas Humphry, (2012) recommends the application of ASTM C 127. In table 6, a summary of different test carried out in different studies are provided.

Table 6: Summary of different tests for waste tire

Material	Particle Size (US Sieve Designation)	Specific gravity	Methods	Note	References
tire crumbs	0.6 to 1.18 (No. 30 - No. 16)	1.20	ASTM D 854	fabric and steel removed	Kershaw and Pamukcu, 1997
	2.0 (No. 10)	1.12	AASHTO T 85-91 & T 100-93	-	Benda, 1995
	0.1 to 4.8 0.2	1.07	ASTM D 854	-	Masad et al., 1996
	9.5 (3/8 in)	1.18	AASHTO T 85-91 & T 100-93	-	Benda, 1995
tire shreds	19.0 (0/75 in)	1.08	AASHTO T 85-91 & T 100-93	-	Benda, 1995
	30.0	1.08	-	-	Newcomb and Drescher, 1994
	38.0 (1/5 in)	1.11	AASHTO T 85-91 & T 100-93	steel removed	Benda, 1995
	6 to 25	1.22	-	-	Park et al., 1996
	50 x 75	1.13 to 1.36	-	depending on metal content	Edil and Bosscher, 1994
	-	1.15	-	without metal content	Edil and Bosscher, 1994
sands	-	2.63 to 2.67	-	-	Das, 1982
styrene butadiene rubber (SBR)	-	0.91	ASTM D 792	component of modern tires	Perry et al., 1997
natural rubber (NR)	-	0.93	ASTM D 792		Perry et al., 1997
reclaimed SBR	-	1.18	-	-	Borchardt, 1991

(Hong, 2000)

3.3.3 Compaction Characteristics

Having an almost 50% less specific gravity renders TDA a suitable material for lightweight fillings like embankments on loose foundations, backfill for retaining walls or reinforcing the earth (Humphrey et. al., 2000). Hence, the compaction characteristics of TDA are of high value for determining the optimum compaction.

The dry compacted density and maximum and minimum index void ratio (MIVR) of tire crumbs were determined by (Masad et. al., 1996). In ASTM 1997, the reference void ratio (RVR) at minimum index density is defined as maximum index void ratio and the RVR at maximum index density is defined as MIVR.

During the process of test, a 12kg steel block is placed on each of 12 layers of material and the mold is tapped 15 to 25 times by a rubber mallet. Then the MIVR is calculated via:

$$e_{min} = \frac{\rho_w . G_{avg}}{\rho_{dmax}} - 1 \qquad (1)$$

Where e_{min}= MIVR, ρ_w= water density, ρ_{dmax}= maximum index density, G_{avg}= weighted average specific gravity (ASTM D 4253). There is another simpler formula for e_{min} which is:

$$e_{min} = (\rho_s/\rho_d) - 1 \qquad (2)$$

Where ρ_s is solid density (kg/m^3) and ρ_d is dry solid mass (kg/m^3)

According to (Masad,et al. 1996) the maximum void ratio and the minimum void ratio were 1.36 and 0.6 respectively. The same mold was used for determination of compacted dry unit weight and desired compaction level was obtained via tamping with a metal rod. With relative density equal to 90% the compacted dry unit weight was equal to 6.2 kN/m^3.

However, duo to absorbent character of rubber (Edil et. al., 1994) found the ASTM D 4253 an inappropriate method for study of compaction behavior of rubber. In another research involving field experience, (Edil et. al., 1990) show ineffectiveness of vibration on compaction of tire shreds. They used ASTM D 698 and ASTM D 1557 instead. The density they found was between 5.5 and 5.8 kN/m^3. Table 7 summarizes the results and compaction results:

Table 7: Summary of compaction results

Material	Particle Size (US Sieve Designation)	Compaction method	γ_d (kN/m^3)	References
tire crumbs	2 mm (No. 10)	AASHTO Test Method T 99-93	5.2	Benda, 1995
	< 4.75 (No. 4 minus)	Nonstandard A[7]	6.6[a]	Masad et al., 1996
	< 4.75 (No. 4 minus)	Vibration[2]	4.4[b]	Masad et al., 1996
	< 4.75 (No. 4 minus)	Nonstandard B[8]	6.2[c]	Masad et al., 1996
	6.3 mm (1/4 in)	Modified[1]	5.3	Ahmed, 1993
	6.3 mm (1/4 in)	Standard[3]	5.8	Ahmed, 1993
	6.3 mm (1/4 in)	Vibration[2]	5.3	Ahmed, 1993
tire crumbs /shreds	0.85 to 12.5 mm (No. 20 - 0.5 in)	Modified[1]	5.5 to 5.9	Cecich et al., 1996
tire shreds	12.5 mm	Vibration[2]	4.6	Ahmed, 1993
	16 mm	Vibration[2]	4.8	Ahmed, 1993
	25 mm	Vibration[2]	4.6 to 5.1	Ahmed, 1993
	50 x 75 mm	Standard[3] (6 in & 12 in mold)	5.5 to 5.8	Edil and Bosscher, 1994
	25 to 75 mm	Loose[4]	4.9 to 3.3	Humphrey et al., 1992, 1993; Humphrey and Sandford, 1993
	50 mm	Loose[4]	4.0	Manion and Humphrey, 1992; Humphrey and Manion, 1992
	25 to 50 mm	Loose[4]	4.8 to 4.6	Ahmed, 1993; Ahmed and Lovell, 1993
	12.5 to 25 mm	Vibration[2]	4.6 to 4.9	Ahmed, 1993; Ahmed and Lovell, 1993
	12.5 to 25 mm	50% Standard[5]	6.3 to 6.0	Ahmed, 1993; Ahmed and Lovell, 1993
	25 to 75 mm	60% Standard[6]	6.1 to 6.3	Humphrey et al., 1992, 1993; Humphrey and Sandford, 1993
	50 mm	60% Standard[6]	6.1	Humphrey et al., 1992, 1993; Humphrey and Sandford, 1993
	30 mm	Loose[4]	4.9	Newcomb and Drescher, 1994
	50 mm	Loose[4]	2.3 to 3.4	Newcomb and Drescher, 1994
	38 mm	AASHTO Test Method T 99-93	5.9	Benda, 1995
	19 mm	AASHTO Test Method T 99-93	5.6	Benda, 1995
	9.5 mm	AASHTO Test Method T 99-93	5.0 to 5.9	Benda, 1995

(Source: (Hong, 2000))

[1] Modified: Impact compaction with compaction energy of 2693 kJ/m3.

[2] Vibrations: ASTM Test Method D 4253.

[3] Standard: Impact compaction with compaction energy of 593kJ/m3.

[4] Loose: no compaction; tire rubber loosely placed into compaction mold.

[5] 50% Standard: Impact compaction with compaction energy of 296kJ/m3,

[6] 60% Standard: Impact compaction with compaction energy of 356 kl/m3,

[7] Nonstandard A: Compaction in 12 layers in a mold; each layer resigned with 12 kg; load while sides tapped sharply 15 IO 25 limes.

[8] Nonstandard B: Similar to Nonstandard A, but with no load and side tapping,

[9] Not specified

[a] Calculated from $e_{min.}$

[b] Calculated from e_{max}.

[c] Prepared at 90% relative density.

3.3.4 Compressibility

Understanding the compressibility behavior of TDA in indispensable when it comes to appreciation of possible settlement related behavior of the TDA. These behaviors include long-term or short-term settlements and also temporary dynamic loading effect. The compressible nature of the grains and also reduction of the void ration renders TDA a much higher compressibility in comparison with soil.

The compressibility of the TDA has been measured using two different methods, one being the oedometer method (Edil et. Al., 1994) and other is triaxial method (Wei et. Al., 1997).

Through oedometer method the dry materials have to be placed in 150 to 737 mm molds and then they should be subjected to one-dimensional loading to measure the strain parallel to the loading direction.

In triaxial method, sizes of the specimens were 100 mm in diameter and had 200 mm height. The compaction was carried out according to AASHTO T 99 and consolidation has been carried out in a 165 mm triaxial cell and under isotropic stress.

3.3.5 Dilatancy

As a basic property of soil, dilatancy is defined as voidage increase in firmly compacted soil duo to introduction of shear deformation. (Campanella et. al., 1993) define dilatancy as the volumetric change in soil duo to application of shear strain.

Since there is a high level of interlocking between soil particles, it should also be overcome as well as frictional resistance before occurrence of shear failure. Because dilatancy is phenomenon related to interlocking between the soil particles, different grading, grain size, in situ stress and mineralogy are among those parameters that cause substantial differences in dilatancy characteristics of various soil types (Guo, 2000). Dilatancy can be perceived from different kind of graphs. For example those curves relating shear stress and strain for loos and dense sand obtained from direct shear test like the one depicted in Figure 11. The dense sands curve show a peak point in relatively low strain region, but as the resistance is reduced due to overcoming the interlocking among particles, the stress starts to fall and strain increases.

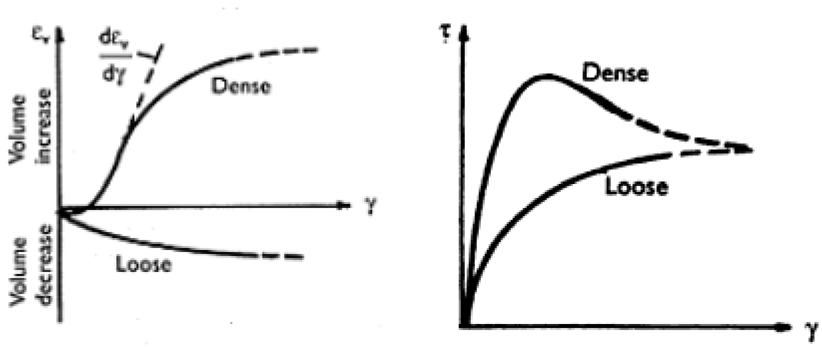


Figure 13: Dilatancy graph(Knappett & Craig, 2012)

Casagrande in his works (Casagrande, 1938) introduced the concept of dilatancy into the soil mechanics and discussed the friction angle change on volumetric changes of soil. Then (Taylor, 1948) applied the energy theory for justifying the shear stress to volumetric change and friction which was further developed by Newland and Allely (1957) (As cited by (Guo, 2000)). They added two other factors which are interaction of particles and reorientation granular soil particles. Using microscopic approach (Rowe, 1962) the stress-dilatancy were described based on assembly properties of soil. In modern mechanics the first dilatancy theory belongs to Rowe and in his theory he devised the following formula:

$$\frac{\sigma_1}{\sigma_3}=KD;\ \ K=tan^2(\frac{\pi}{4}+\frac{\varphi_\mu}{2});\ \ D=(1-\frac{d\mathcal{E}_v^p}{d\mathcal{E}_1^p}) \tag{3}$$

In his theory he made the following assumptions:

1. Internal geometry constraint is driving reason behind dilatancy
2. The granular material's strength comprises sliding resistance of particles, volumetric dilation energy and energy lost duo to rearrangement of particles.
3. The minimum dissipation of energy (minimum absorption of energy)

Despite strong supportive data and experiments (Horne, 1969) there are some limitations attracting criticism like (De Jong et. al., 1967) who criticized the use of minimum energy principal. Another limitation of Rowe's formulae was the use of φ_μ which is only valid for very dense sand under small strains. In order to overcome such a shortcoming (Rowe, 1971) he used the friction angle φ_f which is a characteristic property of different materials and has specific values for different strain levels and densities.

3.3.6 Direct Shear Test (DST)

Even though the strength test on different material like metal, glass and wood dates back to 17th century when Leonardo Da Vinci started testing the tensile strength of iron (Lund et. al., 2001), one material that has lagged behind the aforementioned material is soil because of its different nature like granular composition, diverse types etc. Hence, almost a century later (Henri, 1717) studied the angle of repose for design of retaining walls but, the first test concerning the properties of soil has been carried out by Belidor in 1729 that are considered the first test in the history of soil related studies that lead to numerical results (Das, 2009).

One of early devised apparatuses for testing the shear strength of soil belongs to Collin (1846) (as cited by (Wood, 2002)). In this apparatus a specimen made of clay is transversely loaded at the center and the load has to be increased until the specimen fails.

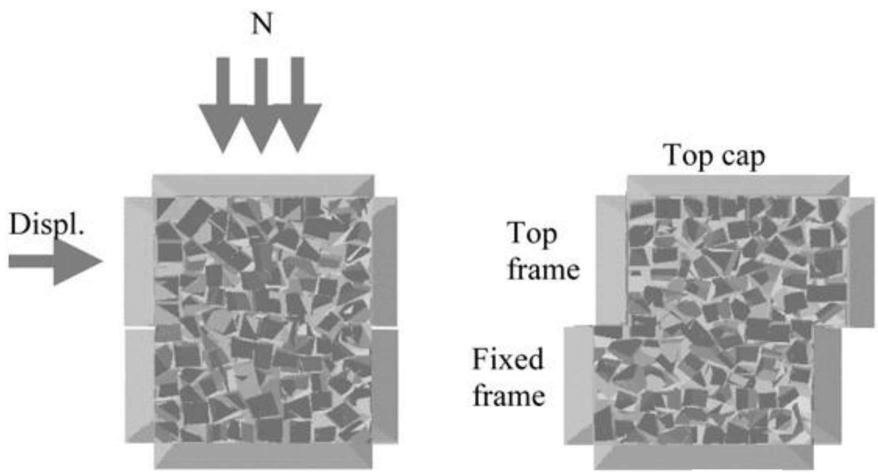
Leygue (1885) invented another apparatus for DST that were designed for cohesion less soils and comprises a box that should be tilted until the top half of the box slides on the lower half due to its weight. Despite advantages like ease of application and speed, it has some shortcoming like non-uniformity of stress and strength.

According to (Kjellman, 1951) the Swedish Geotechnical Institute devised the first device for direct shear testing that was able to deform the specimen uniformly. In 1953 a square box shear test was developed at university of Cambridge for sand (McGuire, 2011). Then in 1957 Petlier developed a shear-box that through its sides, the middle principal plane is subjected to a controlled force. This machine was further developed to test the gravels by making bigger boxes and increasing the scale of it (McGuire, 2011).

An in-situ test apparatus that can be used in small (60x60x8.5 cm) and large (120x120x17 cm) sizes for DST on coarse–grained soils were developed by Matsuoka et al(2001), in (1999). The simplicity and high accuracy are two advantages of this method but the most important drawback of this method is the pre-selection of the shear surface (Zhang, 2003).

The effects of boundary conditions, when performing DST on reinforced sand, were studied by Jewell (1989). A new analysis method based on relation among dilatancy and shear strength was introduced for DST which allowed independently examine the results of conventional analysis and the consistency of DST data. Through comparison of conventional test (free top) results with symmetric (fixed top) test’s results, symmetric test was validated as an effective method for measuring the plain strain, direct shear angle of friction and also angle of dilation of sand. As a result of (Jewell, 1989) study, a suggestion concerning the standard test data analysis and a modification for DST device were recommended (Zhang, 2003).

In DST a specimen confined in a cubic or cylindrical box is subjected to a shear force, T, and meanwhile a normal force, N, in vertical direction. To move the top half of the box over the lower half of the box, the T force is applied horizontally to the top half of the box. The vertical N load is applied via a rigid plate that is able to move vertically when the specimen deforms. The application of T force causes a shear along the thin layer between lower and upper half of the shear box. This is illustrated in Figure 13.



(a) (b)

Figure 14: Direct shear test box
(Zhao et. al., 2006)

Before application of lateral load, the principal stress state is similar to that depicted in figure 13 (a). The minor and major stresses are considered uniformly distributed before shear force is introduced.

After the introduction of shear load, the state of principal stresses rotates as depicted in figure 13 (b). The deformation parallel to confining or normal load is uniform outside of shear zone or rotating inside the zone. Although, the strains are extremely non-uniform within soil, but at the corners of box the strains concentrate at the shear surface and are maximum. At the central zones of the box the strains are much uniform and in term of magnitude they are the smallest (Zhang, 2003).

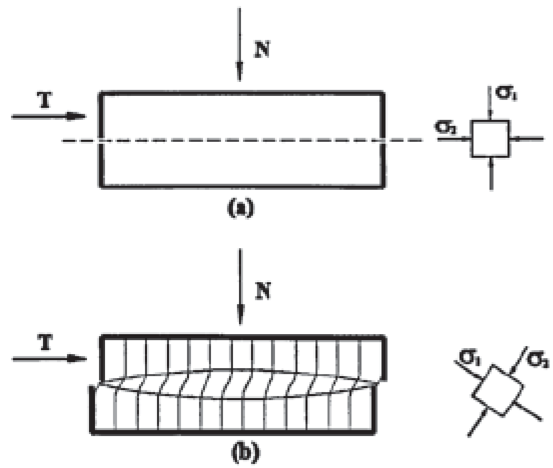


Figure 15: State of principal stresses (Zhang, 2003)

Chapter 4

MATERIALS AND METHODS

4.1 Materials

4.1.1 Natural Soil

In the course of this thesis, sand which has been collected from the Silver Beach next to Famagusta town at the eastern coast of Cyprus has been used. The sample has been collected using a brass shovel at a depth of 10-50cm, and dried in an oven for at least 24 hours, at 105°C to remove the moisture. This sample was not used in its original condition and was not washed therefore it contained some amount of salt.

4.1.2 Tire

In this thesis, shredded tire waste of a tire which was obtained from a tire factory in Erzincan, Turkey was used for the treatment of the Silver Beach sand. The wastes obtained from this factory, regarding to their size, have been categorized into two groups, tire buffing and tire powder.

4.1.2.1 Tire Buffing

Tire buffing is wastes which have passed through the sieve No. 4 (4.750 mm) and have not passed through the sieve No. 20 (0.840 mm).

4.1.2.2 Tire Powder

Tire powder is tire wastes which have passed through the sieve No. 20.

4.2 Material Properties

4.2.1 Sieve Analysis

The distribution of the sand was established using a mechanical sieve analysis according to ASTM D421- D422. The particle-size distribution was then described on several plots. Goal of this test is to determine the soil particle size distribution and classify the soil according to the Unified Soil Classification System, USCS.

The various sizes in soil mass should be classified in different size groups and this work is done by finding the mass that passes through each sieve.

