

DETERMINATION AND ASSESMENT OF SHEAR STRENGTH PARAMETERS OF
SAND WITH TIRE WASTE INCLUSIONS

by

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ABSTRACT

Using tire wastes as lightweight material in constructions is a good alternative to benefit them rather than disposing as waste. Thus, many economical, environmental and technical advantages are gained. To use tire wastes as construction materials, they are processed and different sizes of tire wastes are produced. Until now many studies have been done but it is still not very clear about the shear strength parameters and characteristics of tire wastes.

The objective of this study is to investigate the possibility of using tire wastes to reinforce sand. Large-scale direct shear tests were conducted on the mixtures of dry sand, tire crumb and tire buffings. The following factors were studied to evaluate their influence on shear strength; normal stress, tire waste shape and tire waste content. On the basis of experimental results, it is seen that the inclusion of tire waste to the sand increased the shear strength parameters.

ÖZET

Lastik atıklarını hafif ağırlıklı yapı malzemesi olarak kullanmak, onlardan faydalanmak için iyi bir seçenektir. Böylece birçok ekonomik, çevresel ve teknik avantaj sağlanabilir. Atık lastikler, yapı malzemesi olarak kullanılabilmesi için işlemlerden geçirilir ve değişik boyutları oluşturulur. Şu zamana kadar atık lastikler hakkında birçok çalışma yapılmasına rağmen hala tam olarak kuvvet parametreleri ve çeşitli özellikleri tam olarak bilinmemektedir.

Bu çalışmanın amacı, atık lastikle mevcut kumun kuvvetlendirilme olasılığının incelenmesidir. Kuru kum, lastik kırıntıları ile karıştırıldı ve bu karışımlara büyük ölçekli direk kesme deneyleri uygulandı. Kesme kuvveti üzerindeki etkilerini incelemek için şu faktörler incelendi; normal basınç, atık lastik şekli ve miktarı. Deneysel sonuçların ışığında atık lastiklerin kumla kullanımının kesme kuvveti parametrelerini arttırdığı görülmüştür.

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LIST OF SYMBOLS/ABBREVIATIONS

c	Cohesion of material
γ	Unit weight of material
ϕ	Angle of internal friction of the material
ASTM	American Society of Testing Materials
FEM	Finite Element Method
HDPE	High Density Polyethylene
LCRS	Leachate Collection and Removal System
MSW	Municipal Solid Waste
TB1	Tire buffing with sizes between 2mm and 4mm
TB2	Tire buffings with the sizes greater than 4mm
USEPA	United States Environmental Protection Agency

1. INTRODUCTION

1.1. General

Due to the developing industry and growing population, huge amounts of wastes are produced. And, as the amounts increase, it becomes harder and more expensive to dispose them safely without threatening ecology. So, recycling and reuse of these waste materials become more popular. Usage of these waste materials; prevents depletion of the natural resources, avoids the disposal costs of these wastes, avoids the environmental problems and gives these wastes an economical value.

There is a rapid increase in the number of used tires each year and this leads to an important environmental problem. So, ways to utilize these tire wastes in large volumes are being investigated. Using them as construction materials in civil engineering applications is a common way that has been studied for many years. The lightweight and high drainage characteristics of tire waste lead them to be used as construction materials in embankments. Tire wastes are used as whole tires or as processed tires. Processed tires form tire shreds, tire crumbs, chips and buffings.

For the design of an embankment, the soil characteristics must be considered in two ways. First, the soil must have the required strength to withstand the embankment weight in order to be a safe construction. And as a second point, the soil must be stable, not compress excessively in a short or long time period.

If the embankment weight is more than the bearing capacity of the soil, then construction will collapse. So, to overcome such a problem, the weight of the embankment must be transferred to another soil stratum that is able to bear the load. This may be achieved by changing the location of the construction, or improving the soil, or using construction methods such as piling. Also another way of overcoming this overburden weight is to decrease the weight of the embankment until reaching the required allowable bearing capacity of the soil.

Secondly, the excessive settlement due to the consolidation of the soil must be avoided in an embankment construction. Increasing the permeability of the soil, or adding drainage systems to the construction, or adding surcharge weights over the embankment during constructing period are some methods that may be used.

This thesis aims to evaluate the shear strength parameters of the tire waste by-products, tire crumb and tire buffings, mixed with clean sand in certain proportions to be used in embankments as construction materials.

1.2. Problem Statement

Types of lightweight materials are many and all around the world physical properties of them are investigated in order to use the right material in the right place. Also in the last years, the lightweight material concept coincided with an environmental problem of getting rid of the scrap tires. Scrap tires reached huge deposits all around the world and still the deposits are increasing in number and this creates a hazardous environmental effect. Although governments take some precautions against tire pollution (reducing them in size and numbers), more deposits are generating in serious amounts. A great alternative is to process them in a specific manner and use them as fill materials in specific civil engineering applications, especially in embankment constructions. Shredded tires are mixed with sand. As a result, a strong mixture is achieved which is stronger than the soil or the tires alone. Because the mixture is lighter and stronger, this directly translates into cost savings. The unit cost of the mixture gets cheaper and also savings in construction materials are achieved. The other identified advantages of scrap tires as fill material are thermal insulation, high drainage ability.

1.3. Objective of the Thesis

The thesis mainly focuses on determining the possibility of using tire waste to reinforce sand. Lightweight materials as tire crumb and tire buffings, manufactured by processing the tire waste were used to determine the shear strength parameters. A brief study about certain types of lightweight materials and then a deeper look at the tire waste reuse as a lightweight material is followed throughout the thesis. At the last sections, the

laboratory results are evaluated and a summary for the shear strength characteristics of the specific lightweight materials as tire crumb and tire buffings, is given.

1.4. Organization of Thesis

The thesis starts with the general information about the lightweight aggregates and continues with the literature study about the tire wastes. The experimental procedures and results are included in further sections and finally a summary section is included conducting the test results with the previous studies about the tire waste usage as embankment material.

2. LITERATURE REVIEW

2.1. Why Using Lightweight Aggregates?

The usage of lightweight aggregates is a requirement for a construction in order to gain overall load reduction and improving strength parameters of the soil, thus, exceeding the bearing capacity of the soil and excessive embankment settlement is avoided. Also lightweight aggregates improve other properties of the soil like insulation, drainage and etc. However this situation may be coped with alternative solutions. These are:

- Relocation of the Construction
- Soil Improvement
- Reinforcing the Construction
- Reduction of the Weight

2.2. Commonly Used Lightweight Aggregates Other Than Tire Waste

2.2.1. Expanded Polystyrene

Expanded polystyrene has been used extensively in block form in Alaska, the United Kingdom, and Scandinavia (in Figure 2.1. an EPS road construction is seen). The benefits of using EPS are not limited to the load reduction only in embankments. Control of frost penetration and ground thawing beneath roadways is also achieved when placing EPS sheets in predominantly horizontal layers. This type of application is of particular interest in permafrost areas, where road embankments can substantially change the freezing and thawing characteristics of the underlying ground.

Thompsett et al. (1995) presented the history of the use of EPS in road embankments in Europe, including a description of acceptable use of EPS blocks as specified in design requirements in the United Kingdom.

According to Thompsett et al., the first use of EPS in a fill occurred near Oslo in 1972. Prior to that, the embankment's rate of settlement had increased with each year, and at the time of reconstruction with EPS fill, the rate of settlement was between 200 and 300mm/year. The reconstructed roadway had an initial rate of settlement of 80mm/yr for the first year after reconstruction, with no significant additional settlement in the following twelve years. This success led to extensive testing and use of EPS as a lightweight fill.

The application of EPS blocks in embankments has now become a standard practice in Norway and Sweden. An additional benefit is the material's very low Poisson's ratio, simplifying the design of retaining walls or abutments, since minimal lateral stresses are transmitted when these blocks are placed adjacent to rigid walls.

Limitations of this method include the necessity of using labor to hand-place and cut to size the EPS blocks as shown in Figure 2.1. Since the material must be stockpiled on site, care must also be taken to protect it from excessive ultraviolet light, solvents or heat, EPS blocks *cannot* be used as fill below the water level in an embankment since its density is significantly lower than that of water. Buoyant forces could cause heaving problems in the embankment. Compressive stresses for typical EPS of varying densities range from 50 to 220 kPa. Most peak stresses were developed within 5 per cent vertical strain.

Esch (1990) summarized the service history of an EPS-insulated road in Alaska over twenty years, discussing the beneficial effects of using EPS for insulation. Insulation under frost-susceptible soils reduces the penetration of frost, and reduces the resultant frost heave. It also reduces ground thawing in permafrost regions, as the summer heat is prevented from warming the soil underlying an exposed roadway. The EPS boards used in this application were only 51mm thick, and therefore had negligible impact on the weight reduction of the embankments.