The test results obtained from the sieve analysis were plotted and the particle size distribution curve of the sand was obtained. The sample range of particle size and shape of the distribution curve were defined by the coefficient of uniformity (C_u) and the coefficient of curvature (C_c) which can be obtained from the particle size distribution curve. The particle size distribution curve drawn for the natural sand is given in Figure 16.

$$C_U = \frac{D_{60}}{D_{10}} \tag{4}$$

$$C_c = \frac{D_{30}^2}{D_{60} D_{10}} \tag{5}$$

Where:

C_u: Uniformity coefficient

C_c: Coefficient of curvature

D_{10}: Diameter corresponding to 10% finer

D_{30}: Diameter corresponding to 30% finer

D_{60}: Diameter corresponding to 60% finer

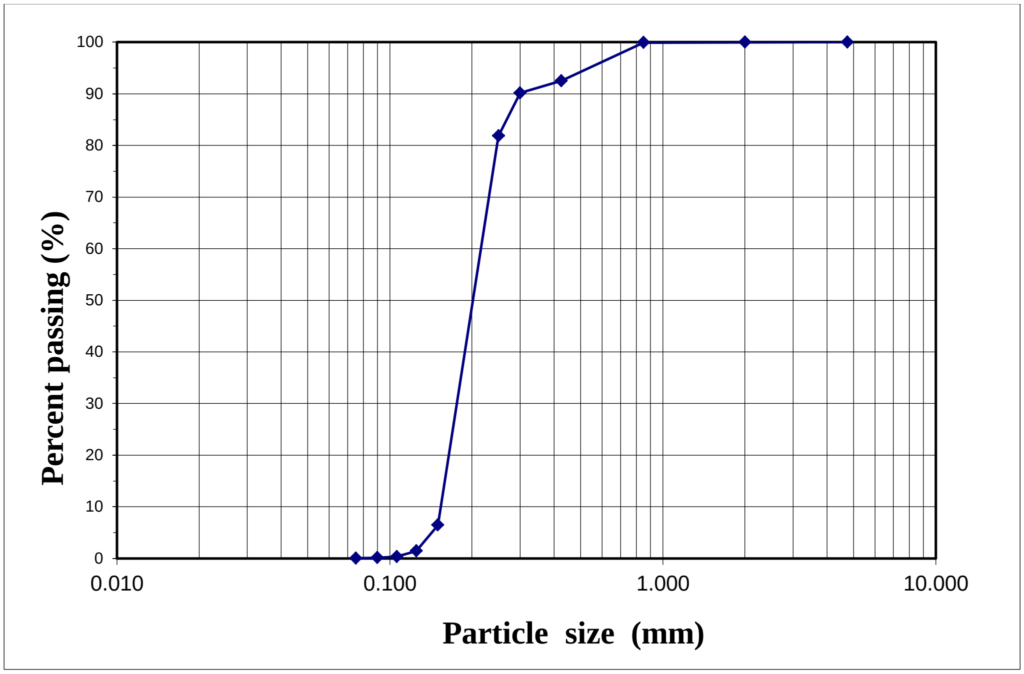


Figure 16: The particle size distribution curve for the natural sand

The values of the uniformity coefficient, C_u and the coefficient of curvature, C_c obtained from Figure 16 are given in Table 8. According to the USCS, the natural sand was classified as poorly graded uniform sand.

Table 8: The uniformity coefficient, Cu and, coefficient of curvature, Cc of natural Silver Beach sand

Soil	**D_{10}(mm)**	**D_{30}(mm)**	**D_{60}(mm)**	**C_u**	**C_c**	**Sand Type**
silver sand	0.16	0.183	0.222	1.39	0.95	SP

4.2.2 Specific Gravity (G_s)

According to ASTM standard D854-10, the specific gravity test was conducted to determine the G_s of each one of the materials which have been used in this research.

The equation (Equation 6) given below was used to calculate the Gs of the natural sand.

$$G_s = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \tag{6}$$

Where:

m_1: Weight of pycnometer with cap

m_2: Weight of pycnometer with cap and soil

m_3: Weight of pycnometer with cap, soil and water

m_4: Weight of pycnometer with cap and water

Since tire buffing and tire powder have a specific gravity less than water, they both floats on the water. Thus, the test procedure for these materials will be conducted using gasoline instead of water. This will give the specific gravity of the material related to specific gravity of gasoline, in order to convert this to well-known specific gravity (relative to specific gravity of water), it should get multiplied by:

$$\frac{\gamma_{Gasoline}}{\gamma_{water}} = \frac{719.23}{981} = 0.74 \tag{7}$$

The specific gravity values of the pure sand, tire buffing and tire powder are given in Table 9.

Table 9: The specific gravity values of the pure materials

Specimen	**Specific gravity (G_s)**
Pure sand	2.69
Tire powder	0.86
Tire buffing	0.98

In order to calculate the specific gravity of mixtures, for different amount of tire buffing and tire powder which are 10, 20 and 30 percent, the following formula, which has been proposed by Montanez (2002), was used.

$$G_{mix} = \frac{100}{\frac{\%\,Sand}{G_{Sand}} + \frac{\%\,Tire\,buffing}{G_{Tire\,buffing}}} \tag{8}$$

$$G_{mix} = \frac{100}{\frac{\%\,Sand}{G_{Sand}} + \frac{\%\,Tire\,powder}{G_{Tire\,powder}}} \tag{9}$$

Table 10 presents the specific gravity of the sand-tire mixtures used in this research.

Table 10: The specific gravity of the sand-tire mixtures

Mixture	**Specific gravity(G_s)**	
Tire buffing	10%	2.29
	20%	1.99
	30%	1.76
Tire powder	10%	2.27
	20%	1.97
	30%	1.47

4.2.3 Relative Density

The relative density test is implemented to define the relative density (D_r) of cohesionless, free draining soils. Relative density is a ratio which is stated as a percentage of the variation between the maximum void ratios of cohesionless free draining soil to a maximum of a reference matter (Reddy, 2002).

This test has been conducted on pure sand and the sand treated with different percentages of tire buffing and the maximum and minimum void ratio values of these soils were determined. The maximum void ratio determination was performed by using the ASTM D 4254- standard test methods for Minimum index density and unit weight of soils and minimum void ratio determination was done by ASTM D4253 - standard test methods for minimum index density and unit weight of soils using a vibratory table.

Relative density value is generally used for evaluating the degree of compactness of granular soils. The soil properties, such as compressibility, shear strength, bearing capacity and permeability are dependent on soil's compaction level. In the literature, there are different types of procedure used for the determination of the relative density of granular soils. For this reason, the test procedure followed in this study is presented below.

4.2.3.1 Relative Density Test

4.2.3.1.1 Equipment

The equipment that were used in this thesis are Standard mold, vibrating table, guide sleeves, surcharge weights, surcharge base-plate and its handle, dial indicator gage, scoop, balance, straightedge .

4.2.3.1.2 Relative Density Test Procedure

The mold should be stuffed with soil, using a funnel or a scoop approximately 1 inch above the mold, the soil must be poured into the mold totally loose. To decrease the particle segregation the Spiraling movement should be appropriate; The extra soil on top of the mold should be carefully trimmed off using a straightedge; The soil and mold mass should be recorded, the mold should be unfilled afterwards; The mold should be loaded with soil (not the same soil used before). Previous steps should be redone, the sides of the mold should be struck a few times with a rubber hammer or a metal bar to descend the soil so that surcharge base plate can be easily placed and after the vibration initiated no surge of air from the mold will be; The surcharge base plate on the soil should be placed and twisted so it would be placed firmly and equally in contact with the top of the soil. The handle should be removed afterwards; The mold should be connected to the vibrating table; The dial indicator gauge holder should be inserted in each brocket on both sides of the guide brackets to determine the primary dial reading. Three readings on each side of each guide brackets (six sets in total) should be obtained; the primary dial gage reading is the average of these 12 numbers, R_i. R_i should be rounded to the nearest 0.025 mm; The guide sleeve should be firmly connected to the mold and the sufficient surcharge weight should be lowered, which for this size of mold is 25.6±0.2 kg on the base plate; The assembly and soil specimen should be shaken for 8 minutes with frequency of 60 Hz; The gage readings should be noted and determined as in step 7, the average of these readings will be Rf; The base plate should be taken away from the mold and the mold should get disconnected from the vibrating table; The soil and mold mass should be noted (M_2);The empty mold weight should be determined; To calculate the calibrated volume of the mold, $V_{c,,}$ the mold dimensions should be noted , the thickness of the surcharge base plate should also get defined, T_p.

In the study, the above procedure was applied to pure sand and the sand-tire buffing mixtures and the obtained values were presented in Table 11. Table 11 gives the minimum and maximum void ratios of the pure sand and the sand-tire buffing mixtures used in this research.

Table 11: The minimum and maximum void ratio of the pure sand, sand-tire buffing and powder mixture

Specimen	**Mixture percent (%)**	**ρ_{min} (g/cm^3)**	**ρ_{max} (g/cm^3)**	**e_{min}**	**e_{max}**
Pure Sand	0	1.43	1.65	0.60	0.85
Tire Buffing	10	1.10	1.46	0.54	1.04
	20	0.85	1.33	0.47	1.29
	30	0.63	1.33	0.30	1.74
Tire Powder	10	1.11	1.50	0.48	1.00
	20	0.87	1.37	0.41	1.21
	30	0.55	1.16	0.24	1.63

4.3 Moisture-unit Weight Relationship (Dynamic Compaction Test)

ASTM standard D 698-7 covers laboratory compaction methods which were used to investigate the relation between water content and dry density of the soil in order to define the optimum water content. Lee and Suedkamp (1972), conducted series of laboratory tests on 35 soil samples and showed four different compaction curves which can be observed in Figure 17 and Table 12.

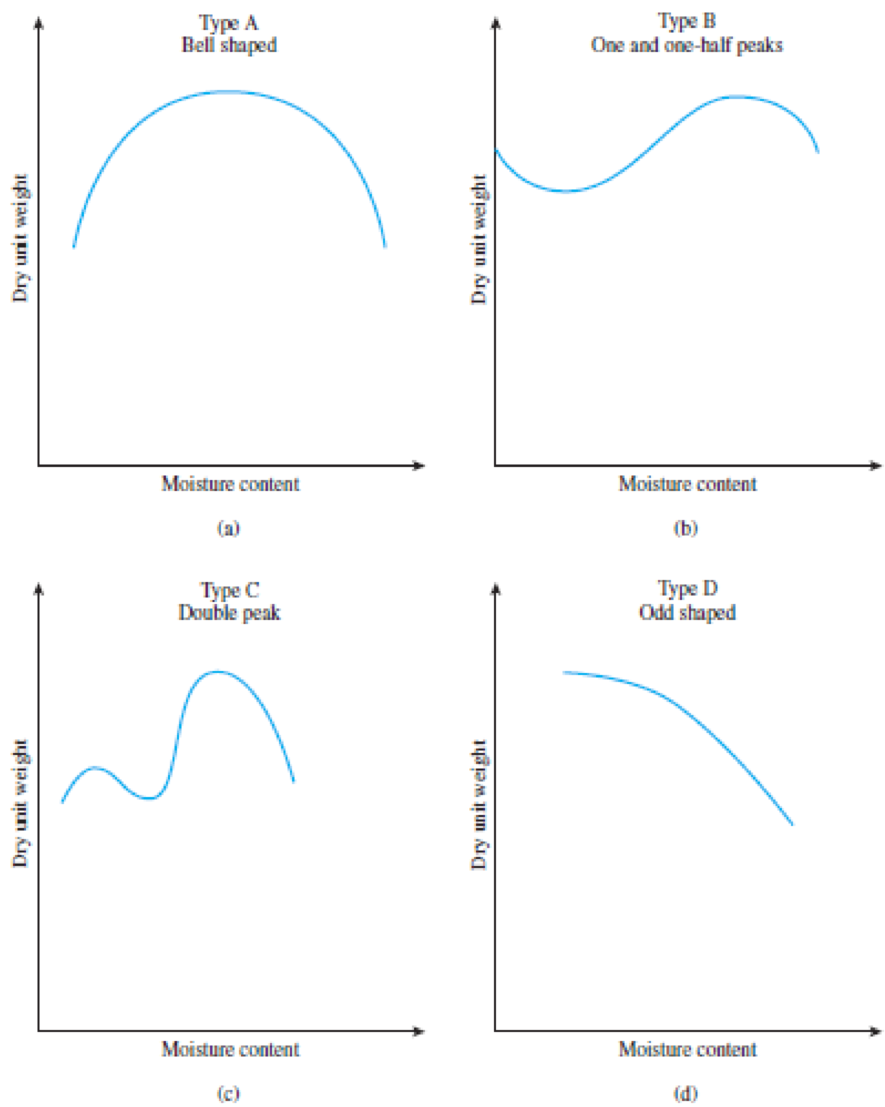


Figure 17: Different shapes of compaction curves obtained on 35 soil samples (Lee and Suedkamp, 1972)

Table 12.Description of compaction curves in Figure 17

Type of compaction curve	Description of curve
A	Bell shaped
B	1-1/2 peak
C	Double peak
D	Odd shaped

The soil samples in the impact compaction test were compacted using a 24.5 N rammer dropped from height of 304.8 mm, creating a 600 kN-m/m^3 in a 101.6 mm diameter mold. 10 samples of poorly graded sand with various amounts of water content were prepared and kept in plastic bags for 24 hours before the test. The compaction of each sample has been performed in 3 layers while each layer has been compacted 25 times. In order to determine the water content of each sample, 3 sections in each specimen, one on top, one from bottom, and one in the middle of the mold, have been taken; the average of these three amount will be the water content of the sample.

In this thesis, 10 different samples with different water content values have been prepared and tested and the obtained results were given in Figure 18.

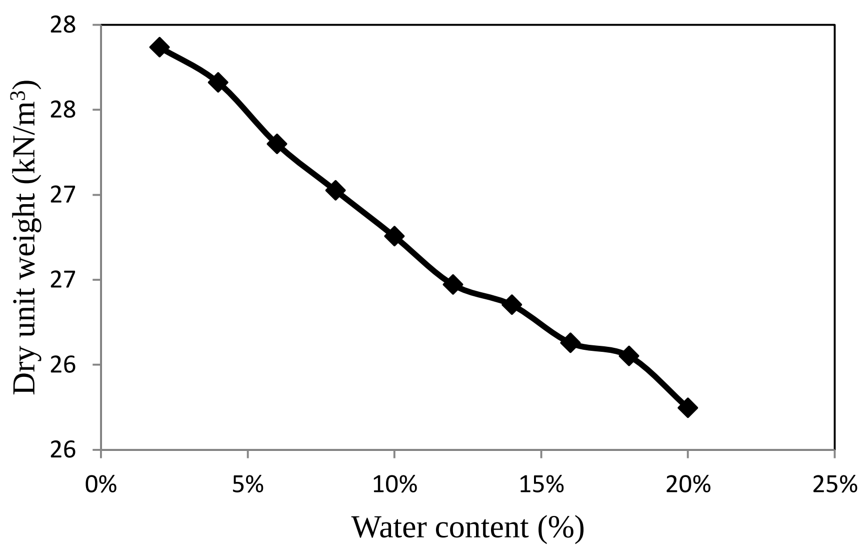


Figure 18: Compaction curve for the pure sand

As it can be seen from the Figure 18, the compaction curve for the pure sand did not fit to any shape. That is Because of the poor grading of the sand, it is difficult to compact the soil and the curve does not give a definite peak.

4.3.2 Direct Shear Test

In order to determine the drained shear strength parameters of sand, series of direct shear tests have been conducted.

Generally the direct shear test uses a cylindrical or rectangular specimen, which is enclosed in a split box. In this research, rectangular samples have been used. In the testing device, a normal force, N, applies to the top of the box in the vertical direction, and a horizontal force, T, shears the specimen along a thin plane between the two halves of the box, by acting on the top part of the box.

In this research, according to ASTM D-3080, each specimen has been tested in a shear box with dimensions of 6 x 6 x 2.2 cm, under three different normal stresses of 20, 30, and 50k N/m^2, in order to obtain the shear strength parameters. The rate of shear deformation has been set on 1.5 mm/min to create a drained condition.

The main purpose of this research was to find the influence of tire treatment on the shear strength parameters of the sand. In the study, two different sizes of tire shreds: tire buffing and tire powder, have been mixed with sand with three different percentages by weight: 10, 20, and 30 percent. Because of the uniform grading of the sand used in the study and not being able to obtain an optimum water content, two different water content values were chosen: 5 and 10 percent and the samples were prepared at these water content values and they were subjected to various tests . Table 13 shows the number of specimens prepared at different percentages of sand-tire mixtures, different percentages water content, and relative density values. As it can be seen from the table a total 14 different specimens are introduced in the table 13.

Table 13: Number of specimens prepared at different percentages of sand-tire mixtures, water content, and relative density values.

Specimen	**Sand (%)**	**Tire buffing (%)**	**Tire powder (%)**	**Relative density (%)**
Pure sand-ω:5%	100	0	0	4.0
Sand-10% Tire buffing	90	10	0	3.8
Sand-20% Tire buffing	80	20	0	4.2
Sand-30% Tire buffing	70	30	0	4.5
Sand-10% Tire powder	90	0	10	3.7
Sand-20% Tire powder	80	0	20	4.3
Sand-30% Tire powder	70	0	30	4.6
Pure sand-ω:10%	100	0	0	4
Sand-10% Tire buffing	90	10	0	3.6
Sand-20% Tire buffing	80	20	0	4.3
Sand-30% Tire buffing	70	30	0	4.8
Sand-10% Tire powder	90	0	10	3.8
Sand-20% Tire powder	80	0	20	4.1
Sand-30% Tire powder	70	0	30	4.7

In this research, the sand-tire specimens, which will be subjected to testing, were prepared at the relative density value between 3.6-4.8%. This value of relative density indicates that the prepared specimens were at the very loose state which is the worst case in sand. In the study, ASTM D3080 was used in the direct shear box test.

During the test, data readings from time, lateral displacement, and shear force at the desired interval of displacement were recorded and test continued to at least 10 percent relative horizontal displacement.

4.3.3 California Bearing Ratio (CBR)

In order to determine the effect of tire shreds on the bearing capacity of the specimens, California Bearing Ratio, CBR test has been performed. Due to lack of tire powder, the CBR test was conducted on only 4 different types of samples; pure sand and mixtures of sand-tire buffing at 10, 20, and 30 percent by weight of the pure sand. The sand-tire buffing mixtures were prepared at two different water contents: 5% and 10% percentage. The CBR test was performed according to the ASTM D1883-07 standard.

According to ASTM D698-12 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort) each sample should be compacted by 56 blows on each of its three layers with a 24.47 N rammer dropped from a 304.8 mm height and surcharged weight of 4.54 kg should be placed on top of the specimen inside the mold. The penetration piston should be seated on the specimen, with the smallest possible load, but in no case more than 44 N.

The load on the penetration piston should be applied in order to achieve the penetration rate of 1.27 mm/min and the load gauge should be noted at following penetrations: 0.64, 1.27, 1.91, 2.54, 3.18, 3.81, 4.45, 5.08, 7.62, 10.16, and 12.70 mm.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Introduction

In this chapter, the results of the tests which have been explained in the previous chapter (Chapter 3) will be discussed. The aim of these tests is to investigate the effects of tire buffing and tire powder on strength parameters of sand.