EPS Advantages;

- **Ultra-Lightweight EPS:** it weighs only 1.00-2.00 lb/ft³, approximately 1 per cent the density of soil or rock.

- **Reduced Construction Times:** EPS construction is very fast, particularly beneficial with compressed project timelines.
- **Predictable Material Behavior:** EPS is an engineered product, unlike other lightweight fill materials that can be variable in composition.
- **Non-Biodegradable:** EPS physical properties will not degrade, assuring long-term performance in engineered geotechnical applications.
- **Inert:** EPS will not leach into surrounding soils or groundwater and provides no nutritive value for plants or animals.



Figure 2.1. Construction of geofilm road embankment

2.2.2. Expanded Shale, Clay and Slate Lightweight Aggregate

For almost 50 years Rotary Kiln produced Expanded Lightweight Aggregate (LWA) has been effectively used to solve geotechnical engineering problems and to convert unstable soil into usable land. Lightweight aggregate can reduce the weight of compacted geotechnical fills by up to one-half. Where thermal stability is required, LWA provides significantly greater thermal resistance when compared to soil, sand or gravel fill. It affords permanent economical insulation around water lines, steam lines and any other

thermally sensitive vessel. This inert, durable, stable, free-draining and environmentally "friendly" lightweight aggregate is extremely easy to handle and provides economical long term solutions for geotechnical challenges. Figure 2.2 illustrates examples of the expanded clay & shale.

Expanded shale, clay and slate lightweight aggregate (LWA) has a long track record of quality and performance. Since its development in the early nineteen hundreds, LWA produced by the rotary kiln process has been used extensively in asphalt road surfaces, concrete bridge decks, high-rise buildings, concrete precast/prestressed elements, concrete masonry and geotechnical applications. The quality of LWA results from a carefully controlled manufacturing process. In a rotary kiln, selectively mined shale, clay or slate is fired in excess of 2000° F. The LWA material is then processed to precise gradations. The result is a high quality, lightweight aggregate that is inert, durable, tough, stable, highly insulative, and free draining, ready to meet stringent structural specifications. The resulting particles are spherical to subangular in shape, durable and chemically inert. It can be used to replace regular granular material, and its only limitation is that it can not withstand compressive stress to the same degree as regular granular material. Nevertheless, it has been used in construction where materials with lightweight properties were required Baker, 1996; Stoll and Holm, 1985.

Stoll and Holm (1985) tested expanded shale aggregate from six different locations around the United States in triaxial compression and found the materials to have internal angles of friction between 44.5° and 48° in compact condition, with internal angles of friction varying to from 39.5° to 42° for loose material. The densities ranged from 700 to 908 kg/m³ for loose samples, and 828.5 to 1042 kg/m³ for dense samples. The average minimum and maximum densities were 793 and 899 kg/m³. They also found that the stress-strain curve for a consolidation test changed slope at about an axial stress of 100 kPa, corresponding to a degradation of the material at that stress.

Valsangkar and Holm (1990) confirmed these results for internal angles of shear in direct shear tests. Materials tested were all uniformly graded.

Design Advantages are;

- Reduces Dead Loads,
- Reduces Lateral Forces,
- Reduces Over Turning Forces,
- Provides High-Friction Angle,
- Controlled Gradations,
- Free Draining,
- Water Insoluble,
- Acid Insoluble,
- High Insulation Value,
- Chemically Inert,
- High Strength & Durability,
- Easy to Handle and Install,
- Readily Available,
- Environmentally "Friendly".



Figure 2.2. Expanded Clay & Expanded shale

3. GENERAL INFORMATION ABOUT TIRE WASTE

3.1. Introduction

Only in Europe 2 000 000 tons of end-of-life tires are generated each year and these need to be recycled or disposed, ETRMA (2006a). Besides the on-going generation of new end-of-life tires there are in many countries historical stockpiles that need to be taken care of in order to reduce the risk of fire and environmental concern from leachate in stockpiles (Figure 3.1.). In figure 3.2. it is shown the recovered end-of-life tires, including historical stockpiles, in the EU and Japan year 2004 and the U.S. 2003.



Figure 3.1. Since 1996 over 2.5 million scrap tires have been collected and recycled in Saskatchewan

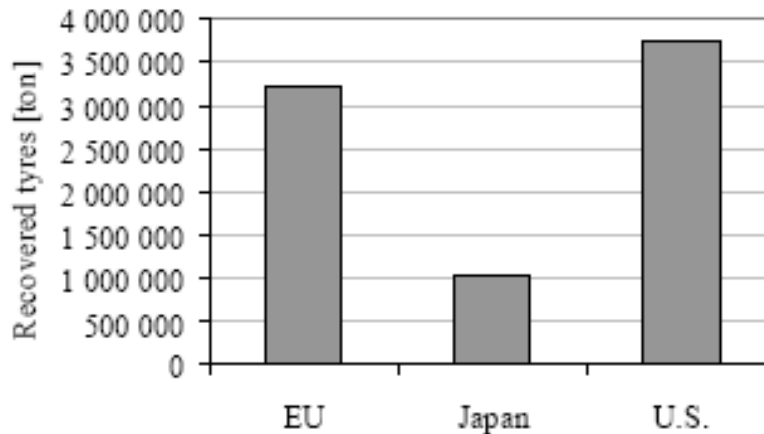


Figure 3.2. Recovered end-of-life tires within the EU and Japan year 2004 and in the U.S 2003, ETRMA (2006)

Perhaps the easiest way of disposing tires is by landfilling. Tires are however not suitable for landfilling since the volumes are large, rubber almost non-degradable and possess a large energy value that aggravates landfill fires. This growing disposal problem has been noticed by the environmental authorities in a number of countries and legislation acts has been taken to encourage other disposal options than landfilling, e.g. by banning tire material on landfills within the European Community, Eur-Lex (1999). The intention of the legislation is to encourage Best Management Practices (BMP) for the reuse of end-of life-tires and to reduce the occupation of valuable deposit space in the landfills by tire wastes. This strategy is also used in other parts of the world, e.g. individual states in the USA, USEPA (2006). Tires as a disposal problem have also been discussed within the United Nations Environmental Programme (UNEP), resulting in technical guidelines for BMP of scrap tires, UNEP (2002). Among the listed options in the technical guidelines is use of tire wastes as construction material listed.

Re-use of end-of-life tires has been utilized ever since rubber tires were invented, e.g. as bumpers in harbors, shoe soles in under developed countries and as swings on playgrounds for children. Common large-scale disposal options, besides using tire wastes or whole tires as construction material and landfilling, are energy recovery in e.g. the cement industry or incineration. These options will always serve as alternatives to other use but are limited in incineration capacity and transportation costs.

The use of tire wastes in construction work has been tested since the 1980's, mainly as a road insulation material, lightweight fill material and as drainage layers in landfills, e.g. MPCA (1990), Manion and Humphrey (1992). The experiences showed that the use of tire wastes were beneficial from engineering and economical aspects and that the leaching, based on the studied elements and compounds, is a minor problem.

Based on the positive experiences, mainly from the U.S.A. and Canada and the encouraging regulations towards alternative disposal options, tire wastes as construction material could be of interest in Europe and Turkey.

Tire wastes are fragmented end-of-life tires, mainly from passenger cars but also from heavy vehicles. The fragmentation is performed by a shredder. Primarily tires are shredded for volume reduction before transportation to recovery or disposal processes. The size of the individual wastes is controlled by sieving and re-shredding of coarse wastes. The first pass results in 100-300mm large tire wastes, the second pass results in 100-150mm and finer tire wastes are re-processed until the material passes the desired sieve size. The result is disc shaped tire wastes with protruding steel cord. Smaller tire wastes have relatively more protruding steel cord compared to coarser fractions, figure 3.3.



Figure 3.3. Different sizes of tire wastes

In the USA there is an established standard for nomenclature and determination of some of the technical properties, ASTM (1998), and in Europe the work with establishing a common standard is now in progress. These two standards will to some extent differ in nomenclature and procedures to determine properties. In table 3.1., the suggested European standard nomenclature and the established standard nomenclature in the USA are given.

Table 3.1. Designations for different sizes of processed tires in Europe, Post-consumer tire materials, CEN (2004), and in the USA, ASTM (1998).

prEN 14243:2004 (Europe)		ASTM D 6270-98 (USA)	
Designation	Size	Designation	Size
Fine powder	<500 μm	Granulated	425 μm –12 mm
Powder	<1 mm	Ground rubber	425 μm –2 mm
Granulate	1–10 mm	Chip	12–50 mm
Chip	10– 50 mm	Shred	50–305 mm
Shred	50–300 mm	Rough shred	50×50×50 < X < 762×50×100

3.2. Environmental problems with tire waste stockpiles

3.2.1. Mosquitoes

Mosquitoes have long been identified as pests and vectors of disease. Waste tires are breeding grounds for mosquitoes. Because of their shape and impermeability, waste tires can hold water for long periods of time, providing sites for mosquito larva development.

3.2.2. Fire hazards

Tire fires are dangerous because of the difficulty with extinguishment. A whole waste tire presents a void space of 75 per cent, which makes it difficult to either quench the fire with water or cut off the oxygen supply. Water on tire fires often increases the production of pyrolytic oil, provides a mode of transportation to carry oils off site, and aggravates contamination of soils and water. Air pollutants from tire fires include dense black smoke, which impairs visibility, and toxic gas emissions. Tire fire by-products may cause contamination of surface and subsurface water and soils.

3.3. Tire Wastes Used In Construction

3.3.1. Whole Tire Wastes Used In Construction

3.3.1.1. Reefs and breakwaters. A project in Ft. Lauderdale, Florida, U.S. alone has used 3 million tires and annually adds one million tires per year to reefs. Enthusiasm for this use

has waned, and discarded tire reefs are now only built in minimal numbers. Currently, an estimated 120 000–150 000 tires are used annually in the construction of reefs.

3.3.1.2. Playground equipment. The tire playground and small-scale local and backyard recreational uses are another area of consuming whole tire wastes. Demand for tire playground products is declining as the economy improves and schools and parks select wooden playground equipment.

3.3.1.3. Erosion control. Whole tire wastes can be used for erosion control because in previous projects, discarded tires used with other stabilization materials to reinforce an unstable highway shoulder or protect a channel slope have remained stable. In order to achieve this tires were banded together and partially or completely buried on unstable slopes. Construction costs were reduced from 50 to 75 per cent compared to the lowest cost alternatives such as rock, gabion, or concrete protection.

3.3.1.4. Highway crash barriers. The use of discarded tires as crash barriers was studied in the late 1970s by the Texas Transportation Institute. It was found that stacked tires bound by a steel cable and enclosed with waste glass reduce or absorb impact of automobiles travelling up to 71 mph. However, no widespread use of tires in this application has occurred.

3.3.2. Processed Tire Wastes Used In Construction

3.3.2.1. Introduction. Based on beneficial technical use and acceptable environmental impact a selection of best management practice has been performed. Based on the tire waste material properties the following applications have been identified as potential interesting. In all applications the environmental point of view must be considered.

3.3.2.2. Lightweight Fill. Lightweight fills are used to reduce stress on the underlying soil in order to reduce consolidation settlements or to increase global stability of constructions by reducing load. The low bulk density of tire wastes, compared to soil materials, makes the material suitable as lightweight fill material. The high porosity and drainage capability

limits the presence of water in the fill and the low maximum water content in individual tire wastes preserves the low bulk density over time.

In design the initial compression, creep, maximum in-situ density and thickness must be considered. The initial compression depends on the stress from overlaying layers. If the fill is subjected to load, creep will occur under a long period. The creep results in slightly increased density and should be encountered for in design of lightweight fill applications. To limit the potential leaching effects, the fills should be placed above the ground- or surface water table and ensure the surface run-off beneath the tire waste fill.

In large fills the fire risks should be considered. ASTM (1998) recommends maximum fill height of tire waste fills to 3 m. In a large noise barrier fill, NPRA (2004), 1 m thick vertical clay layers every 70-80 m have been used as fire barriers in order to reduce the risk of horizontal fire spreading in the fills. An example of noise barrier is shown in Figure 3.4.

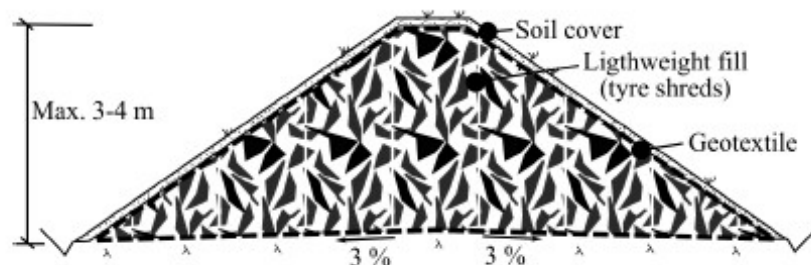


Figure 3.4. Example of lightweight fill of tire wastes in a noise barrier.

In general the experiences of fills less than 4 m thick are positive in terms of functionality. In road embankments the road superstructure must be thick enough to limit the strains in the pavement caused by the high compressibility of the tire wastes.

3.3.2.3. Thermal Insulation. Frost penetration combined with accessibility of water causes frost heave in especially fine grained soils. Thawing and corresponding bearing capacity loss due to low draining capacity in the partly frozen soils is also common. Thermal insulation materials are used to reduce frost penetration. The low thermal conductivity in tire wastes makes the material suitable for thermal insulation material. Combined with the

high permeability the material could decrease the frost heave by acting as capillarity breaking layer and increase bearing capacity at thawing by draining of excessive water.

When the layer of tire waste itself is at freezing condition, i.e. $< 0^{\circ}\text{C}$, even at low freezing index, the layer effectively insulates the layer below. The insulation effect is acting on the underlying soil and reduces the heat transfer. A frost susceptible soil is fine grained, it is recommended to use geotextiles to reduce the migration of the fine grained soil into the tire waste layer. This will preserve the thermal insulation properties and drainage capability of the material.

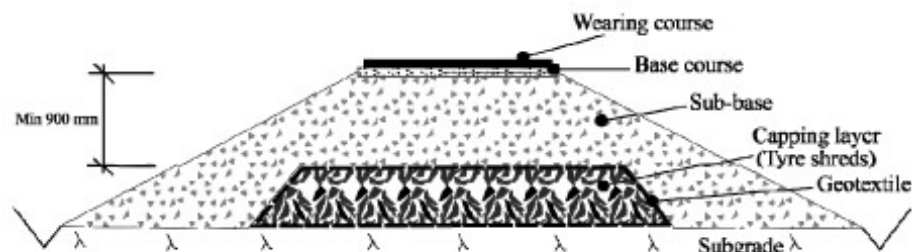


Figure 3.5. Tire wastes used as thermal insulation in road constructions.

The limitations of the use of the material as thermal insulation layer have been discovered to be the demands of the protected structure. In road constructions the resulting strain in the pavement is a limitation factor. Using tire wastes as thermal insulation layer (Figure 3.5.) will result in lower bearing capacity of the road during the frozen period compared to when granular soils are used.

3.3.2.4. Drainage Layer. In landfill construction, drainage layers are used in the bottom construction and in the top cover to protect the sealing layers to have water pressures being built up. The bottom drainage layer is a part of the leachate collection system used for transportation of leachate for treatment or release. Normally a gas drainage system is installed in landfills. The gas drainage system collects landfill gas. The gas has a high greenhouse effect potential due the high content of methane and it also increases the risk for landfill fires. In figure 3.6. the different drainage systems in a landfill are illustrated.

The high permeability makes tire wastes interesting to use as drainage material. In addition, the durability, resistance against chemicals, low bulk density and thermal insulation properties can be utilised in addition to the drainage capability.

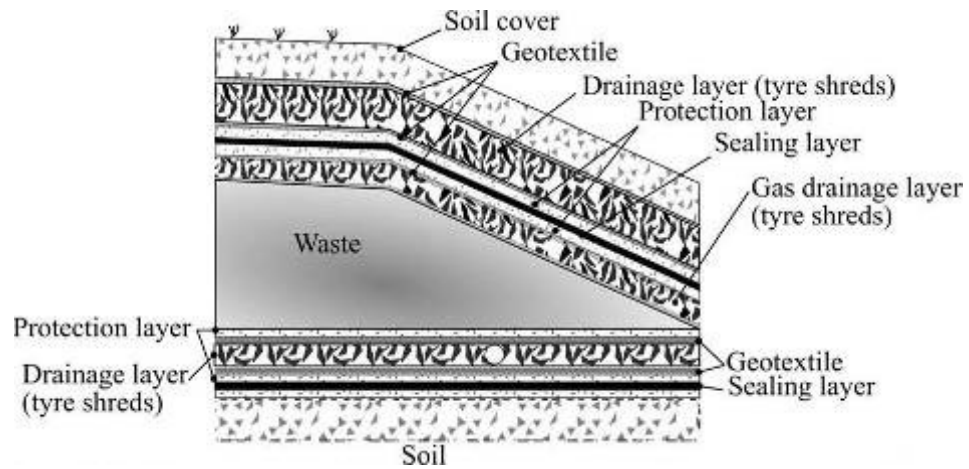


Figure 3.6. Examples of use of tire wastes as drainage layer in top cover, as gas drainage layer and as bottom drainage layer.