The experiments which have been conducted in this chapter will be divided into 2 groups: The first series of experiments were conducted with specimens at 5% water content with different percentages: 10%, 20%, 30% of tire buffing and powder and the second series of tests were conducted with 10% water content.

5.2 Direct Shear Tests

The direct shear tests were conducted under 3 normal stress values: 20 kN/m^2, 30 kN/m^2, and 50 kN/m^2. The shear stress- shear deformation diagrams will be given and discussed in this part and they will be compared with other charts in their categories. As mentioned earlier, the specimens in direct shear tests were prepared at two different water content values: 5% and 10%. Figure 19 shows the shear stress-shear deformation diagram for the natural sand prepared at 5% water content value.

5.2.1 Samples Prepared at 5% Water Content

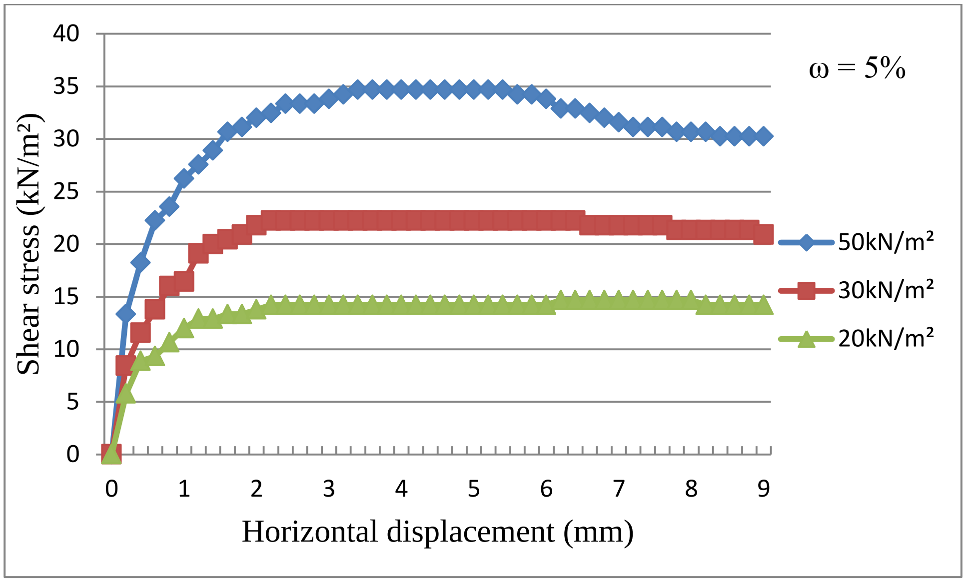


Figure 19: Shear stress-shear displacement diagram for pure sand

The shear stress-shear deformation diagrams for the soils mixed with 10, 20 and 30 percent tire buffing at 5% water content value were given in Figures 20-22.

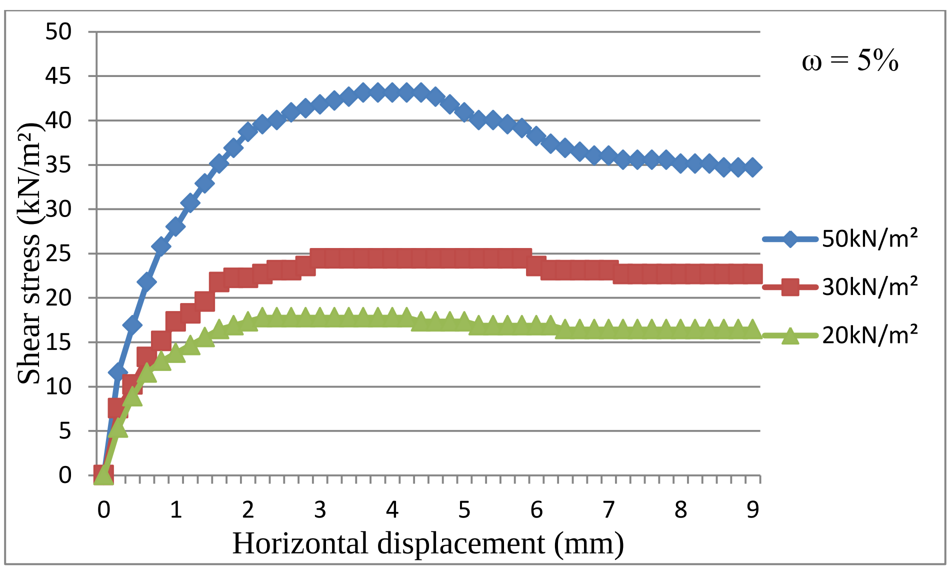


Figure 20: stress-shear displacement diagram for pure sand mixed with 10% tire buffing

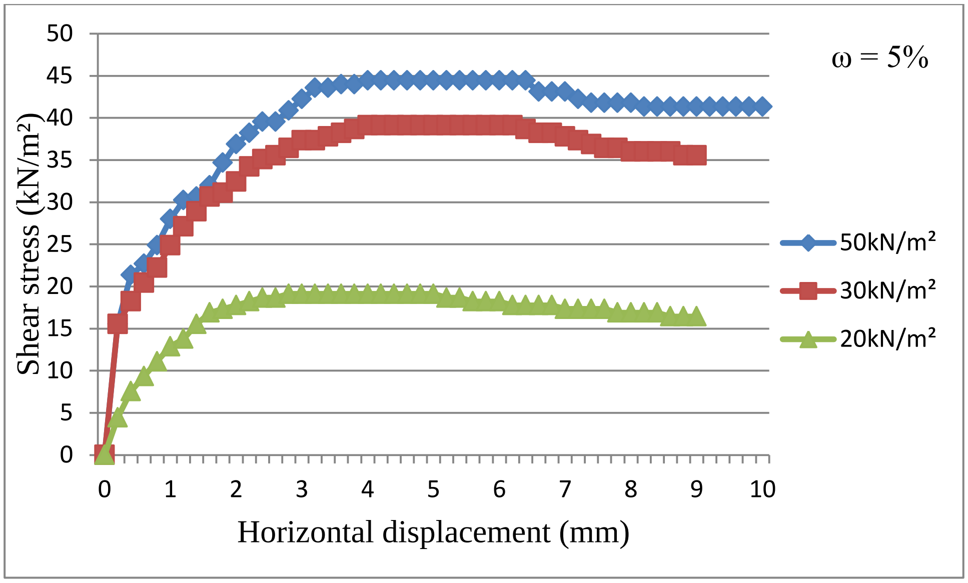


Figure 21: Shear stress-shear displacement diagram for pure sand mixed with 20% tire buffing

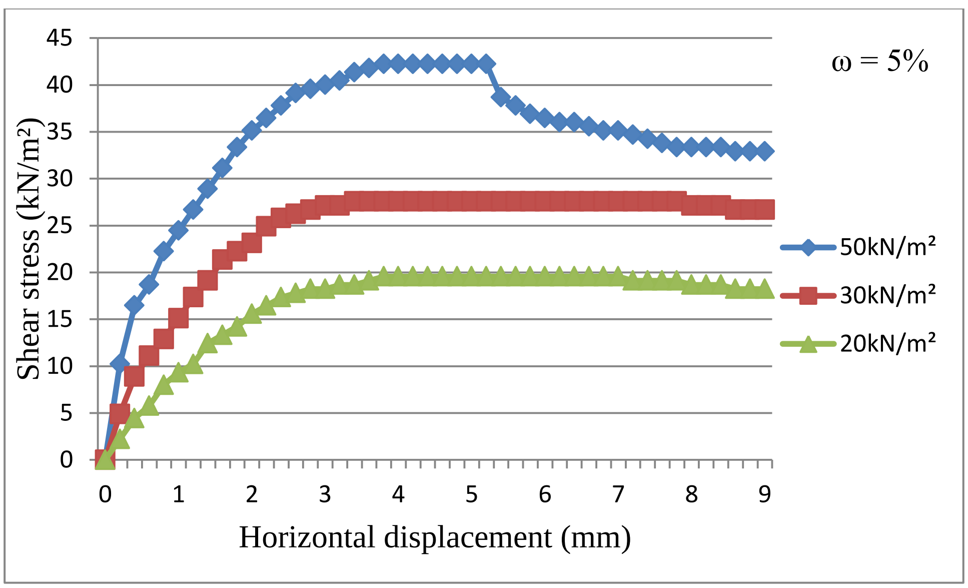


Figure 22: Shear stress-shear displacement diagram for pure sand mixed with 30% tire buffing

Figures 23-25 give the shear stress-shear deformation diagrams for the soils mixed with 10, 20 and 30 percent tire powder at 5% water content value.

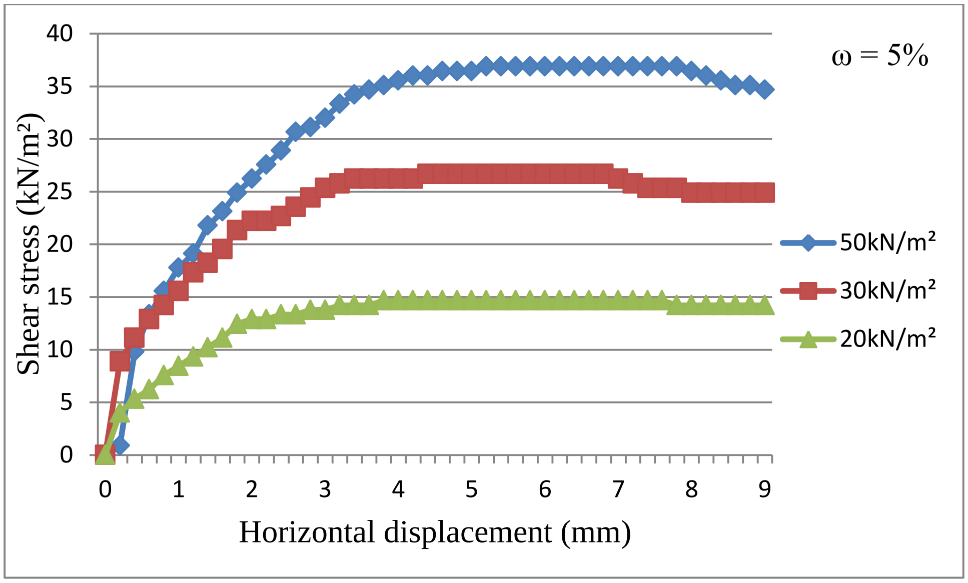


Figure 23: Shear stress-shear displacement diagram for pure sand mixed with 10% tire powder

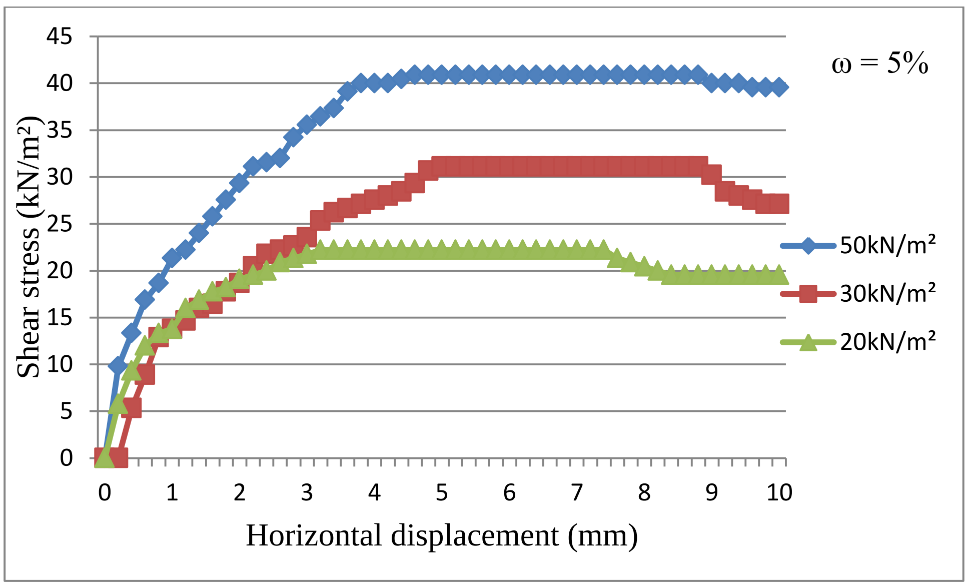


Figure 24: Shear stress-shear displacement diagram for pure sand mixed with 20% tire powder

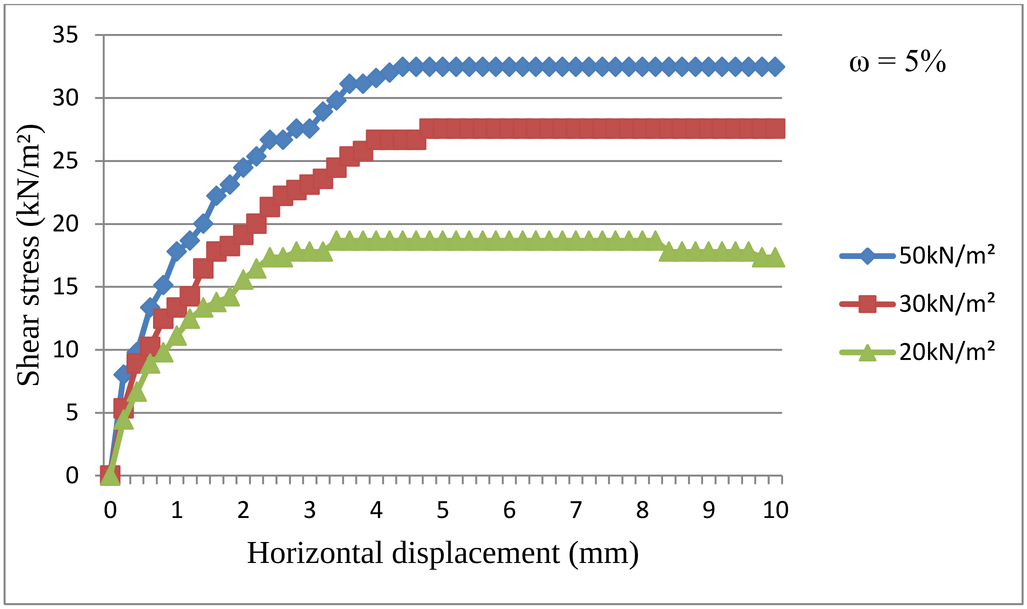


Figure 25: Shear stress-shear displacement diagram for pure sand mixed with 30% tire powder

Figures 19-25 illustrate the shear stress-shear displacement curves under three different normal stress values. In all the figures (19 to 25) it can be seen that by increasing the normal stress, an increase in the shear strength of the soil was obtained. Slip resistance of soil is proportional to the applied normal force. Therefore, by increasing the normal stress of the soil, an increase in the ultimate shear strength was obtained. Considering that interlocking between particles affect the maximum shear strength then by increasing the normal stress, the interlocking will grow and affect the shear strength.

5.2.2 Samples Prepared at 10% Water Content

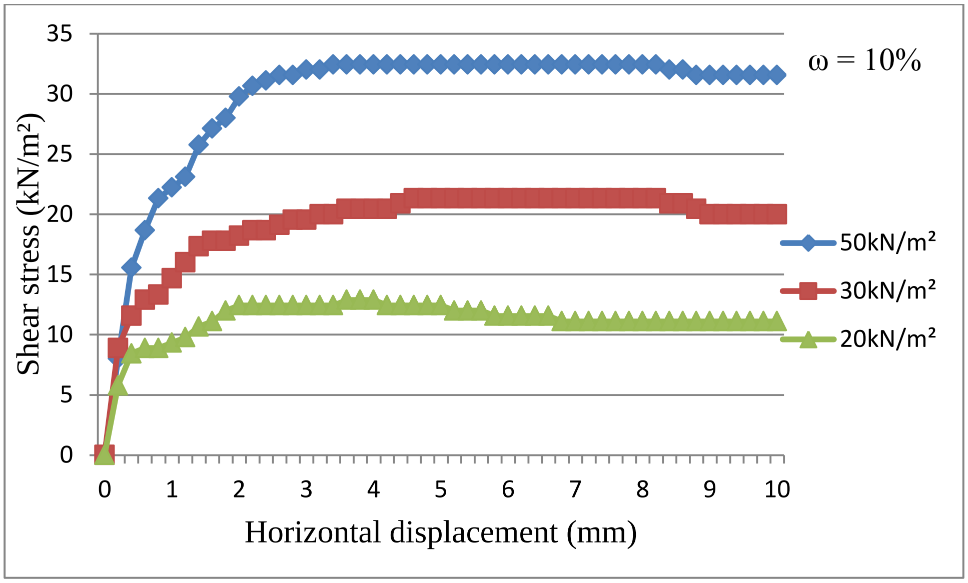


Figure 26: Shear stress-horizontal displacement for pure sand

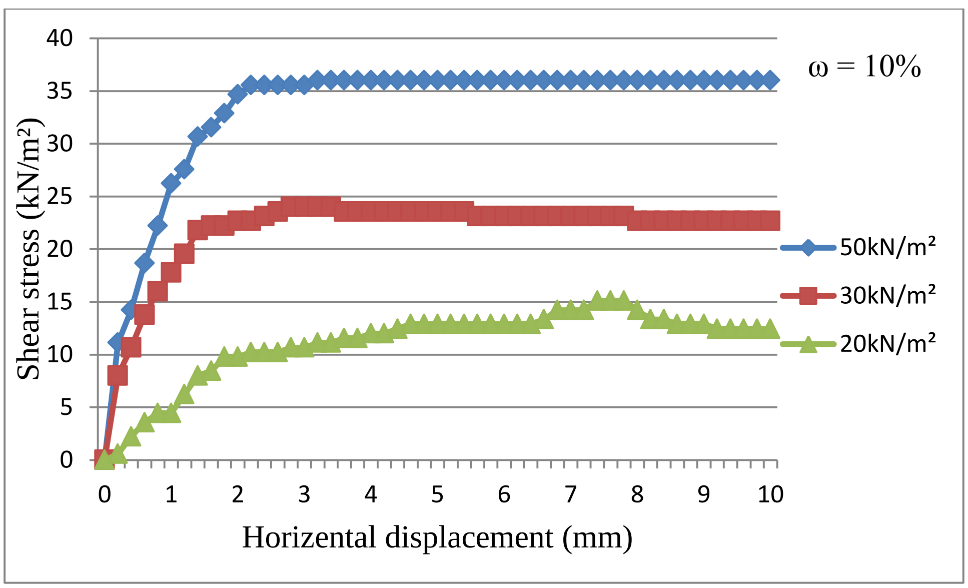


Figure 27: Shear stress-horizontal displacement for pure sand mixed with 10% tire buffing