There are several studies of utilising tire wastes as drainage material. Main focus has been on the use of tire wastes as bottom drainage layer, since it includes most of the design issues. The suitability of tire wastes used as bottom drainage layer has been investigated in several studies, Reddy and Saichek (1998), Warith et al. (1997). Tire wastes have high permeability even at high vertical stress. At a vertical stress of 1 GPa and 65 per cent compression the permeability was approximately 10^{-4} m/s. Reddy et al. (2005) shows that tire wastes resists clogging even at high intrusion of fine soil material. The resistance against leachate degradation has been tested on different leachates, e.g. acidic, and has proven to be persistent.

Despite the high compressibility of tire wastes the permeability is still high. The compressibility must be considered to maintain enough thickness of the drainage layer in a long term perspective. To preserve the permeability, geotextile material should be used to protect the tire wastes from clogging. This is recommended even though laboratory tests suggest high resistance against clogging. Stability and mobilised shear strength in the tire waste layer and in the tire waste/geotextile interface in a long term perspective must be considered. In studies, e.g. Cosgrove (1995), it has been concluded that a shear plane in between the tire waste/geotextile interface is the limiting factor. Cosgrove (1995) recommends maximum slope angles between 10-16° for smooth surfaced geotextiles and textured surfaced geotextiles 21-28° in order to achieve a safety factor of to 1.3 and 1.5

respectively. Tire wastes can not be placed directly on geosynthetic liners for the risk of puncturing. A protective layer of 100-200 mm of e.g. sand is recommended by several authors, e.g. Duffy (1996), and Reddy and Saichek (1998).

An important design factor of the top cover constructions in cold regions is frost penetration. Freezing may affect the sealing layer negatively. By combining the utilisation of tire wastes as drainage material with thermal insulation a lighter top cover may be used which is beneficial for the top sealing layer. It will thus reduce the total settlements. This shown in figure 3.7. where a construction using tire wastes as thermal insulation layer is compared with a conventional construction.

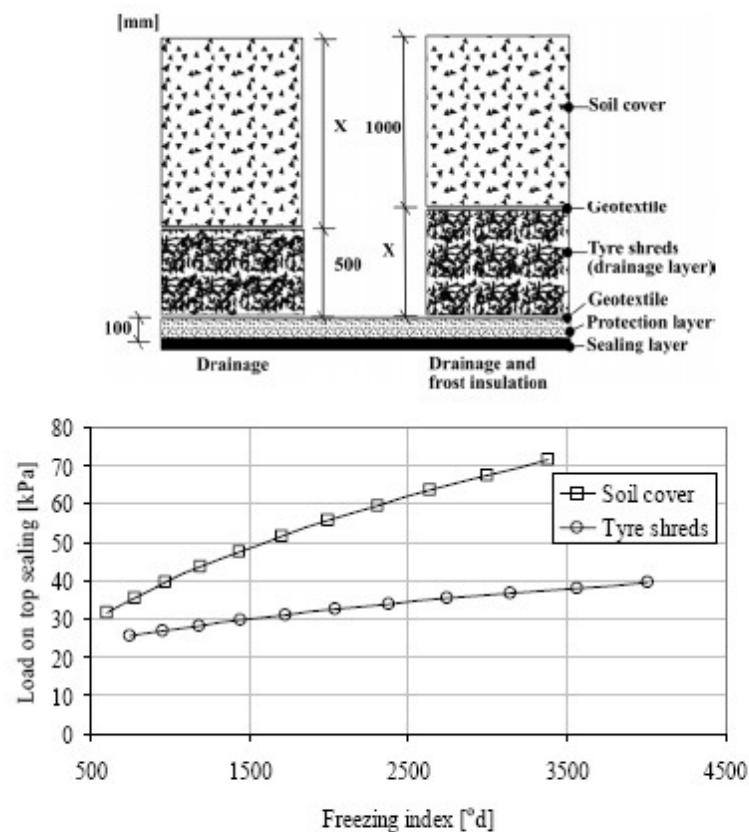


Figure 3.7. The effect on load of using tire wastes as insulation layer in a landfill top sealing construction compared to a conventional top cover. The graph refers to the constructions presented above.

There are no indications of that tire wastes would degrade in a very long time perspective, here more than 1000 years, in such a way that the performance of the drainage

layer would be affected. Chemical effects on different types of landfills must be carefully investigated, but so far, at least for municipality solid waste fills tire wastes are resilient. The effect of a fire on a tire waste layer is severe. The tire wastes are placed beneath a thick top soil cover and a limitation of the drainage layer thickness to maximum 3 m this is regarded as no problem.

3.3.2.5.Backfill Material. Tire wastes reduce earth pressure on constructions when used as backfill material, Tweedie et al. (1998) and Humphrey et al. (1997b). The use as backfill material is both technical and economical motivated, Cosgrove (1996). In addition to low earth pressure the material will serve as drainage layer and as thermal insulation.

3.3.2.6.Elastic Layer. In construction of trotting tracks and paddocks the combination of the prevention of rutting, draining and soft surface is normally hard to achieve. A stiff surface based on coarse unbound aggregates results in a stiff surface that acts hard on the ligaments of the horse. On the other hand fine grained soils results in rutting and drainage problems. The high compressibility of tire wastes and the soft stress-strain response, and high drainage capability can be utilised to create soft surfaces suitable for trotting tracks and paddocks.

3.3.2.7.Limitations in Use. The technical limitations of use of tire wastes are related to the high compressibility and deformation properties. The high compressibility and creep deformation limits the use in foundation engineering design. Differential and long term settlements can cause concrete structures built upon tire wastes to damage. Shear stress causes large deformations before failure in tire wastes compared to that in granular soils. In road constructions tire wastes requires a relatively thick superstructure to achieve required bearing capacity.

Tire wastes have an ignition temperature of about 350 °C. Spontaneous fires have been registered in large and thick tire waste fills. The reason for self ignition is not completely understood, but heat generation by oxidation of free steel cord by microorganisms, presence of organic soils in combination with the low heat transportation out of the fills are suspected to be main factors. In the ASTM standard D 62070-98, ASTM (1998), the use is limited to 3 m thick fills of tire wastes. It is however pointed out that no fills below 4 m thickness has been observed to self ignite. Fire assessments for tire waste

processing recommends temporary fills to be maximum 4 m, Hansson (2003).

Since tire wastes contains potential hazardous compounds, e.g. PAH and antidegradants, some prevention acts is appropriate. Even if only low concentration of target compounds, except for iron and zinc is found in the leachate the use of tire waste should be aimed to limit the potential leaching. From an environmental point of view tire wastes should be placed above the ground or surface water table combined with good drainage conditions. From a leaching point of view neutral pH is ideally considering both element and organic compound leaching.

3.4. Material Processing Requirements

3.4.1. Shredding

The size and shape of tire shreds or chips from tire shredding can vary depending on the type of shredding machinery used. Tire wastes have a wide range of sizes, from 76 mm (3 in) up to 305 mm (12 in), which is ordinarily the largest size recommended. Chip sizes normally range from 12 mm (1/2 in) up to 76 mm (3 in). Usually, tire wastes are irregular in shape with the smaller dimension being the size specified by the manufacturer and the larger dimension possibly being two or more times as much. The chips, on the other hand, are cubical in shape. Some shreds or chips may have pieces of steel belt exposed along the edges. To minimize potential compaction problems (i.e., to reduce void space) it may be desirable to use smaller size tire chips of 50 mm (2 in) or less.

3.4.2. Engineering Properties

Some of the properties of tire chips or shreds that are of particular interest when they are planned for use in an embankment or backfill include particle size and shape, specific gravity, compacted unit weight, shear strength, compressibility, permeability, and combustibility. Due to the differences between tire shreds or chips and stone or soil-like embankment materials, physical characterization of tire shreds or chips represents a specific challenge to the tire user. In the table 3.2., the factors influencing engineering properties are presented, Edeskar (2006).

Table 3.2. Factors influencing basic engineering properties up to 40 kPa vertical stress. (++) high influence, (+) some influence, (0) no influence, (?) unclear influence and (/) not applicable.

Influence factor							
	Stress	Size	Water content	Compaction energy	Reloading ⁽¹⁾	Displacement	Frozen condition
Bulk density	++	+	+	++	+	0	0
Porosity/void ratio	++	+	0	++	+	0	0
Permeability	0	0	0	0	0	0	0
Compressibility	++	+	0	+	+	0	0
Stiffness modulus ⁽²⁾	++	+	0	+	+	0	0
Poisson's ratio	+	0	0	0	0	+	0
Shear strength (σ , c)	+	+	?	+	+	++	0
Coefficient of lateral stress	+	0	0	0	0	+	0
Thermal conductivity	+	+	+	0	0	0	+
Compaction	/	++	+	++	/	/	0

⁽¹⁾ Reloading after unloading, compared to first time loading.

⁽²⁾ Elastic modulus evaluated from different test designs and evaluation techniques.

3.5. Environmental Concerns

3.5.1. Introduction

Environmental considerations must be addressed as well as technical functionality. There are different ways of performing environmental impact analyses. In this section the use of tire shreds in civil engineering applications will be discussed on the aspects; chemical and physical composition and leaching properties.

The chemical and physical composition of the tire wastes have historically been used for identification of compounds of interest from an environmental point of view. The leaching properties serves as a guide of potential compounds that may be transported by percolating water through a tire waste fill and thus, available outside the tire waste construction for mainly aquatic organisms.

Beside the material specific properties and toxicity of individual compounds the exposure paths of the suspected pollutants are important for the actual environmental influence. In general exposure paths from constructions is presented in figure 3.8. Considering the use of the tire wastes, size and durability, particle transport from a construction is not considered to be pollution path from tire wastes. Gaseous release has been concluded to be insignificant, Ulfvarsson et al. (1998). For use of tire wastes covered in this work identified exposure pathways consist of fine particles, i.e. dust, into air during the construction time and water and as aqueous solution to water.

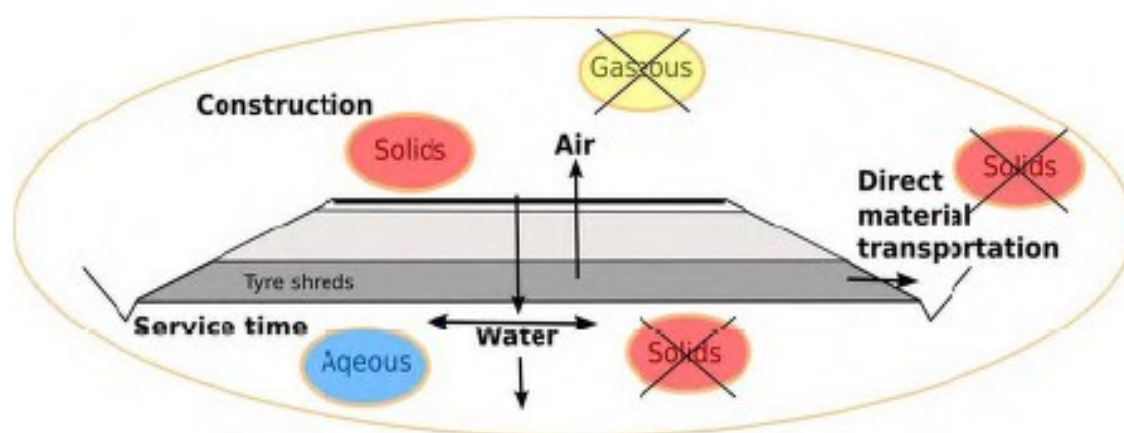


Figure 3.8. Discussed exposure pathways from tire wastes used as construction material.

The release of particles in the air during shredding and handling of tire wastes has been investigated by Ulfvarsson et al. (1998) and found not to require any precautions for the workers in ventilated areas. In Gas as transportation medium is considered to be insignificant for tire wastes and handling of tire wastes does not require any precautions for worker in ventilated areas.

3.5.2. Chemical and Physical Composition

Tires are produced by different manufacturers and produced to work under different conditions and it is also under continuous development. Therefore, there is no exact composition of the end-of-life tire stock, the raw material for tire waste production. However, by dividing the physical and chemical content into different groups, tire

materials can be classified on functional and chemical content.

The difference in composition between new tires and tire wastes is primarily the 10 per cent loss in the tread, i.e. the rubber component, during the service time of the tires. Thus the composition of new tires may serve as good approximation of the content in wastes. This is shown in figure 3.9.

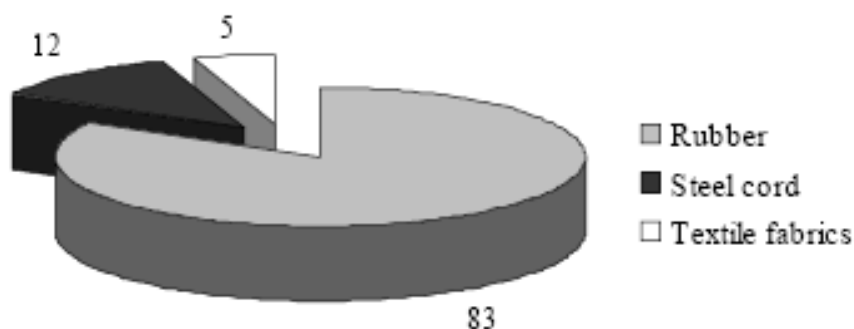


Figure 3.9. Composition by mass of the physical components rubber, steel cord and textile fabrics of an average European car tire

The physical rubber component consists mainly of synthetic rubber and natural rubber. About 80 per cent of the synthetic rubber is styrene-butadiene rubber. In the rubber matrix additives are used for manufacturing processes, e.g. zinc oxide for vulcanisation, and antidegradants. The steel cord is often bronze coated. The textile fabrics are rayon, polyamide (nylon) and polyester, BLIC (2001).

3.5.3. Leaching Properties

The laboratory leaching study was performed by the Edeskar (2006) identified leaching compounds. The study includes both tire granulates (tire rubber material) and tire wastes. Identified factors influencing the leaching properties are size (i.e. the specific surface of the individual aggregates), and leaching agent. The difference in concentrations in the leachate of PAHs (polycyclic aromatic hydrocarbons) was 10-1000 times higher for tire granulates compared to tire wastes. It shows that the surface area is of importance for the leaching properties.

In general the concentrations of elements and organic compounds in the leachate were low, <10 µg/l, for tire wastes at L/S 10 in neutral conditions, except for iron at 750 µg/l and zinc at 160 µg/l. It is primarily iron and zinc that is of concern due to the high concentrations found in the leaching studies. Iron hydroxides could be an aesthetic problem if precipitated outside a construction and will affect the release of other charged ions which may be accumulated absorbed on iron hydroxides or released if the hydroxides are dissolved. For zinc to be toxic high concentrations are needed. If the recipient is sensitive to additional zinc sources the use of tire wastes from large constructions to small recipients should be considered. In most cases the zinc release are acceptable in terms of ecological effect levels in a potential recipient. Leaching of PAH compounds is insignificant. This is supported by the conclusions by e.g. CSTE (2003). Tire waste leaches phenols. In evaluation of the effects natural sources and sinks, i.e. biological degradation, must be considered. Aerobic conditions in the recipient should be sufficient to biodegrade the obtained phenol concentrations in the leachate.

3.6. Theoretical Development of Fiber Reinforcement

Soil Reinforcement is an effect and reliable technique for improving strength. In conventional methods of reinforced soil structures, the inclusions (bars, grids, fabrics, strips etc.) are oriented in a preferred direction where else the fiber reinforced soil has discrete fibers which are randomly distributed.

The discrete fibers are simply added and mixed randomly with soil, much the same was as cement, lime, or other additives. Thus, by using randomly distributed fibers, a strong isotropy and absence of potential planes of weakness along the oriented reinforcement is maintained.

Experimental results reported by various researchers (McGown et al. 1978, Verma and Char 1978, Hoare 1979, Gray and Ohashi 1983, Gray and Al-Refeai 1986, Gray and Maher 1989, Maher and Gray 1990, Al-Refeai 1991) have shown that fiber reinforcement causes significant improvement in strength and stiffness of sand. More importantly fiber-reinforced soil exhibits greater extensibility and small loss of post-peak strength. (greater ductility in the composite material) as compared to sand alone or sand reinforced with high

modulus inclusions (Gray and Ohashi 1983, Gray and Al-Refai 1986). The increase in strength and stiffness is reported to be a function of sand characteristics, e.g., particle size, shape, and gradation; fiber characteristics, eg., weight fraction, aspect ratio, skin friction, and modulus of elasticity, and test conditions, e.g., confining stress (Grey and Maher, 1989, Maher and Gray, 1990; Al-Refai, 1991). They reported that the strength of reinforced sand increases with increase in fiber content, aspect ratio, and soil fiber surface friction.