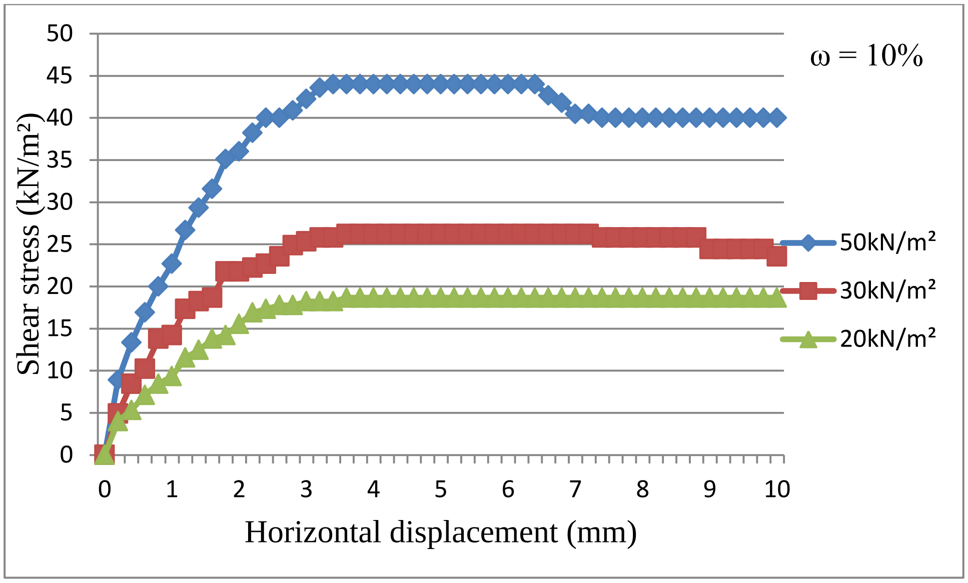


Figure 28: Shear stress-horizontal displacement for pure sand mixed with 20% tire buffing

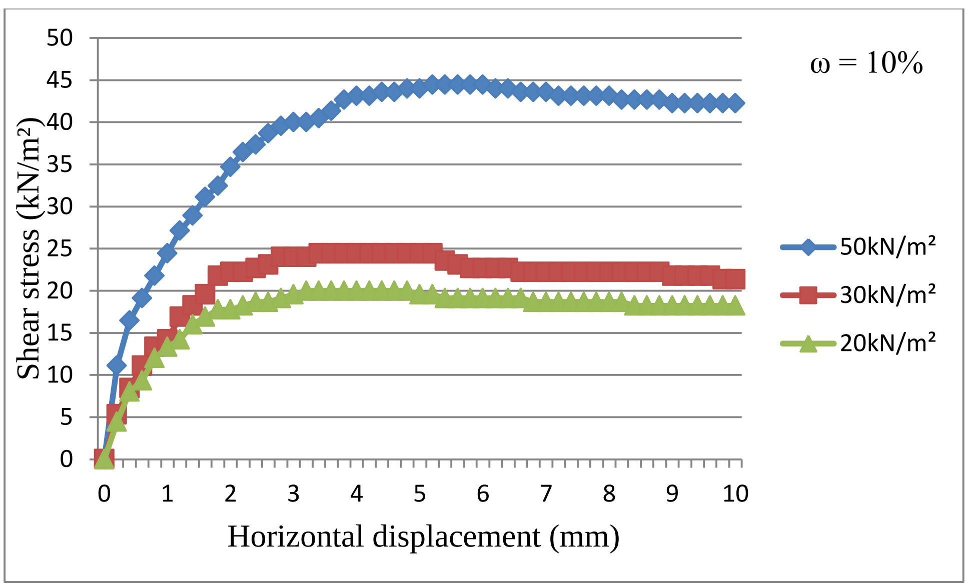


Figure 29: Shear stress-horizontal displacement for pure sand mixed with 30% tire buffing

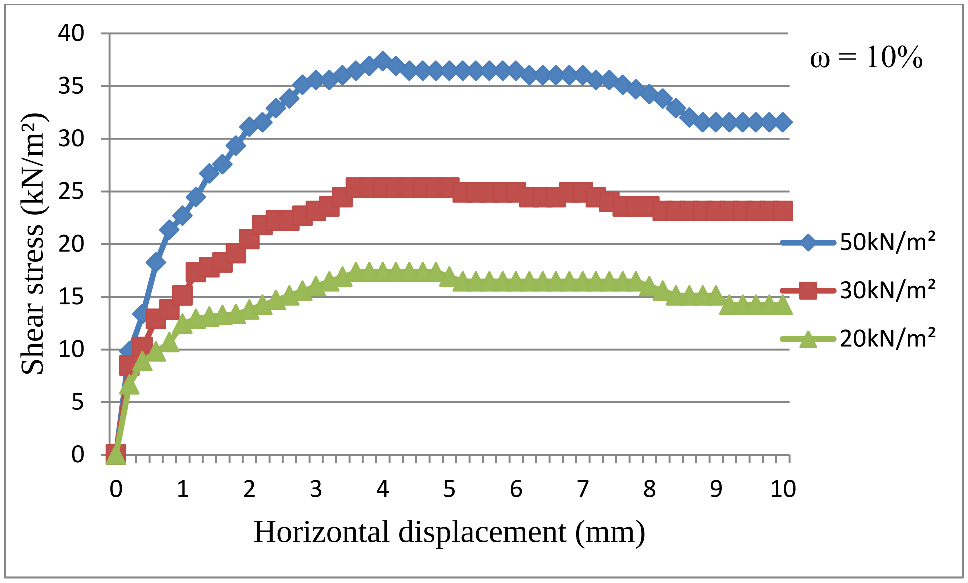


Figure 30: Shear stress-horizontal displacement for pure sand mixed with 10% tire powder

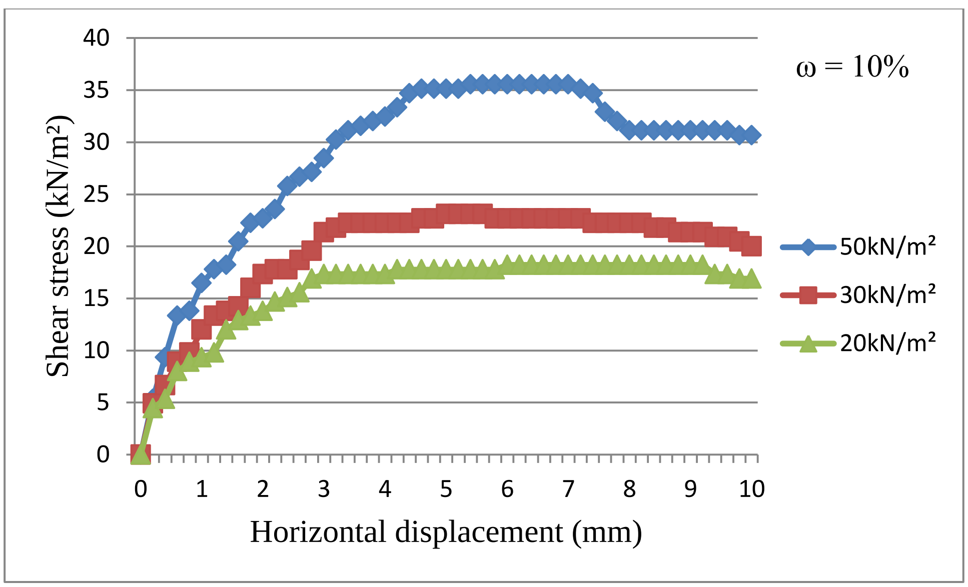


Figure 31: Shear stress-horizontal displacement for pure sand mixed with 20% tire powder

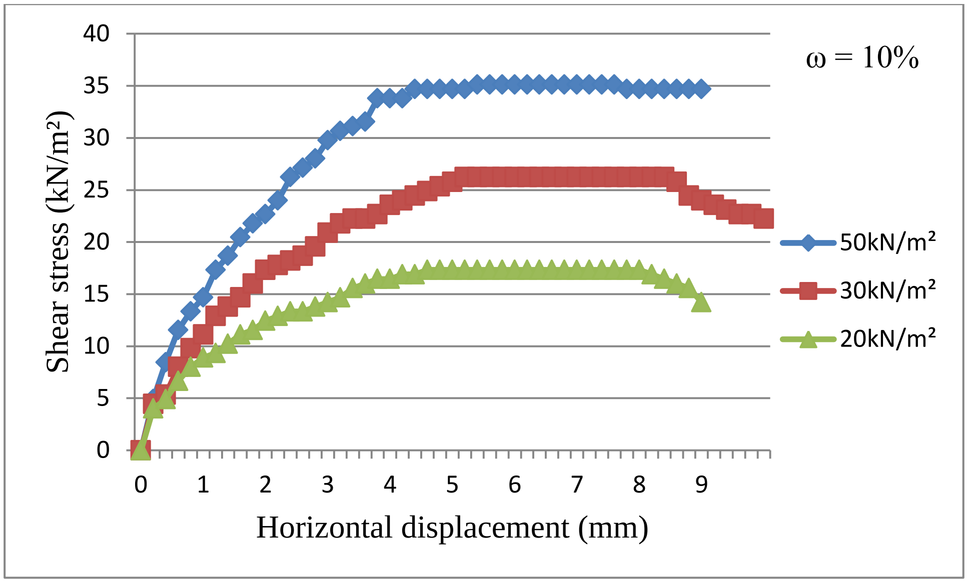


Figure 32: Shear stress-horizontal displacement for pure sand mixed with 30% tire powder

Figures 26-29 give the shear stress versus shear displacement diagrams for the soil treated with different percentages of tire buffing, whereas Figures 30-32 show the shear stress versus shear displacement diagrams for the soil treated with different percentages of tire powder. Test results indicated that the shear strength of all soils increased with the increase in the normal stress values. From the test results, it can be seen that the stress-strain diagrams of the soil treated with different percentages of tire powder at higher normal stress values gave a clear peak similar to dense sand behavior.

5.2.3 Comparison of the Shear Stress versus Shear Displacement Diagrams

5.2.3.1 Soils Prepared at 5% Water Content

The charts below demonstrate the shear stress changes with respect to the normal stresses. The shear stress versus shear displacement curve of the pure sand was compared with the sand treated with different percentages of tire buffing and tire powder under different normal stress values.

The shear stress versus shear displacement curves of the pure sand the sand treated with different percentages of tire buffing, under 20, 30 and 50 kN/m^2 normal stress values were given in Figures 33, 35 and 37 respectively. Figures 34, 36 and 38 gave the shear stress versus shear displacement curves of the pure sand and the sand treated with different percentages of tire powder under 20, 30 and 50kN/m^2 normal stress values respectively.

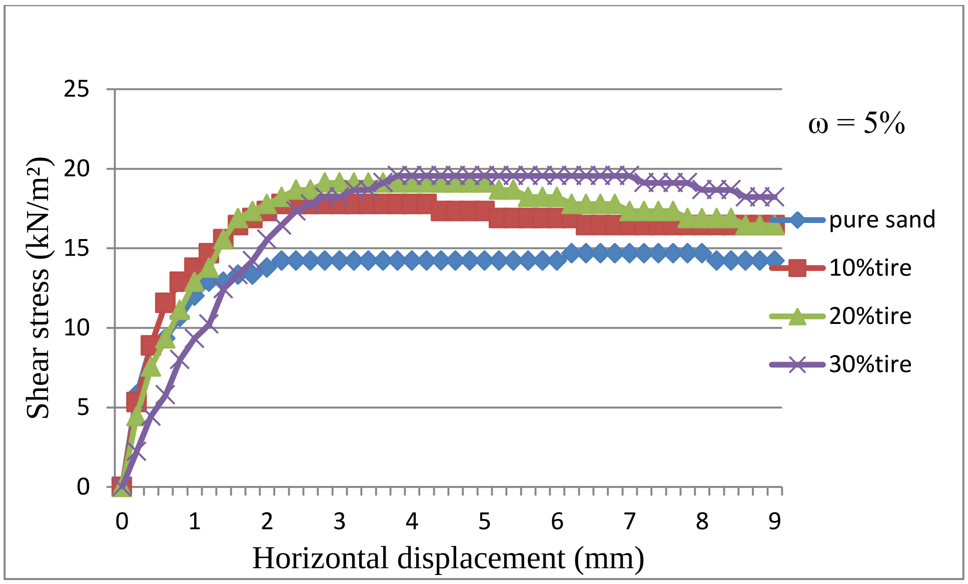


Figure 33: Pure sand and the sand treated with different percentages of tire buffing under the normal stress value of 20 kN/m^2

Figure 33 indicates that at a given normal stress applied on specimens, the shear strength of the soil treated with different percentages of tire buffing is greater than that of sand alone under the same normal stress value. Figure 33 indicates that the shear strength of the soil treated with different percentages of tire buffing under 20 kN/m^2 normal stress value increases with the increase in percentage of the tire buffing. The 30% tire buffing curve shows the maximum amount of shear stress which is 19.55 kN/m^2. The figure indicates that the shear strength of the 30% tire buffing treated soil increased from 14.6 kN/m^2 (pure sand) to 19.6 kN/m^2. Figure 33 indicates that the increasing percentage of tire buffing cannot change significantly the shear strength of the soils. The shear strength of the 20% and 30% tire buffing treated soils are 19.1 kN/m^2 and 19.6 kN/m^2 respectively which indicates that the values are very close to each other.

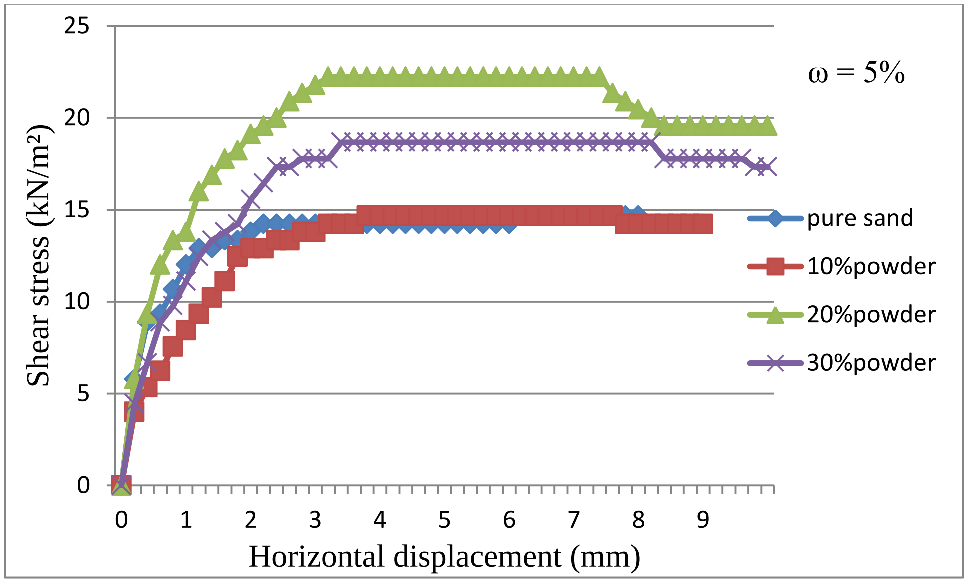


Figure 34: Pure sand and the sand treated with different percentages of tire powder under the normal stress value of 20 kN/m^2

Figures 34 shows the shear stress versus shear displacement curve of the pure sand the sand treated with different percentages of tire powder under 20 kN/m^2 normal stress value. The figure indicates that 10% tire powder does not have any effect on the shear strength of the treated soil. The maximum shear strength (22.2 kN/m^2) of the soil was obtained with 20% tire powder. The figure indicates that the shear strength of the powder treated soils does not increase in a regular manner with the increase in the powder percentage. Figure 34 indicates that the shear strength of the 30% powder treated soil was below the shear strength of 20% powder treated soil. The figure indicates that under 20 kN/m^2 normal stress value, 20% powder is optimal to obtain the higher shear strength. Higher percentage of powder (30%) decreases the shear strength of the treated soil.

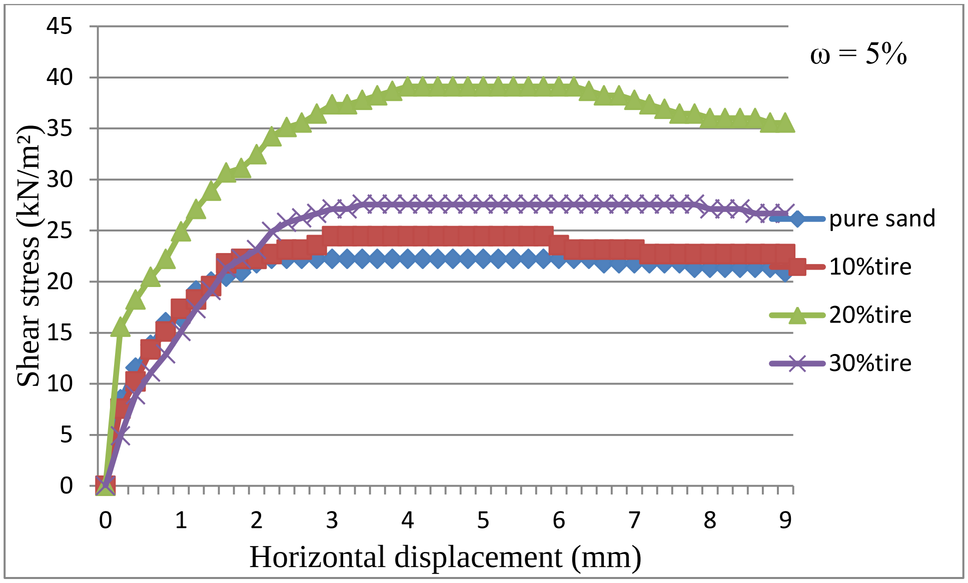


Figure 35: Pure sand and the sand treated with different percentages of tire buffing under the normal stress value of 30 kN/m^2

Figures 35 and 36 show the shear stress versus shear displacement curves for the pure sand and the sand treated with different percentages of tire buffing and tire powder under 30kN/m^2 normal stress value, respectively. Figure 35 indicates that under 30 kN/m^2 normal stress value, 10% tire buffing is not very effective. The maximum shear strength value is obtained at 20% tire buffing treated soil. When the percentage of tire buffing is increased above 20%, reduction in the shear strength of the soil is obtained. The 20% tire buffing sample shows the utmost shear stress value (39.11kN/m^2).

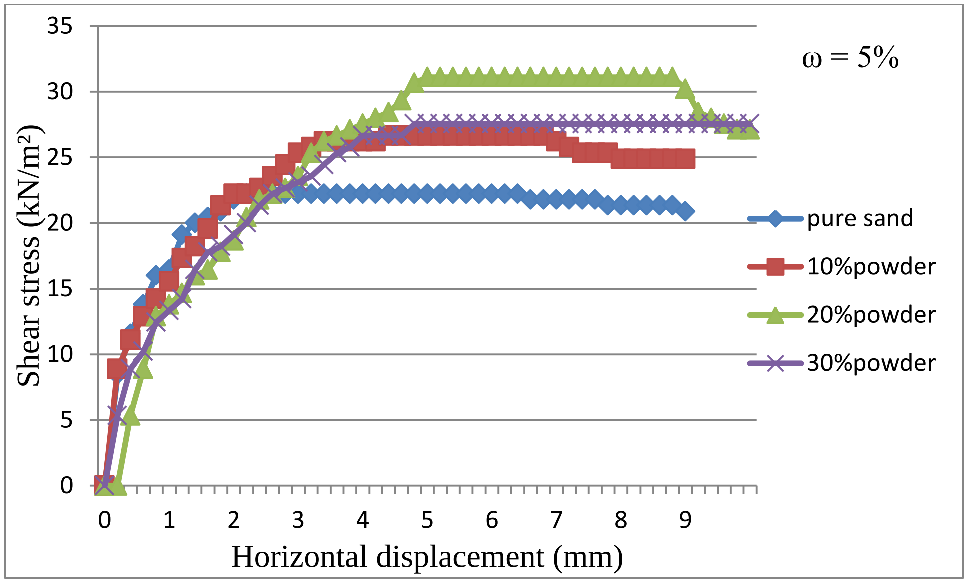


Figure 36: Pure sand and the sand treated with different percentages of tire powder under the normal stress value of 30 kN/m^2

Figure 36 shows the shear stress versus shear displacement curves for the pure sand and the sand treated with different percentages of tire powder under 30 kN/m^2 normal stress value. Under this normal stress value, the figure indicates that the greatest shear strength (31.1 kN/m^2) is again obtained with the sample treated with 20% tire powder. The shear strength of the soil increases from 22.2 kN/m^2 (pure sand) to 31.1 kN/m^2 with 20% powder treatment. The shear strength of the soil decreases to 27.6 kN/m^2 with 30% powder treatment.

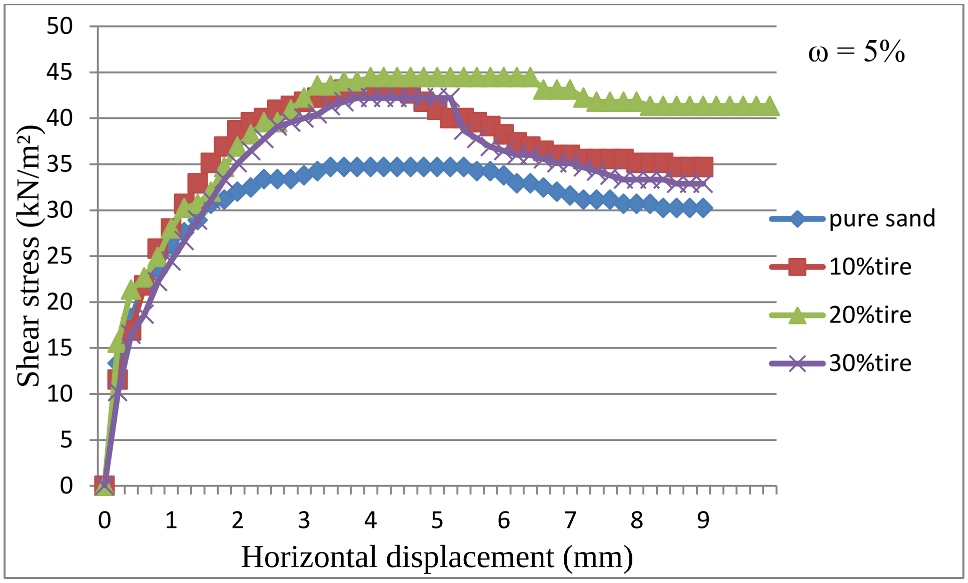


Figure 37: Pure sand and the sand treated with different percentages of tire buffing under the normal stress value of 50.kN/m^2

Figure 37 shows the shear stress versus shear displacement curves for the pure sand and the sand treated with different percentages of tire buffing under 50 kN/m^2 normal stress value. The figure demonstrates that the 20%, 10% and 30% tire buffing samples have almost the same values of shear strength (44.44 kN/m^2, 43.11 kN/m^2 and 42.22 kN/m^2, respectively) and the pure sand has the smallest shear strength value of 34.66 kN/m^2 among the others. The figure shows that under the high normal stress value of 50 kN/m^2, the shear stress-shear displacement curves of the tire buffing treated soils tend to show a distinct peak in shear stress, indicating dilation characteristics. The figure indicates that the tire buffing treated soils are initially condensed and then dilate upon shearing. The dilation effect is more pronounced in 30% tire buffing treated soil. That is because the tire particles surround the sand grains and produce higher void ratios and during shearing, under the applied normal stress, the sand particles penetrate to these void and at further deformation values, the sand particles are forced to roll over the tire particles resulting in increased dilatancy effect.

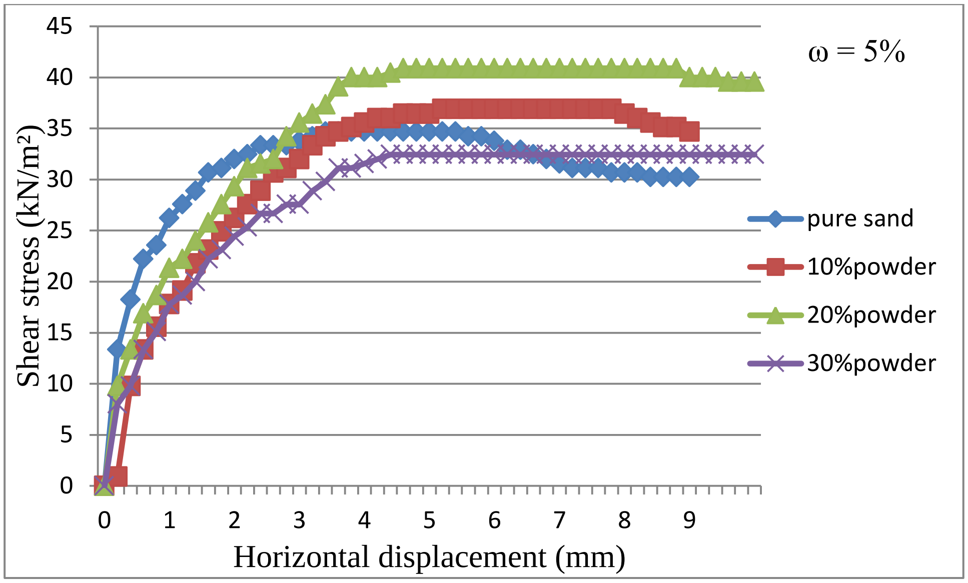


Figure 38: Pure sand and the sand treated with different percentages of tire powder under the normal stress value of 50 kN/m^2

Figure 38 shows the shear stress versus shear displacement curves for the pure sand and the sand treated with different percentages of tire powder under 50 kN/m^2 normal stress value. Figure 38 clarifies that the 20% tire powder sample has the greatest shear strength among the others which will be followed by the 10% tire powder sample with 36.88 kN/m^2, and the 30% tire powder with 32.44 kN/m^2. Figure 38 indicates that the shear stress-shear displacement curves of the tire powder treated soils do not show a distinct peak in shear stress. There are no dilation characteristics in powder treated sands. That might be due to the very fine particles of the tire powder which completely fills the void space of the powder treated soils and prevents the sliding of the sand particles over the others.

Figures 33-38 illustrate that the 20% tire has the highest shear strength value in both tire buffing and tire powder treated soils.

4.2.3.2 Samples Prepared at 10% Water Content

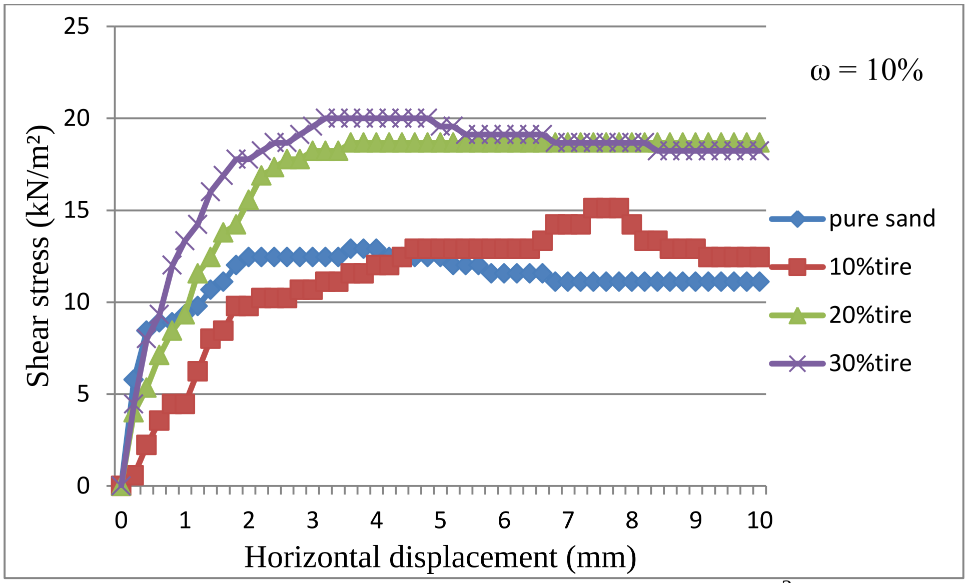


Figure 39: shear stress-horizontal displacement for 20.KN/m^2 normal stress

Figures 39-44 show the shear stress versus shear displacement curves for the pure sand and the sand treated with different percentages of tire buffing and tire powder under different normal stress values. Figures 39 illustrate the shear stress versus shear displacement curve of tire buffing treated soil under the 20.165 kN/m^2 normal stress. The results in the figure indicate that the sample with 30% tire buffing has the greatest shear stress value followed by the 20%, and 10% tire buffing.

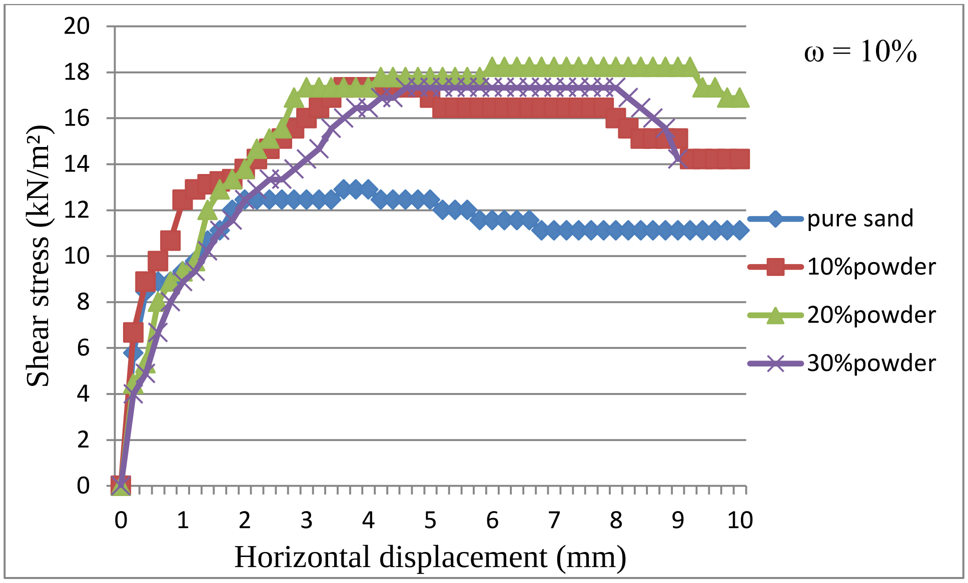


Figure 40: Shear stress-horizontal displacement curve for the tire powder treated soil under 20 kN/m^2 normal stress

Figure 40 shows the shear stress-horizontal displacement curve for the tire powder treated soil under 20 kN/m^2 normal stress value. The figure indicates that the 20% tire powder treated soil has the greatest shear strength value (18.22 kN/m^2) and the samples with 30% and 10% tire powder have the same maximum shear stress value (17.33 kN/m^2) which is slightly lower than the 20% tire powder shear stress value.

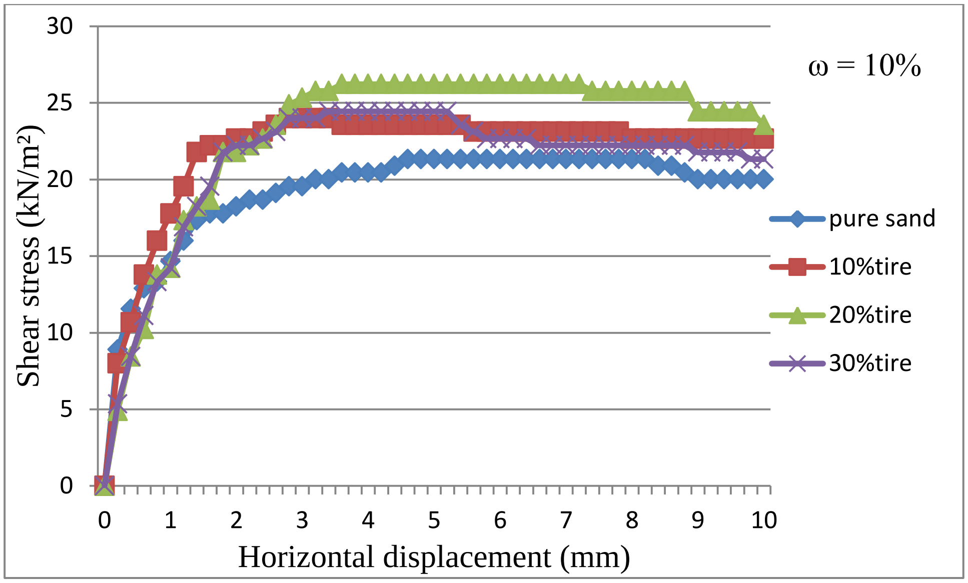


Figure 41: Shear stress-horizontal displacement curve for the tire buffing treated soil under 30 kN/m^2 normal stress

Figure 41 shows the shear stress versus horizontal displacement curve for the tire buffing treated soil under 30 kN/m^2 normal stress value. The figure indicates exactly the same results as in Figure 40. That is the 20% tire buffing curve has the largest shear strength value (26.22 kN/m^2), and the 30% and 10% tire buffing curves has the same (24.00 kN/m^2) maximum shear strength. The pure sand gives a peak of 21.33 kN/m^2.

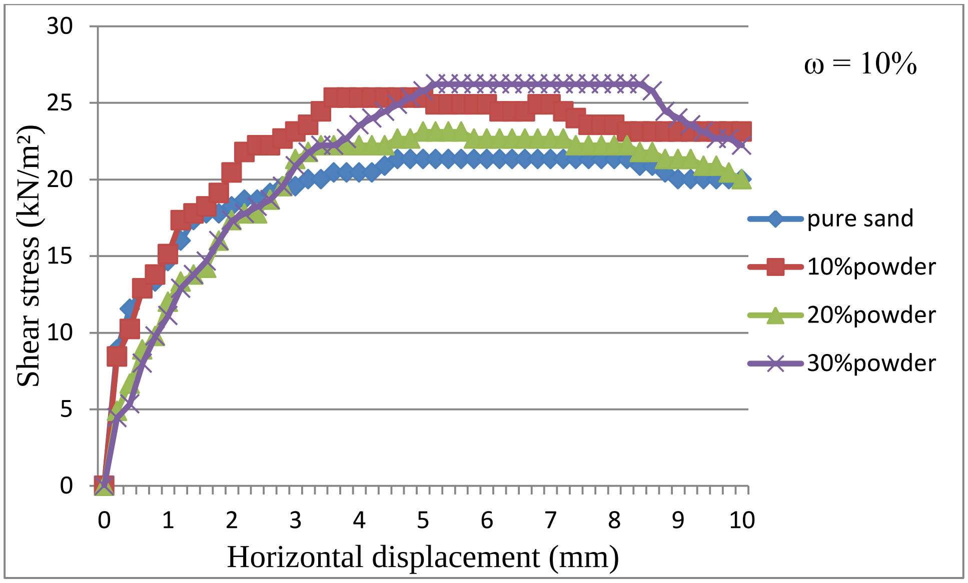


Figure 42: Shear stress-horizontal displacement curve for the tire powder treated soil under 30 kN/m^2 normal stress

Figure 42 gives the shear stress versus horizontal displacement curve for the tire powder treated soil under 30 kN/m^2 normal stress value. In the figure, the highest maximum shear strength (26.22 kN/m^2) belongs to the 30% tire powder then the 10% tire powder curve give the value of 25.33 kN/m^2 shear strength and 20% tire powder curve gives the lowest shear strength value (23.11 kN/m^2).

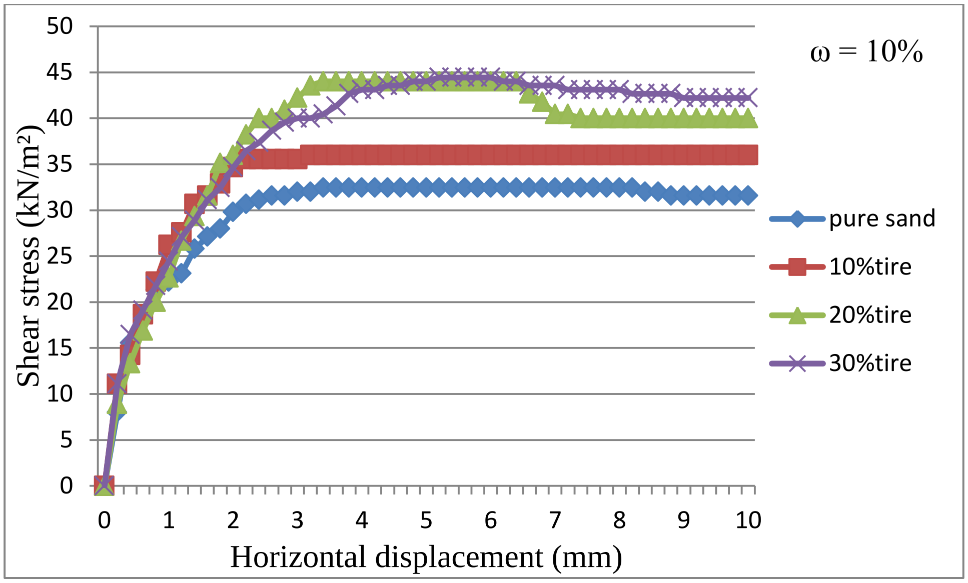


Figure 43: Shear stress-horizontal displacement curve for the tire buffing treated soil under 50 kN/m^2 normal stress

Figure 43 shows the shear stress-horizontal displacement curve for the tire buffing treated soil under 50 kN/m^2 normal stress value. The figure shows that the 30% and 20% tire buffing curves have the same maximum shear stress value of 44.44 kN/m^2 which is the largest shear strength under 50 kN/m^2 normal stress value.