Experimental investigations on fiber reinforced soil have been reported by several investigators. A simple force-equilibrium model (Figure 3.10.) was proposed by Waldron (1977) to describe the load deformation characteristics of soils reinforced with plant roots and this model was used by Gray and Ohashi (1993) to describe the deformation and failure mechanism of fiber reinforced soil and to find the increase in shear strength (ΔS) for oriented fibers crossing a shear plane. The model is simply:

$$s = c + \sigma \tan \Phi + \Delta S$$

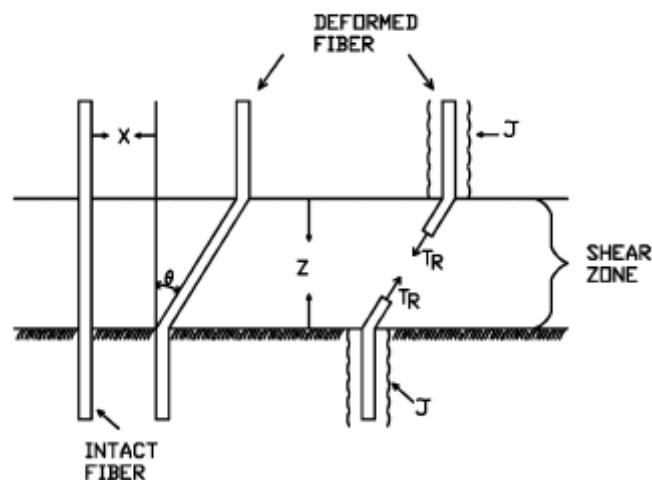


Figure 3.10. Model of Oriented Fiber Reinforced Sand

The inclusion of discrete fibers increased both the cohesion and the angle of internal friction of the specimens. The increase in cohesion of typically cohesionless

materials due to the inclusion of discrete fibers was termed the “apparent cohesion” of the material (Arteaga 1989; Liausu and Juran 1995; Stauffer and Holtz 1995). The improvement of the engineering properties due to the inclusion of discrete fibers was determined to be a function of a variety of parameters including fiber type, fiber length, aspect ratios (length/diameter), fiber content, orientation, and soil properties. The discrete fibers are mixed randomly with soil in certain weight proportions and this randomly used fibers lead to important advantages. One, very important advantage is that the mixture is uniform in any direction, so there are no potential planes of weakness that can develop parallel to the oriented reinforcement. The peak strength (shear, compressive, tensile, etc.) reportedly increased with increasing fiber content and length up to a limiting amount of each beyond which no additional benefits were observed (Gray and Ohashi 1983; Gray and Al-Refeai 1986; Arteaga 1989; Gray and Maher 1989; Maher and Ho 1994; Ranjan et al. 1996; Webster and Santoni 1997).

3.7. Background

The rising stockpiles of tire waste resulted in an interest of developing new ways to reuse or recycle tire wastes. Shredding tire waste and using it as a construction material is an option to reuse the tire waste, so many studies are done to evaluate the characteristics of the tire waste alone and as an additive to a basic material as sand, clay, concrete or asphalt. In some of these studies, the tire waste shear strength properties were determined just like in this thesis will be done in further sections.

Humphrey et al. (1993) has conducted large-scale direct shear tests with three different tire chips. Tire chips with length smaller than 72mm were used. This study reported that friction angles and cohesion were ranging between 19° and 25° and 7.7-8.6 kPa respectively. In the study it is stated that tire chips are useful for constructing lightweight embankments over soft soils.

Bosscher et al. (1993), Ahmed and Lovell (1993), and Humphrey and Manion (1992) reported that tire shreds and soil-tire shred mixtures can be compacted using common compaction procedures. They have found that unit weight is primarily controlled by the amount of the soil in the mixture, whereas compactive effort has little influence.

They reported adding tire chips to sand increases the shear strength of sand. The observed angle of friction was up to 65° for dense sand containing 30 per cent tire chips by volume.

In a study conducted by Foose et al. (1996), five factors affecting the shear strength of the dry sand-tire shred mixtures were evaluated by large scale direct shear tests. From the factors; normal stress, sand unit weight, shred content, shred orientation, shred length, just two of them, which were sand unit weight and shred content, were reported as the most significant characteristics. In any proportion, the mixtures were reported as having higher shear strength parameters than the sand alone.

Tatlisoz et al. (1998) conducted a the large scale direct shear tests with tire chips, sand, sandy silt, sand-tire chips and sandy silt-tire chips mixtures. In the study, it is reported that sand-tire chips mixture had an increasing behavior of shear strength as the volume of the tire chips increased up to 30 per cent, whereas the sandy silt-tire chip mixture did not have a change in the angle of internal friction, but just an increase in the cohesion.

Edincliler et al. (2004) conducted the large scale direct shear tests with tire buffings, sand and sand tire buffings mixtures. In the study, it is reported that 10 per cent by weight tire buffings addition to sand alters the deformation behavior of the mixture by stiffening the material at low strains and softening the mixture at large strains. Test results of this study are given in further chapters (Table 5.3.).

Rosa et al. (2001) investigated to identify and quantify the effect of numerous variables on the performance of fiber-stabilized sand specimens. Laboratory unconfined compression tests were conducted on sand specimens reinforced with randomly oriented discrete fibers to isolate the effect of each variable on the performance of the fiber-reinforced material. They concluded that the inclusion of randomly oriented discrete fibers significantly improved the unconfined compressive strength of sand.

A series of triaxial compression tests were carried out on cohesionless soils reinforced with discrete randomly distributed fibers, both synthetic and natural, to study the influence of fibers characteristics (i.e., weight fraction, aspect ratio, and surface

friction) soil characteristics and its density, and confining stress on shear strength of reinforced soils (Ranjan et al, 1996). A regressive analysis of test results has been carried to develop a mathematical model to bring out the effect of these factors on the shear strength of reinforced soil. On the basis of the experimental investigation and statistical analysis, they concluded that the shear strength of short, randomly distributed fiber-reinforced soil is a function of fiber weight fraction, aspect ratio, and surface friction, soil characteristics (i.e. angle of internal friction, Φ) and its density and confining stress.

4. EXPERIMENTAL PROGRAM

4.1. General

The aim of this section is to determine the shear strength parameters of tire rubbers, *tire crumb* and two different sized *tire buffings*, *TB1* and *TB2*. In the first part of the experimental program, various mixtures of sand and tire waste are tested to in order to observe the per cent effect of the materials. Direct shear test is performed to observe this effect. In the second part of the experimental study, tire buffings and tire crumb are used with sand in various proportions to maintain a result about both the per cent effect and shape effect of the lightweight materials. The direct shear tests are performed to determine the required parameters. In the second part, a large scale direct shear apparatus is used to be able to make comparisons with the results of the previous studies done.

4.2. Materials Used

4.2.1. Soil

A sand is used for the tests (Figure 4.1.). Sand is tested alone and with common proportions of tire crumb. The type of sand was considered to be representative of granular fill material commonly used in embankments.



Figure 4.1. Sand used during the test.

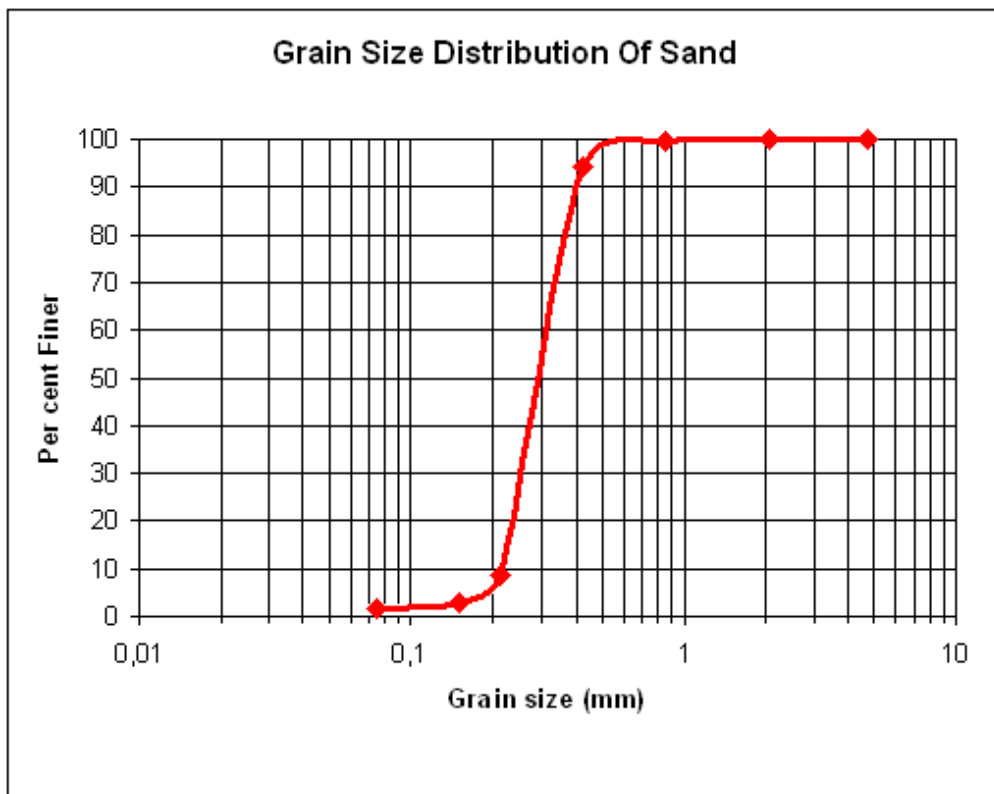


Figure 4.2. Grain size distribution of the sand.

Due to the grain size distribution graph of the sand (Figure 4.2.), coefficient of uniformity (C_u) value is found 1,5. So used sand is considered as uniform, because the value is smaller than 4. And the coefficient of curvature (C_c) value is found 1.04 which means that the sand is well-graded, because the value is between 1 and 3.