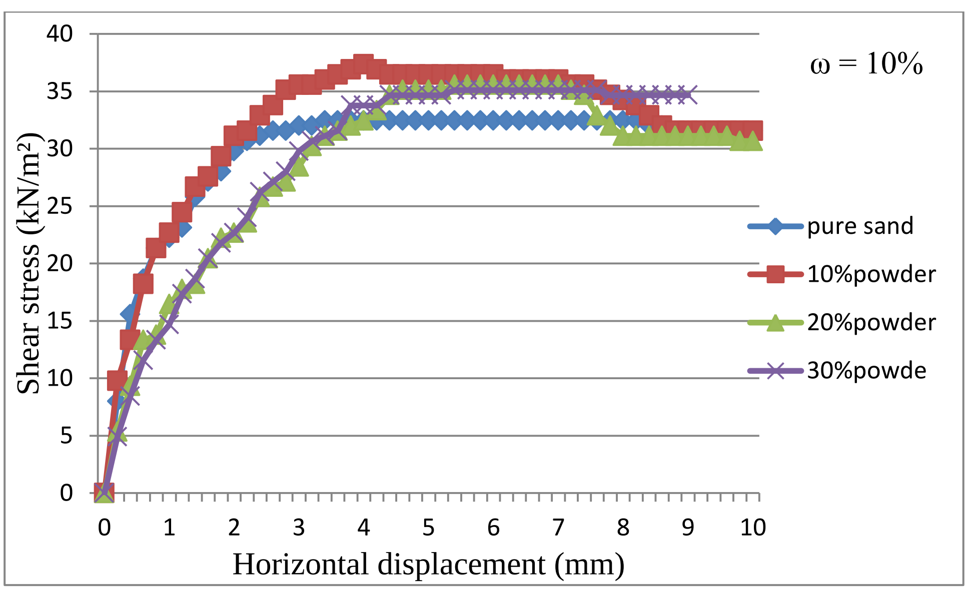


Figure 44: Shear stress-horizontal displacement curve for the tire powder treated soil under 50 kN/m^2 normal stress

Figure 44 shows the shear stress-horizontal displacement curve for the tire powder treated soil under 50 kN/m^2 normal stress value.

Figure 44 illustrates the shear stress-horizontal displacement curve for the tire powder treated soil under 50 kN/m^2 normal stress value. As it can be seen from the figure, unlike the other figures, the 10% curve gives the maximum shear strength as 37.33 kN/m^2 followed by the 20% and 30% curves which give almost the same shear strength value 35.55 kN/m^2.

All the figures in 39-44 except Figure 44 indicate that 20% tire buffing or tire powder is optimal to obtain the highest shear strength in the soils. The addition of 30% tire does not significantly increase the shear strength.

5.2.4 The Shear Strength Parameters: Internal Friction Angle (ϕ) and Cohesion (c)

In this section by using the shear stress-normal stress curves obtained for each sand-tire mixture under different normal stress values, the shear stress at failure will be obtained from these curves and the value of shear stress at failure will be plotted against the normal stress values. Then the shear strength parameters: the internal friction angle ϕ and cohesion c, will be obtained from the best line fitting the plotted points.

Table 14 and Table 15 given below are the two tables giving the shear stress at failure for sand-tire buffing and sand-tire powder mixtures prepared at 5% water content and 10% water content values respectively.

Table 14: The values of shear stress at failure for sand-tire buffing samples prepared at 5% water content

Normal Stress / Soil Type	20 kN/m^2	30 kN/m^2	50 kN/m^2
Pure sand	14.7	22.2	34.6
10% buffing	17.8	24.4	43.1
20% buffing	19.1	39.1	44.4
30% buffing	19.6	27.5	42.2
10% powder	14.7	26.6	36.8
20% powder	22.2	31.1	40.8
30% powder	18.7	27.5	32.4

Table 15: The values of shear stress at failure for sand-tire buffing samples prepared at 10% water content

Normal Stress / Soil Type	20 kN/m^2	30 kN/m^2	50 kN/m^2
pure sand	12.8	21.3	32.4
10%buffing	15.1	24	36
20%buffing	18.6	26.2	44
30%buffing	20	24.4	44.4
10%powder	17.3	25.3	37.3
20%powder	18.2	23.1	35.5
30%powder	17.3	26.2	35.1

The shear stress values in Table 14 and Table 15 are used and the shear strength versus normal stress values is drawn in Figures 45-48. Figure 45 and Figure 46 give the shear strength versus normal stress curves for the sand-tire buffing and sand-tire powder samples prepared at 5% water content respectively.

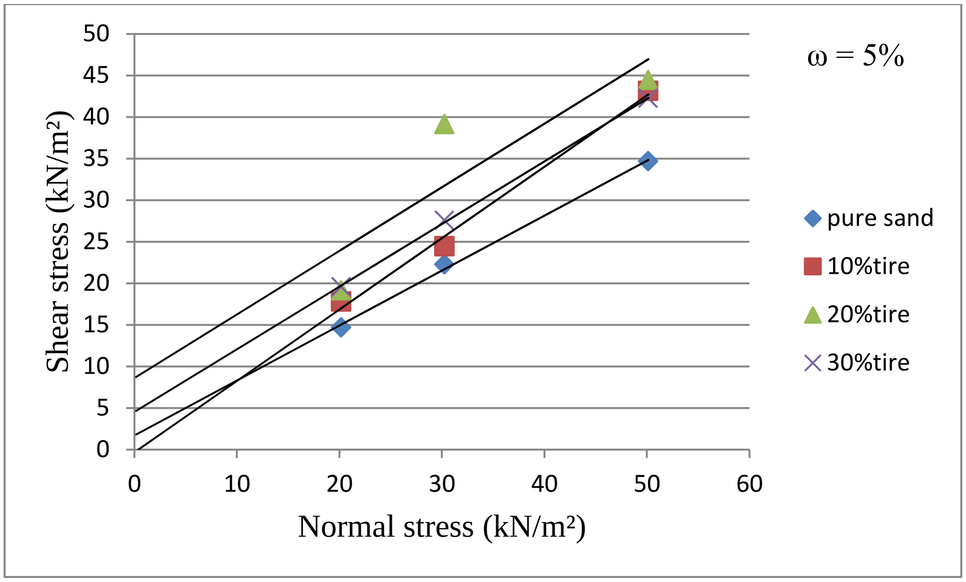


Figure 45: Shear stress-normal stress curve for pure sand and sand-tire buffing samples

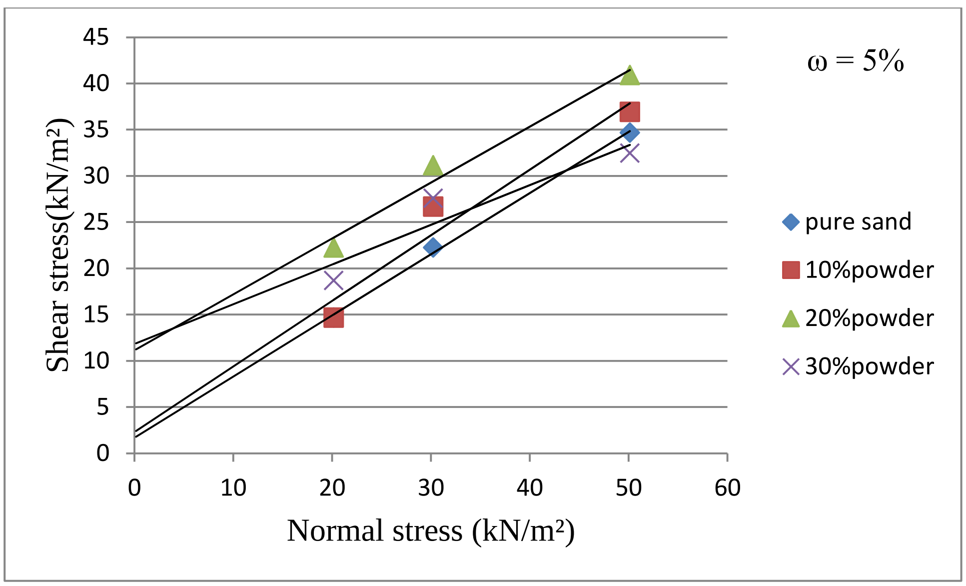


Figure 46: Shear stress-normal stress curve for pure sand and sand-powder samples

Figure 47 and Figure 48 give the shear stress versus normal stress curves for the sand-tire buffing and sand-tire powder samples prepared at 10% water content value.

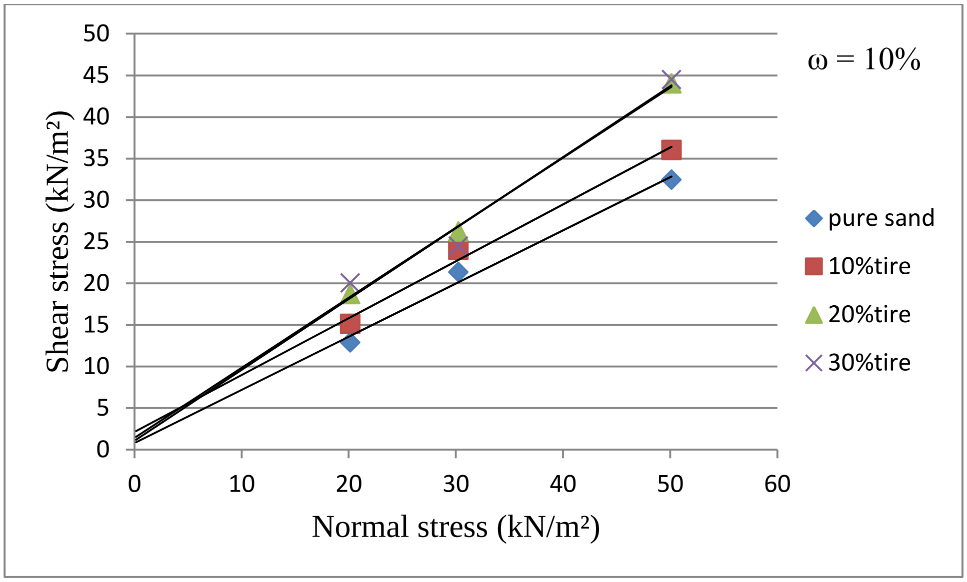


Figure 47: Shear stress-normal stress curve for pure sand and sand-buffing samples

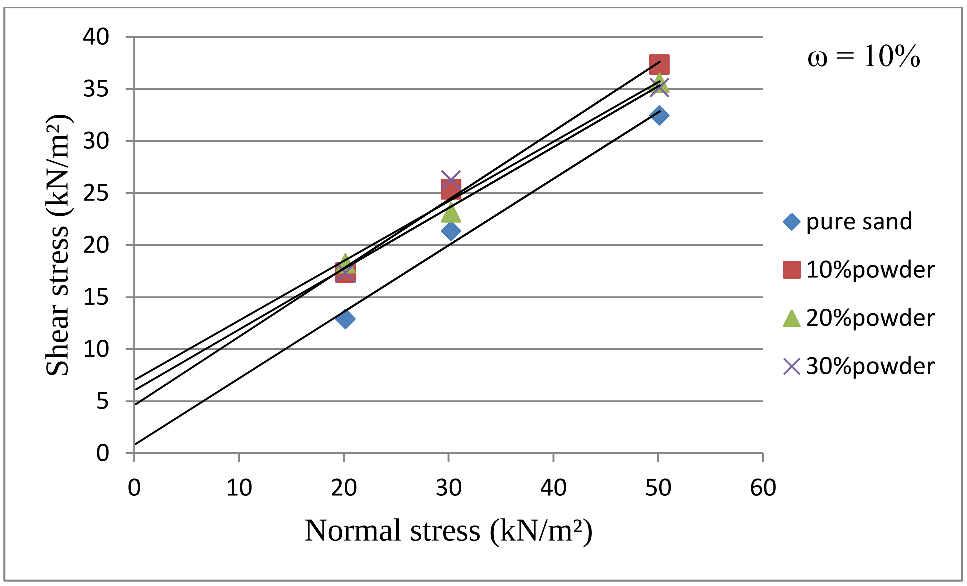


Figure 48: Shear stress-normal stress curve for pure sand and sand-powder samples

The shear stress parameters ϕ and c values determined from Figures 45-48 are given in Table 16-19.

Table 16: Internal friction angle, ϕ and cohesion, c values for pure sand and sand-tire buffing samples prepared at 5% water content

Tire buffing (%)	**Internal friction angle (Φ°)**	**Cohesion (kN/m^2)**	**Coefficient of determination (R^2)**
0	33.5	1.7	0.9992
10	40.4	0.0	0.9976
20	37.4	8.6	0.9091
30	36.9	4.5	0.9999

Table 17: Internal friction angle, ϕ and cohesion, c values for pure sand and sand-tire powder samples prepared at 5% water content

Tire powder (%)	**Internal friction angle (Φ°)**	**Cohesion (kN/m^2)**	**Coefficient of determination (R^2)**
0%	33.4	1.6	0.9992
10%	35.3	2.2	0.9804
20%	31.1	11.1	0.9909
30%	23.2	11.8	0.9549

Table 18: Internal friction angle, ϕ and cohesion, c values for pure sand and sand-tire buffing samples prepared at 10% water content

Tire buffing (%)	**Internal friction angle (Φ°)**	**Cohesion (kN/m^2)**	**Coefficient of determination (R^2)**
0	32.5	0.7	0.9958
10	34.3	2.1	0.9964
20	40.4	1.0	0.9994
30	40.0	1.4	0.9902

Table 19: Internal friction angle, ϕ and cohesion, c values for pure sand and sand-tire powder samples prepared at 10% water content

Tire powder (%)	**Internal friction angle (Φ°)**	**Cohesion (kN/m^2)**	**Coefficient of determination (R^2)**
0	32.5	0.0	0.9958
10	33.3	4.6	0.9982
20	30.3	6.0	0.9964
30	29.7	7.0	0.9655

All the figures and the outcomes of the tables above are used to draw the diagrams below in order to compare and find out the optimum percentage of tire buffing or tire powder mixture at different water content ratio.

Various diagrams have been represented below in order to compare different curves with various parameters.

Figure 49 gives the internal friction angle, ϕ obtained for the sand-tire mixtures prepared at 5% water content value. The figure compares tire powder and tire buffing internal friction angel, ϕ. Figure 49 indicates that in both curves ϕ is increasing with addition of 10% tire buffing and tire powder treatment and then at higher percentages of tire buffing and tire powder, ϕ value starts to decrease. The increase in ϕ value at 10% tire buffing is more pronounced than the increase in tire powder.

This increase in tire buffing mixture is because of the reinforcement role, which the buffing particles with their elasticity have. Although with increasing their percentage, this property is increasing, in the same time, the absorption of water by the tire materials is increasing too; this leads to a water-content less than the amount is needed to grease the sand particles in order to fit into each other to increase the interlocking feature. Thus in the mixtures of more than 10% of tire buffing, the internal friction angle decreases. (Das & Singh, 2012)

On the other hand, in the mixtures of tire powder, powder's small size, enables it to fill the void spaces between the sand particles. This leads to a well graded grain size distribution, hence a better compaction and a greater internal friction angle. Although this story explains the increase in the 10% mixture, adding more tire powder results into sand's particles become further hence decreases the interlocking feature (Yoon,et al. 2006) Moreover, tire powder particles have a smoother surface than sand grains, thus their internal friction is less than sand's and they slip on each other and decrease the internal friction angle of the mixture. Absorption of water by the tire material is another reason to decrease the water content of the mixture and like the tire buffing mixture, while the water content is 5%, this leads to a water content level less than the amount needed for greasing the sand particles. These three reasons result in decreasing the internal friction angle of mixtures with more than 10% tire powder (Das & Singh, 2012)

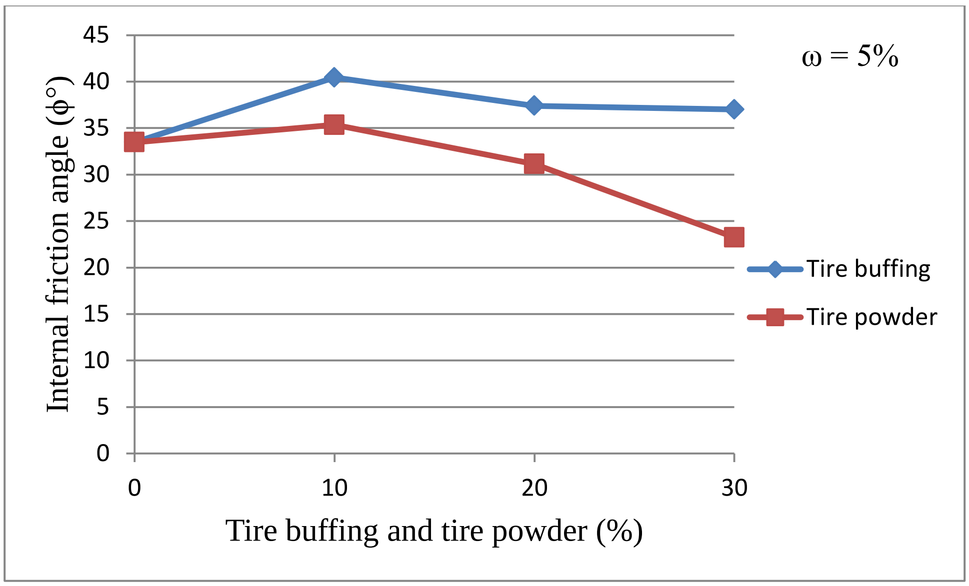


Figure 49: Internal friction angle, ϕ obtained for the sand-tire mixtures

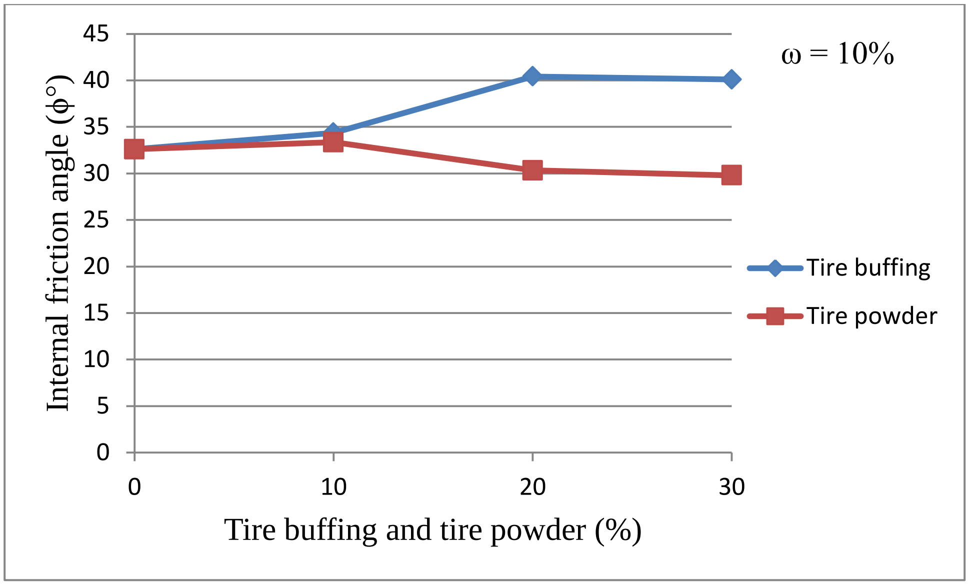


Figure 50: Internal friction angle, ϕ obtained for the sand-tire mixtures

Figure 50 gives the internal friction angle, ϕ obtained for the sand-tire buffing and sand-tire powder mixtures prepared at 10% water content value. The comparison of the two curves: tire buffing and tire powder at 10% water content, demonstrates that the addition of tire powder into the soil at 10% water content is not effective to improve the shear strength parameter, ϕ of this soil whereas a continuous increase in the ϕ value is obtained for the sand treated with different percentages of tire buffing. The figure indicates that the internal friction angle of this soil increases continuously with the increase in percent tire buffing. The increase at 10% tire buffing is not very significant but the figure indicates that at 20% tire buffing treatment, significant increase in the internal friction angle is obtained.

In the tests on samples with water content of 5%, absorption of water by 10% tire material results in water content near optimum amount, on the other hand, in samples with water content of 10%, this occurs in the presence of 20% tire material. Other reasons and effect which have been explained in the previous part are still resolute.

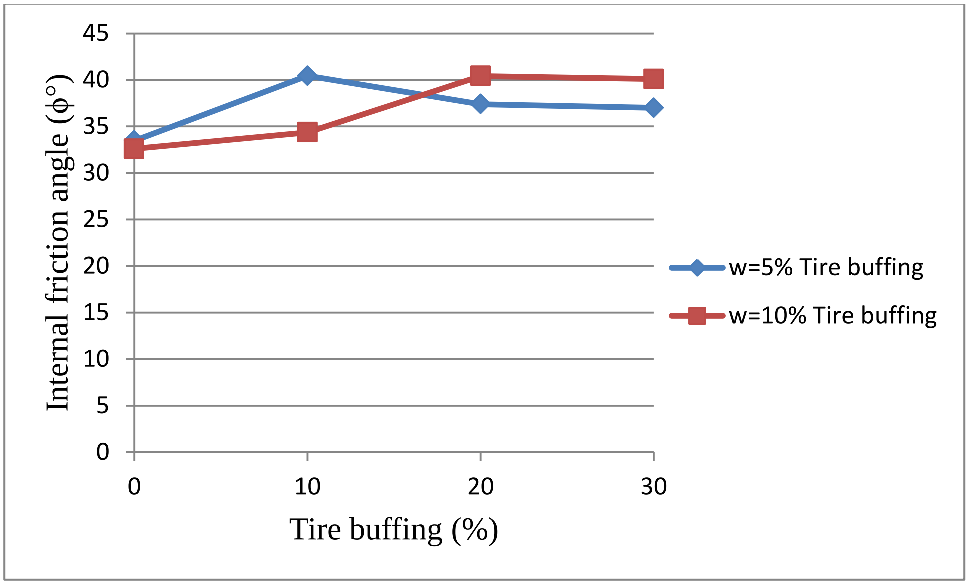


Figure 51: Comparison of the internal friction angle of the tire buffing treated soils at different water content values

Figure 51 gives the comparison of the internal friction angle of the tire buffing treated soils at 5% and 10% water content values. The figure indicates that the internal friction angle of the soil increases continuously at 10% water content value.

The figure shows that the sand-tire buffing mixture at 5% water content gives a maximum value at 10% tire buffing and then it shows reduction in the internal friction angle.

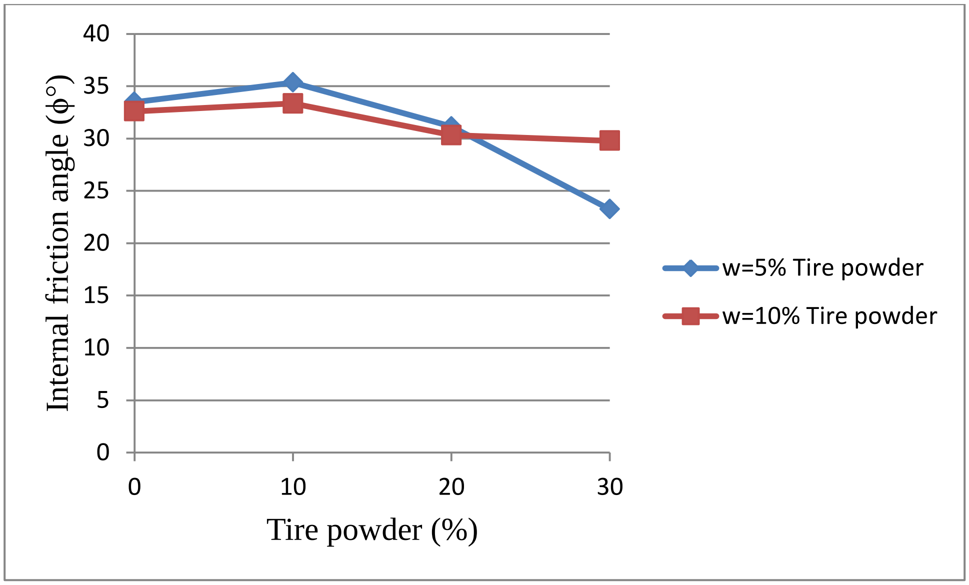


Figure 52: Comparison of the internal friction angle of the tire powder treated soils at different water content values

Figure 52 gives the comparison of the internal friction angle of the tire powder treated soils at different water content values. The figure indicates that 10% tire powder treated soil at 5% water content gives slightly higher internal friction angel than the samples at 10% water content. Then the internal friction angle of the same soil decreases with the increase in tire powder percentage. Figure 52 indicates that for the tire powder treated soils, 10% tire powder is optimal to obtain the greatest friction angle.

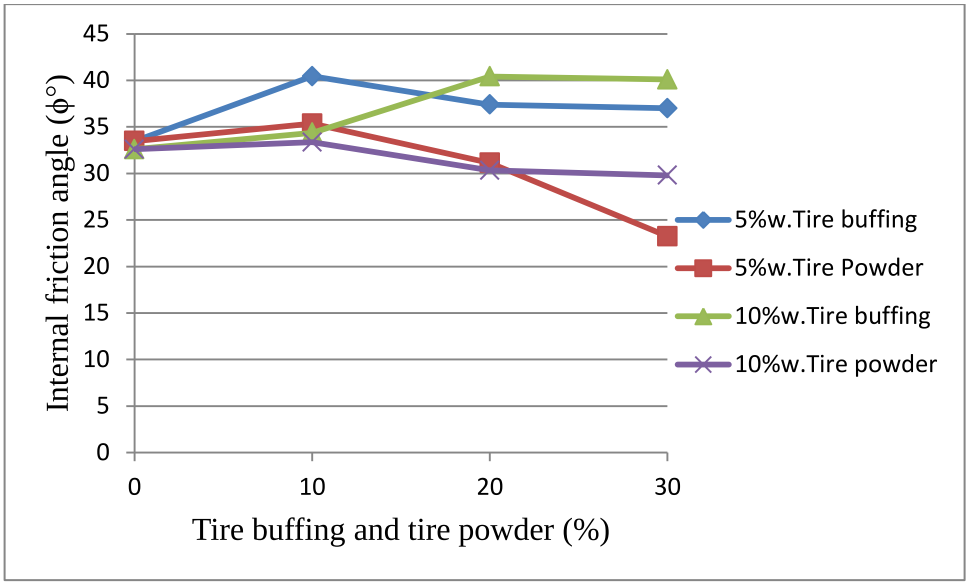


Figure 53: Comparison of the internal friction angle of the tire buffing and tire powder treated soils at different water content values

Figure 53 gives the comparison of the internal friction angle of the tire buffing and tire powder treated soils at 5% and 10% water content values. The figure illustrates the best and most improved sample and trend line by comparing all 4 types of mixtures. The comparison of the graphs in Figure 53 indicates that 10% tire buffing and 10% tire powder samples at both 5% and 10% water content values give the highest friction angle. The 10% tire buffing mixtures prepared at 10% water content values show different behavior and give higher friction angle above 10% tire buffing. The value obtained for 20% and 30% tire buffing mixtures is the same as the value obtained for the 10% tire buffing mixture prepared at 5% water content.

Figures 53 indicates that a greater internal friction can be achieved by adding tire buffing than tire powder this is because of the reinforcement role of tire buffing; furthermore, it can be understood that the optimum amount of added tire material is related to the water content since achieving the optimum water content after water gets absorbed by the tire material depends on the amount of the water content of the mixture.

Direct shear test results given in Table 16-19 indicate that both sand-tire buffing and sand-tire powder treated soils create more plastic material and produce an apparent cohesion in the soil. Due to the presence of the tire material in sand, the plasticity of the treated soils is enhanced because of the penetration of the sand particles into the tire grains. When shear stress is applied, the connection between the sand particles and the tire material is appeared in the form of cohesion. The apparent cohesion values given in Tables 16-19 are drawn against percent tire buffing and tire powder in Figures 54-57.

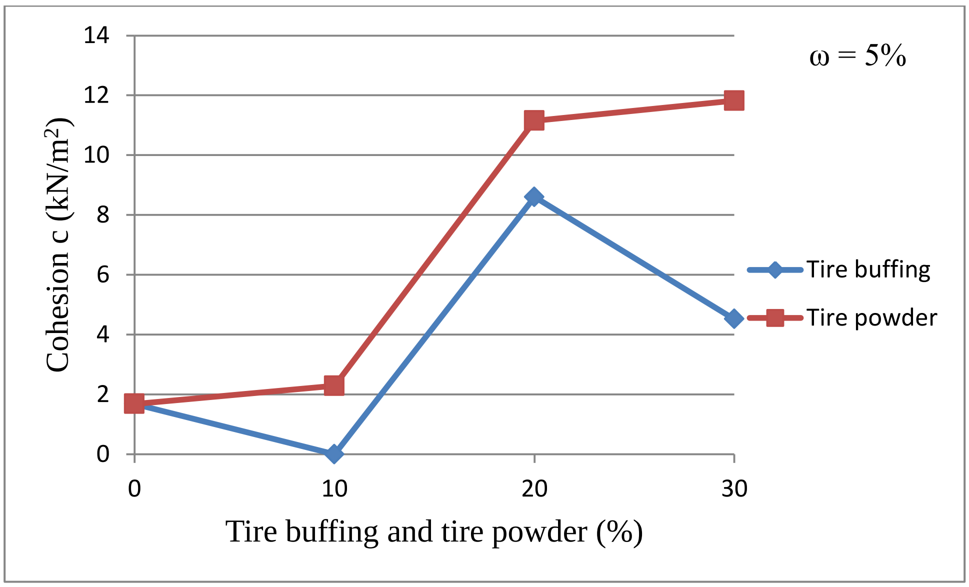


Figure 54: Apparent cohesion of the tire buffing and tire powder treated soils

Figure 54 gives the apparent cohesion values of the tire buffing and tire powder treated soils at 5% water content. The figure indicates that the apparent cohesion value of the tire powder treated soil is much higher than the tire buffing treated soil. That is due to the smaller particle sizes of the tire powder material which fills the void space of the soil and acts as a fine grained material and enhances the plasticity. As a result, higher apparent cohesion is obtained for the tire powder treated soil.

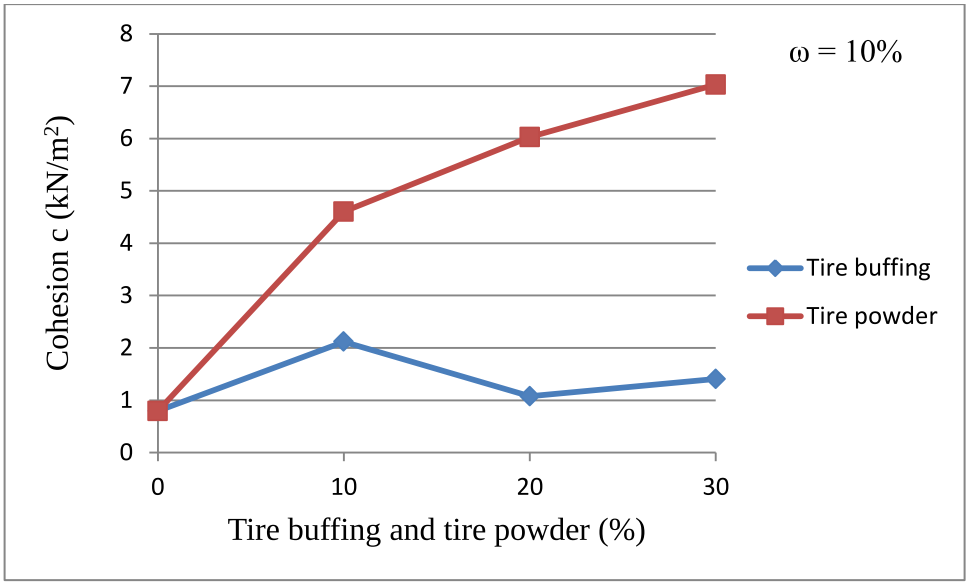


Figure 55: Apparent cohesion of the tire buffing and tire powder treated

Figures 54 and 55 indicate that regardless of the amount of water content, the sand with tire powder gives the biggest cohesion value and the apparent cohesion of this soil increases continuously with the increase in the percentage of tire powder.

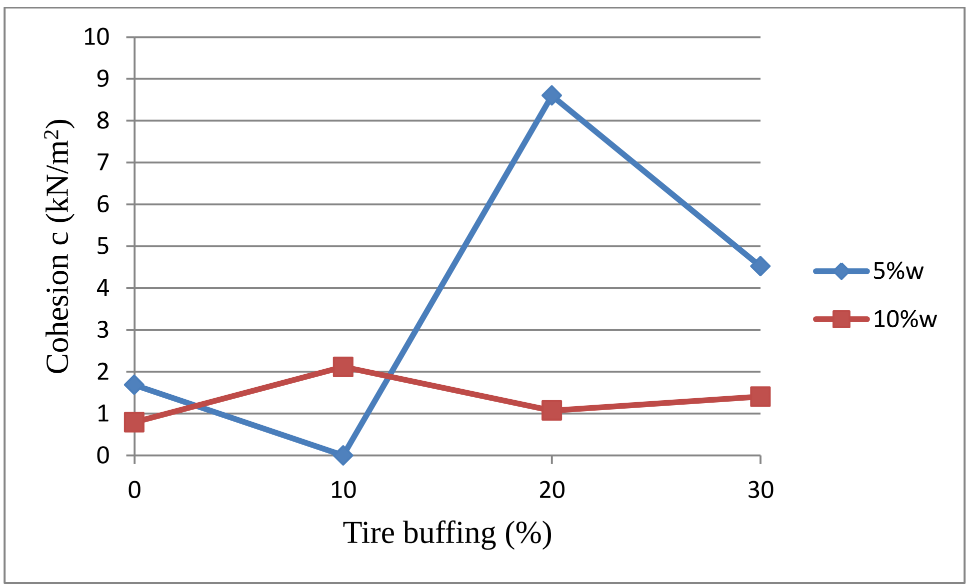


Figure 56: Comparison of the apparent cohesion values of the tire buffing treated soils at different water content values

Figures 56 and 57 compare the tire buffing treated and tire powder treated soils according to their water content level, respectively. The results obtained in both figures indicate that the apparent cohesion value is bigger in all the soils prepared at 5% water content value than the soils prepared at 10% water content except that at 10% tire mixtures. That can be explained due to the increased amount of water which may cause the breakage of the link between the sand particles and the tire materials and a consequent reduction in the cohesion value. Unlike the other percentage of sand-tire mixtures, at 10% water content, the 10% tire-buffing and 10% tire-powder treated soils give lower cohesion value than the same soils at 5% water content.

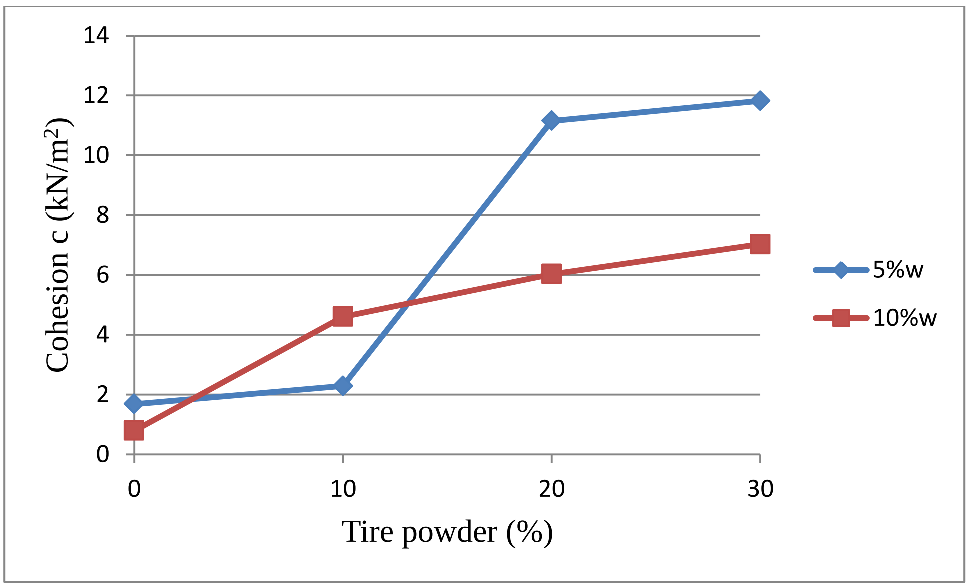


Figure 57: Comparison of the apparent cohesion values of the tire powder treated soils at different water content values

5.3 California Bearing Ratio, (CBR) Tests Results

This section will discuss the results of the CBR test which has been conducted on 8 different samples that can be categorized into 2 groups with 5% and 10% water content , each group consist of 4 samples which has been reinforced using tire buffing (0%, 10%, 20%, 30%).