4.2.2. Lightweight Material

4.2.2.1. Tire crumb. The tire crumb used in this investigation was obtained from the scrap tires (Figure 4.3.). The processed material was bought from a company in İstanbul.

The dimensions of the tire crumb were between 1-3mm.



Figure 4.3. Tire crumb sample

4.2.2.2. Tire Buffings. Tire buffings are a by product of the tire retread process and have an elongated fibrous shapes variable length. Their flexibility and high strength make them ideal extensible inclusions.

Tire buffings used in the tests were by-product of the tire retread process. The buffing particles were found in many dimensions including very fine particles of tire dust. For the test, the buffings are graded and divided into two different groups and the tire dust is eliminated. In the figure 4.4. the graded samples are represented. First groups of tire buffings (TB1) include particles with size between 2mm and 4mm in length and second group tire buffings (TB2) include particles greater than 4mm. Maximum length of the tire buffings that is observed, is 50mm.



Figure 4.4. Graded tire buffings; dust, TB1 (2mm-4mm), TB2(>4mm) respectively.

4.3. Sample Preparation

4.3.1. Grading The Tire Buffings into Two Categories

Sieves with sizes 2mm and 4mm (Figure 4.5) are used to distinguish the tire buffings into two sizes and get rid of the tire dust (Figure 4.9). The used sieves are shown below.



Figure 4.5. Sieves used to grade the tire buffings; 2mm and 4mm respectively

As a result of sieving, two different sized tire buffings are obtained. First one is tire buffing with sizes between 2mm and 4mm, TB1 (Figure 4.8..) and the second is the one with the sizes greater than 4mm, TB2 (Figure 4.7.). And also very huge particles of tire buffing which are bigger than 50mm are eliminated by hand in the TB2. Thus, appropriate samples due to ASTM D 3080 (1998) are prepared.

During the grading, it is observed that TB2 constitutes the 34,5 per cent, TB1 constitutes the 33,5 per cent and the dust constitutes the 32 per cent of the overall tire buffings used (Figure 4.6.).

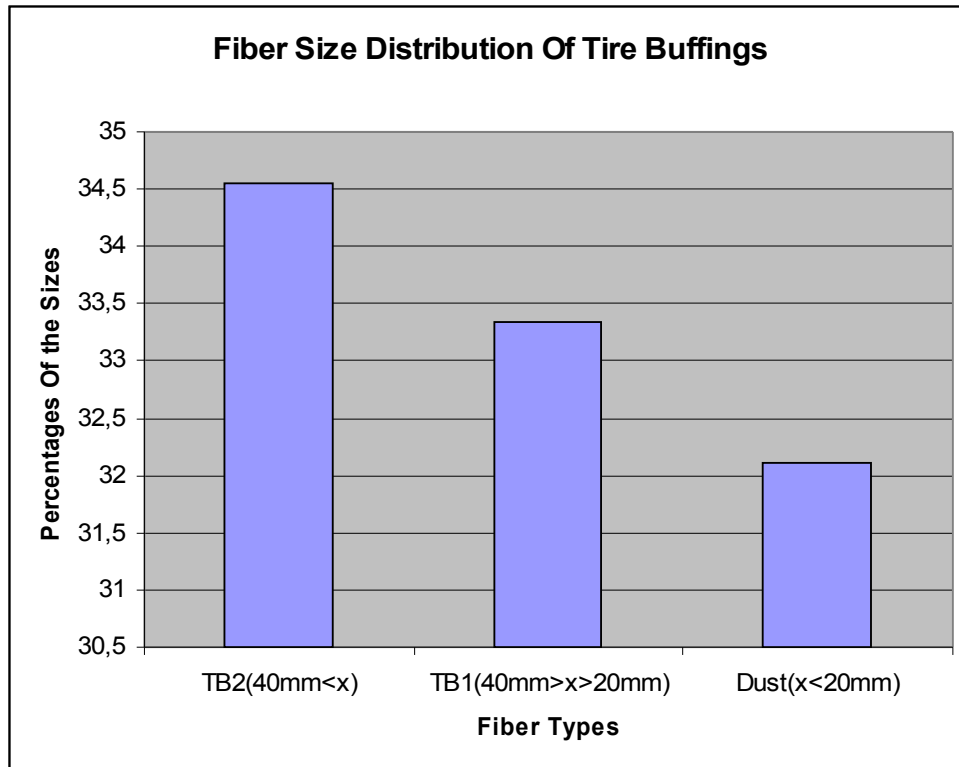


Figure 4.6. The percentages of TB2, TB1 and Dust in overall tire buffings used.



Figure 4.7. TB2 sample



Figure 4.8. TB1 sample

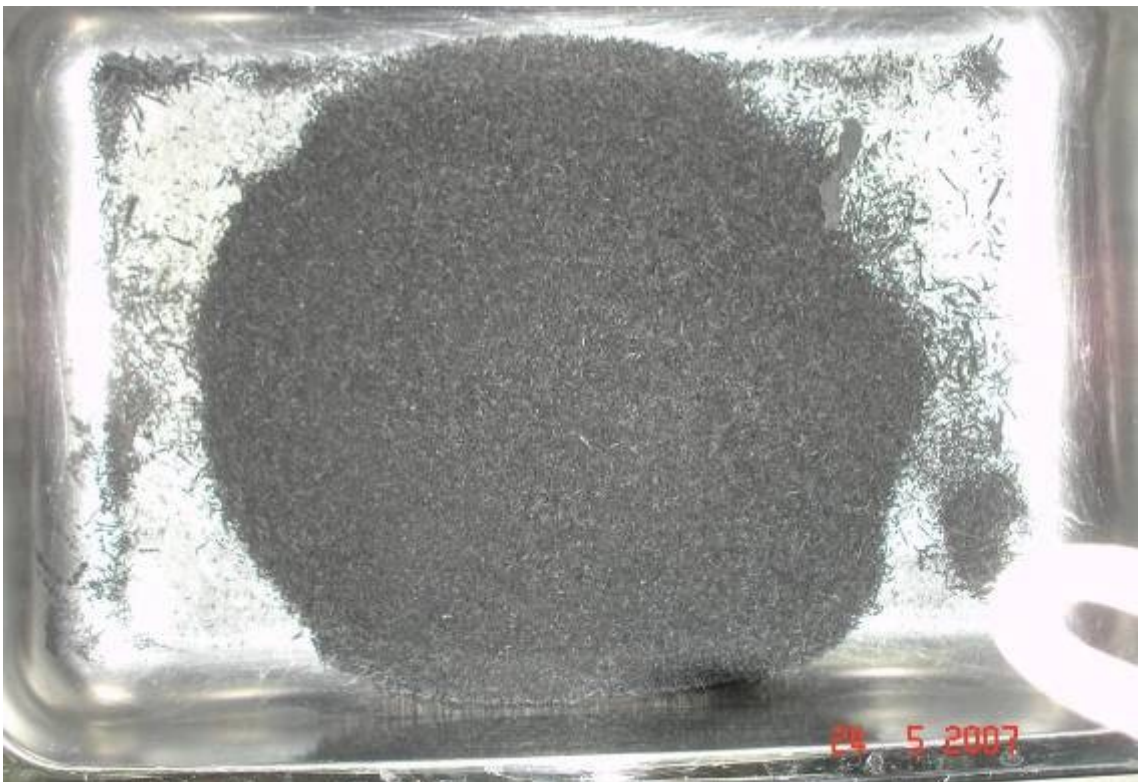


Figure 4.9. Tire dust sample

4.3.2. Unit Weight Determination

For both of the direct shear equipments, samples are prepared by calculating the required weights for the constant volume of the shear boxes. So, unit weights of all of the samples are calculated in order to calculate the required weights for the shear boxes. Unit weight determination is used to obtain the densities and relative densities of the materials used during the experimental program.

The test is performed by using a compaction mold having a certain volume and a standart hammer used for compaction (Figure 4.10.). The test has two phases to obtain both the loose and dense densities. First, the mold is filled with the material without any compaction thus the loosest state of the sample is achieved, and the total weight is recorded. Secondly, the mold is filled with the same sample. During filling it is compacted well by the help of the hammer. Thus the maximum dense state is achieved and the weight is recorded. Using the obtained data, the minimum and maximum densities of the sample are obtained by calculating the weight of the sample per volume of the mold.

The volume of the compaction mold used is 944cm^3 .

For the further direct shear tests, the unit weight tests are done for all of the samples (materials; sand, tire crumb, tire buffings (TB1 and TB2) and their mixes in various proportions).



Figure 4.10. Compaction mold and the hammer

After completing finding out the unit weights of the samples, The maximum and minimum densities of the samples are evaluated and a value between these numbers are chosen and thus the required weight for the samples are calculated by multiplying the density by the previously known shear box volume of 944cm^3 . Also the relative densities of the samples are presented on the table 4.1.