Depicting the results of the test on different graphs, results will be compared and the best sand-tire mixture will be defined.

5.3.1 Samples Prepared at 5% Water Content

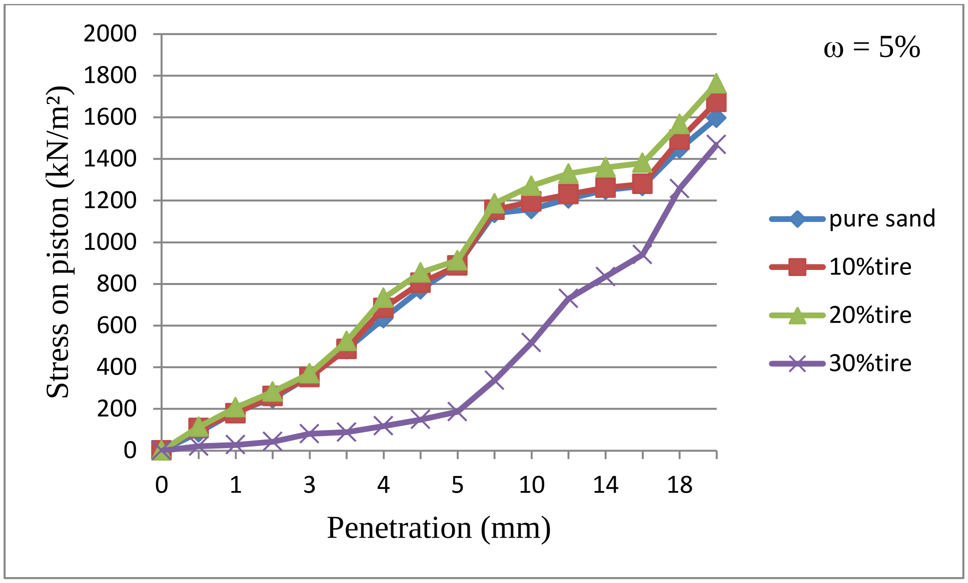


Figure 58: Stress on piston versus penetration values of the sand-tire buffing treated specimens

Figure 58 illustrates the outcomes of the CBR test over the sand-tire buffing treated soils at 5% water content value. The results indicate that addition of tire buffing into the sand does not improve the CBR value of the treated soils. Even, 30% tire buffing treatment make the condition worst and increases the penetration value.

5.3.2 Samples Prepared at 10% Water Content

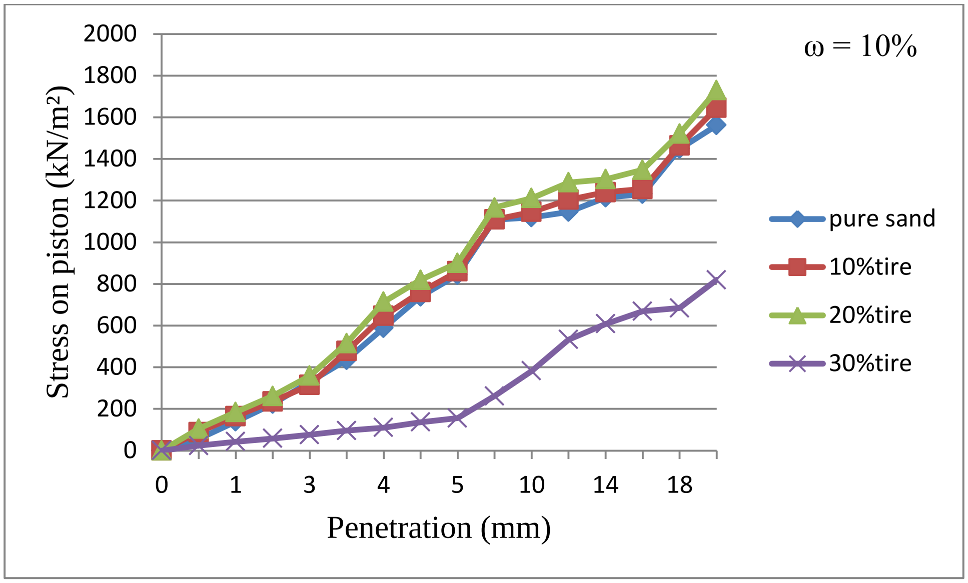


Figure 59: Stress on piston versus penetration values of the sand-tire buffing treated specimens

Figure 59 gives the stress on piston versus penetration values of the sand-tire buffing treated specimens at 10% water content. The curves in this figure indicate that similar behavior is obtained as in Figure 58 That is no significant change in CBR value is obtained for the tire-buffing treated soils. The figure shows that 20% tire buffing sample shows slight improvement in CBR value whereas 30% tire-buffing treatment makes the condition worst and results in more penetration. From Figure 58, it is clear that addition of tire buffing to sand does not improve the penetration resistance of the treated soils. But since sand-tire mixtures are lightweight materials and they apply less lateral earth pressures on retaining walls in comparison with those exerted from sand alone (Tweedie et al. 1998; Lee et al. 1999; and Ghazavi 2004), application of tire buffing into the sand is still promising.

Figure 59 gives the comparison of CBR test results for sand-tire buffing treated soils prepared at 5% and 10% water content at 20mm penetration value. The bar chart shows that the sand-tire buffing treated samples prepared at 5% water content value give higher vertical stress which means that lower penetration is obtained under higher vertical stress values. As it can be seen from the figure the 30% tire buffing is not recommended for improving the penetration resistance of the sand.

5.3.3. California Bearing Ratio, (CBR) number

In this section, using the results of the CBR test and previous figures, the CBR number will be calculated and the results will be presented and discussed in the following figures.

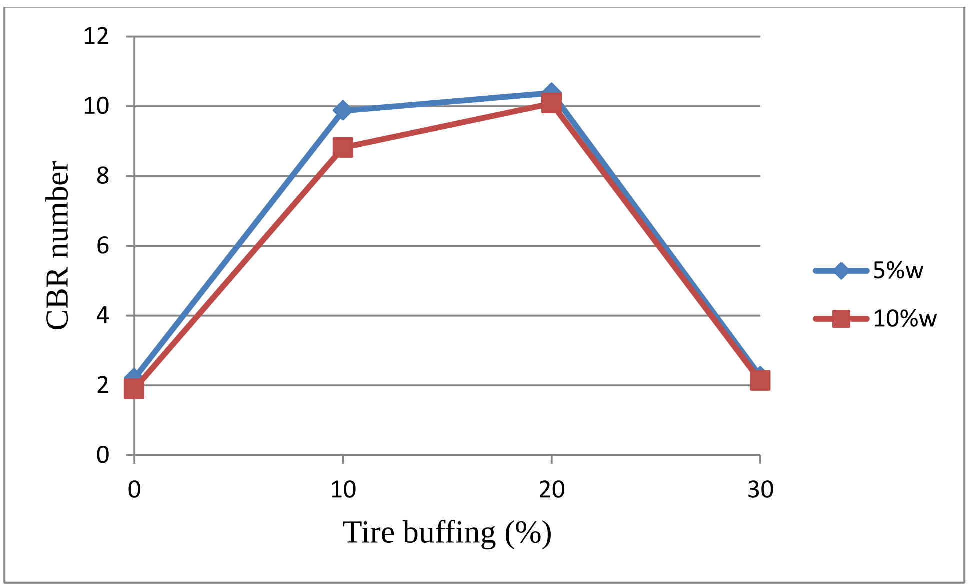


Figure 60: CBR number calculated at 2.54mm penetration value

Figure 60 gives the CBR number for the sand-tire buffing mixtures prepared at different water content values. The CBR values represent the results calculated at 2.54 mm penetration value. The curves show a significant increase in CBR number from 0 to 20% tire buffing then the CBR number decreases drastically at 30% tire buffing. However, because the value of the CBR at 5 mm penetration is more than these values, the CBR of 5 mm should be used.

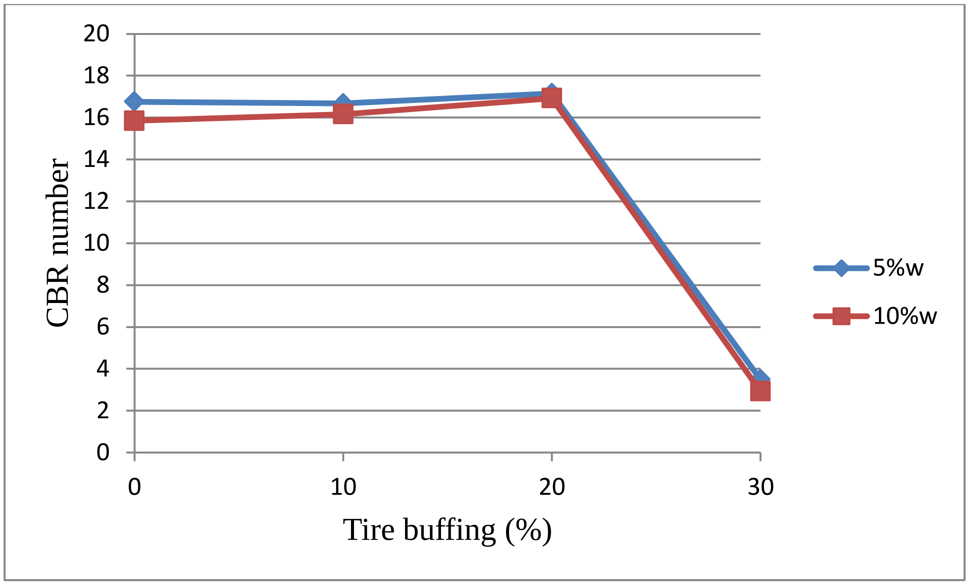


Figure 61: CBR number calculated at 5.08 mm penetration value

Figure 61 gives the CBR number for the sand-tire buffing mixtures prepared at different water content values. The CBR values represent the results calculated at 5.08 mm penetration value. The figure illustrates that the CBR number does not change much with 10% tire buffing and it shows slight increment with the addition of 20% tire buffing and then at 30% tire buffing, the CBR number decreases drastically.

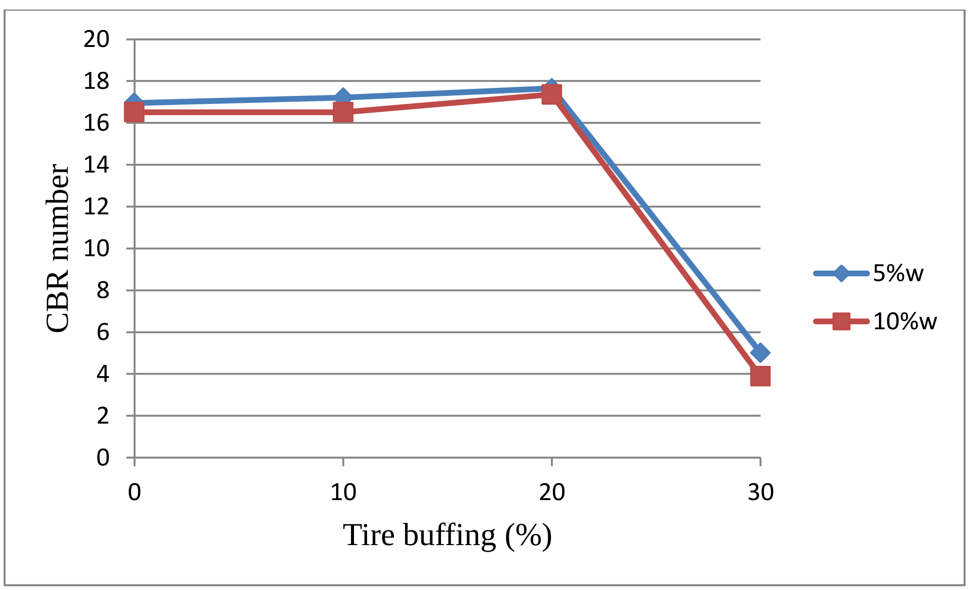


Figure 62: CBR number calculated at 7.62 mm penetration value

In Figures 62-64, the CBR numbers calculated at 7.62, 10.16 and 12.70 mm penetration value are given respectively. From the figures, it can be seen that the same behavior is obtained for the CBR numbers calculated at different penetration values. This means that 10% tire buffing does not change the CBR number much and with 20% tire buffing treatment, slight increment in the CBR number is obtained and then at 30% tire buffing, the CBR number shows a drastic reduction.

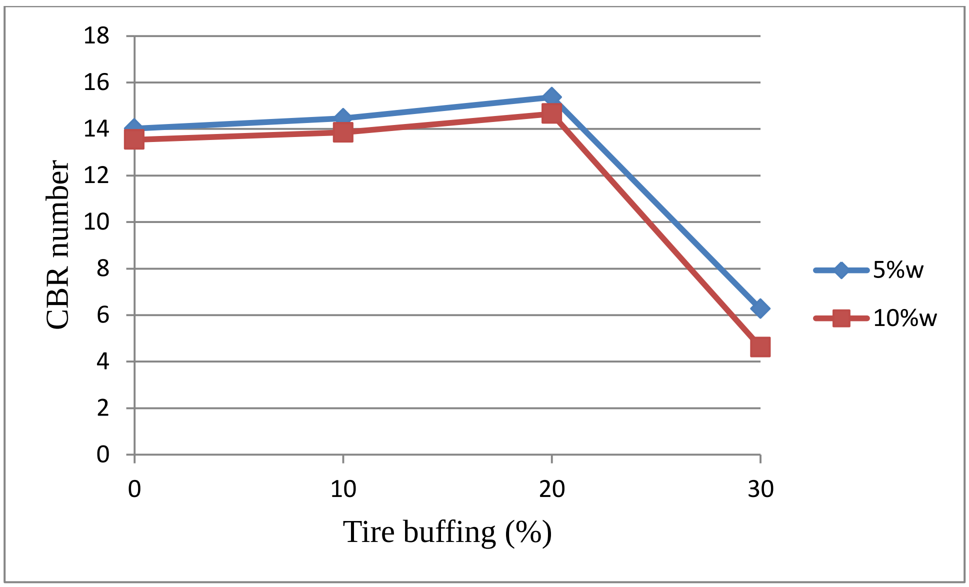


Figure 63: CBR number calculated at 10.16 mm penetration value

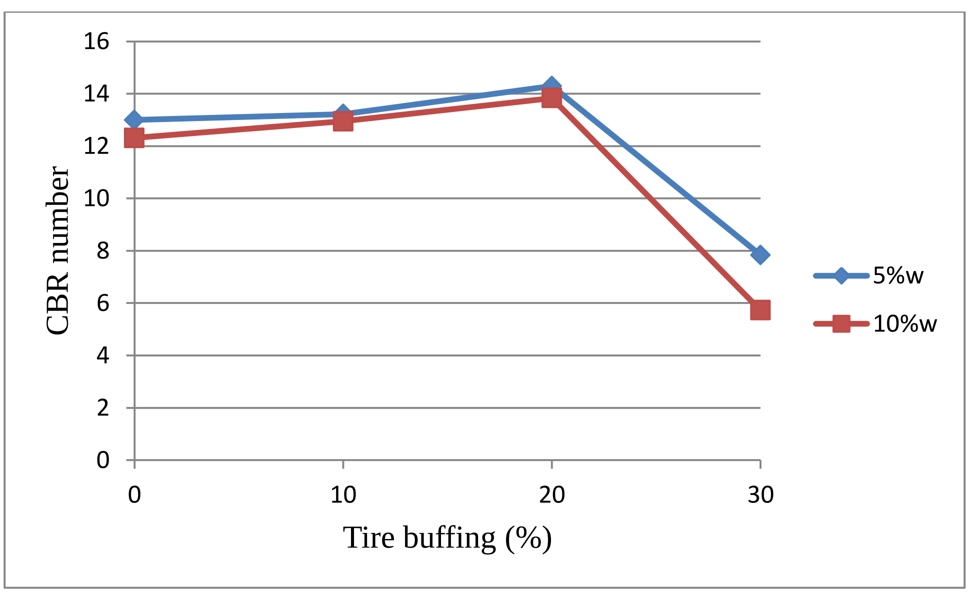


Figure 64: CBR number calculated at 12.70 mm penetration value

Figures 62-64 indicate that the maximum CBR number belongs to the 20% tire buffing treated samples prepared at 5% water content. Regardless of the water content value, CBR number for the 30% tire buffing treated soil reduces drastically.

Chapter 6

CONCLUSIONS

6.1 Conclusion

The application of recycled tire waste has a positive effect on the engineering properties of the poorly graded sand. Tire buffing and tire powder have the potential to improve the strength and the bearing capacity of the treated sand.

Based on the test results, the following conclusions can be drawn:

1. Increasing the amount of tire buffing increased the shear strength parameters; however, its optimum amount depended on the moisture level of the mixture.
2. Since the slip resistance of soil is proportional to the applied normal force, by increasing the normal stress in the tire buffing treated sands, an increase in the ultimate shear strength was obtained. The stress-strain diagrams of the soil treated with different percentages of tire powder at higher normal stress values gave a clear peak similar to dense sand behavior.
3. The shear stress-shear displacement curves of the tire powder treated soils do not show a distinct peak in shear stress. There are no dilation characteristics in powder treated sands. That might be due to the very fine particles of the tire powder which completely fills the void space of the powder treated soils and prevents the sliding of the sand particles over the others. Adding up to 10 % of

tire powder to a sand sample slightly increases the shear strength parameters of the mixture, however, adding more than this amount has a decreasing effect.

4. Direct shear test results indicated that both sand-tire buffing and sand-tire powder treated soils created more plastic material and produced an apparent cohesion in the treated soils. Due to the presence of the tire material in sand, the plasticity of the treated soils was increased because of the penetration of the sand particles into the tire grains. When the shear stress was applied, the connection between the sand particles and the tire material was appeared in the form of cohesion.
5. The maximum CBR number was obtained for the 20% tire buffing treated samples prepared at 5% water content. Regardless of the water content value, CBR number for the 30% tire buffing treated soil decreased drastically. Test results indicated that addition of tire buffing into the sand did not improve the CBR value of the treated soils considerably. Even, 30% tire buffing treatment made the condition worst and increased the penetration value. But since sand-tire mixtures are lightweight materials and they apply less lateral earth pressures on retaining structures, application of tire buffing into the sand is still encouraging.

6.2 Further Studies

In this thesis, the effect of tire buffing and tire powder have been studied separately, influence of adding them simultaneously to the mixture can also be evaluated in further studies.

Since adding more than 30% of tire buffing, leads to a severe decrease in the bearing capacity, effect of another material in addition to tire buffing on the compressibility of the mixture can be studied further.

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