Table 4.1. Density and relative density values for the samples. C represents tire crumb, TB1 represents tire buffings with sizes between 2mm and 4mm, TB2 represents tire buffings greater than 4mm and the samples with percentages represent the mixtures of these materials with sand.

	weight(N)		density(kN/m ³)				volume(m ³)	weight(kN)
	min	max	min	max	taken	Relative (per cent)		
sand	13,21	14,1	13,91	14,84	14	10,11	0,243	3,402
C	4,9	6	5,158	6,316	5,5	29,54	0,243	1,3365
TB1	2,84	4,7	2,989	4,947	3,5	26,07	0,243	0,8505
TB2	2,34	4,7	2,463	4,947	3,5	41,73	0,243	0,8505
10 per centC	12,68	13,7	13,35	14,42	13,5	60,78	0,243	3,402
20 per centC	11,63	13,1	12,24	13,79	13	48,97	0,243	3,159
30 per centC	10,79	12,47	11,36	13,13	12	36,30	0,243	2,916
10 per centTB1	12,09	13,78	12,73	14,51	13,5	43,49	0,243	3,2805
20 per centTB1	10,24	12,11	10,78	12,75	12	62,03	0,243	2,916
30 per centTB1	8,68	10,59	9,137	11,15	10	42,93	0,243	2,43
10 per centTB2	12,12	13,99	12,76	14,73	13,5	37,70	0,243	3,2805
20 per centTB2	9,92	12,11	10,44	12,75	12	67,57	0,243	2,916
30 per centTB2	8,56	11,09	9,011	11,67	10	37,15	0,243	2,43

4.4. Direct Shear Test And Test Apparatuses

A direct shear test is a laboratory test used by geotechnical engineers to find the shear strength parameters of soil.

The test is performed on three samples from a relatively undisturbed soil sample. A sample is placed in a shear box which has two stacked rings to hold the sample; the contact between the two rings is at approximately the mid-height of the sample. A normal stress is applied vertically to the sample, and the upper ring is pulled laterally until the sample fails, or through a specified strain. The load applied and the strain induced is recorded at frequent intervals to determine a stress-strain curve for the normal stress.

Several samples are tested at varying confining stresses to determine the shear strength parameters, the soil cohesion (c) and the angle of internal friction (commonly friction angle)

In this study, two different types of direct shear test apparatuses are used. First one, direct shear test apparatus (Figure 4.11.), is used to evaluate the per cent effect of lightweight materials mixed with sand on the cohesion and internal friction angle. Second one, the large scale direct shear test apparatus (Figure 4.12.) is used to evaluate both the shape effect and per cent effect of three different types of lightweight materials to compare their suitability for the embankment constructions.



Figure 4.11. Direct shear test apparatus



Figure 4.12. Large scale direct shear test apparatus

Throughout the test in which the direct shear test apparatus is used, the samples are loaded horizontally with a strain rate of 0.5mm/min and a 6cm*6cm, square shaped shear box is used. The readings are continued to be taken until the horizontal shear load peaks and then falls, or the horizontal displacement reaches 15 per cent of the diameter. 25, 50 and 100kPa normal stresses are applied to the samples.

The dial readings for the first device actually refer to:

- 1 Horizontal Displacement = 0.01mm/div
- 1 Vertical Displacement = 0.01mm/div
- 1 Horizontal Loading = 0.00203 kN/div

During the tests in which large scale direct shear test apparatus (designed and manufactured by Baykal G, Doven GA, 2000) is used, the samples are loaded horizontally with a strain rate of 3mm/min and a 30cm*30cm square shaped shear box is used. The details of the apparatus are represented in the Figure 4.13. The normal stresses applied are 20kPa, 40kPa and 80kPa. According to the ASTM D 3080 (1998), the maximum grain size used must not exceed one sixth of the depth of the shear box. So, maximum grain size of the tire buffings are limited to 50mm which is one sixth of the depth 30cm. The data are continued to be taken until the sample reaches the peak shear force and then starts to fail.

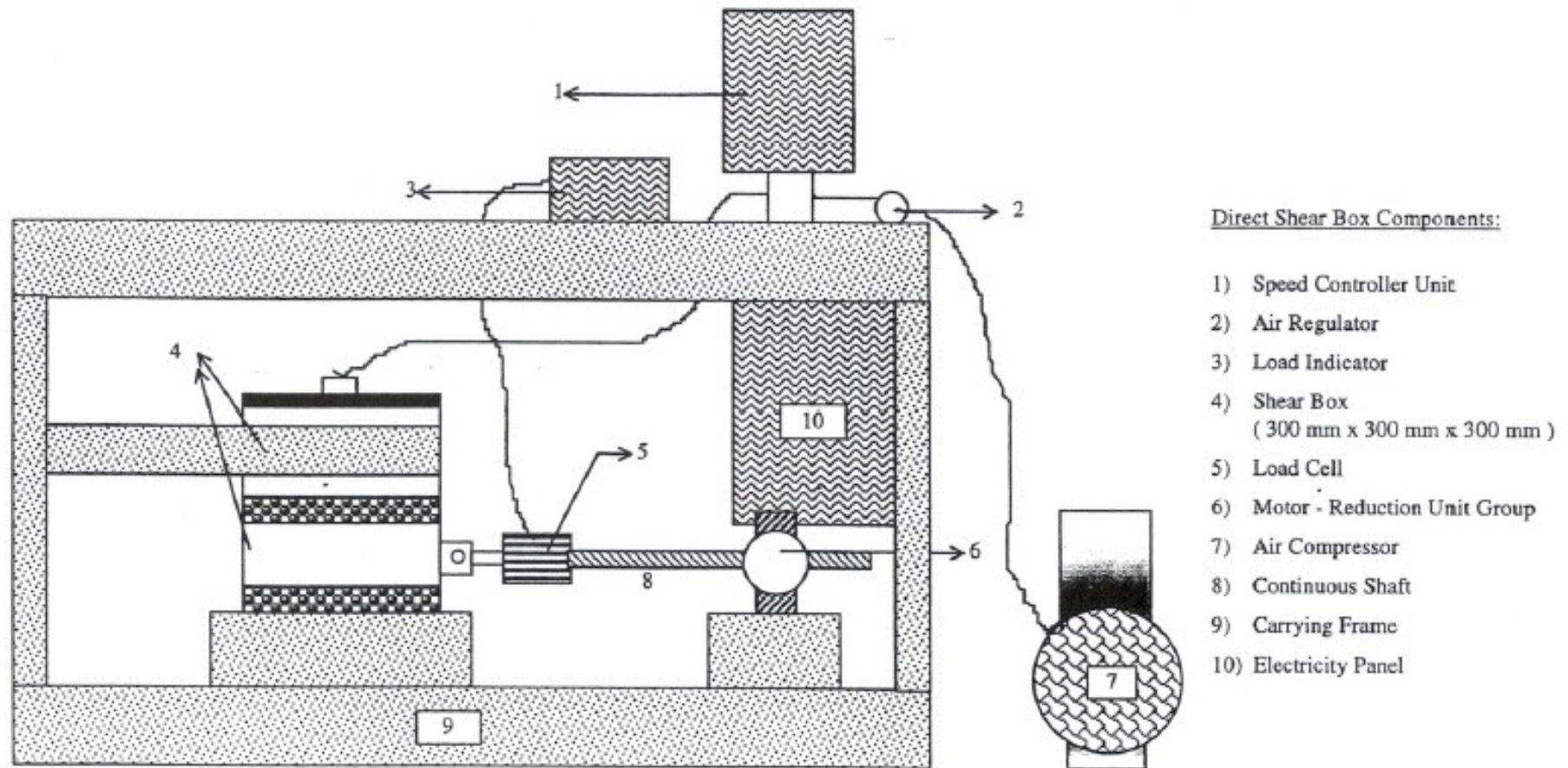


Figure 4.13. A general view and details of large-scale direct shear test apparatus

5. EXPERIMENTAL RESULTS

5.1. Direct Shear Test Results

Tire wastes as tire crumb and their mixtures with sand are tested at different compositions. Tire crumb-sand mixtures having 15, 25, 40 and 50 percent tire crumb by weight are tested. Test are repeated at the normal stresses of 25, 50 and 100 kPa . These are named as Test#1, Test#2 and Test#3. The required values are obtained usually in shorter strains, without any need to test until 9mm of ASTM D 3080 (1998) of max strain of %15 of shear box length. Shear strength parameters are obtained for each tests (ASTM D3080).

5.1.1. 100 per cent Sand

First of all tests, the sand alone is tested. As seen in Figure 5.1., the sand indicated a rise in shear stress until the horizontal displacement reached a value of 3mm. In Figure 5.2., by using the recorded test data of normal and shear stress, the failure envelope is drawn and cohesion and angle of internal friction values are found.

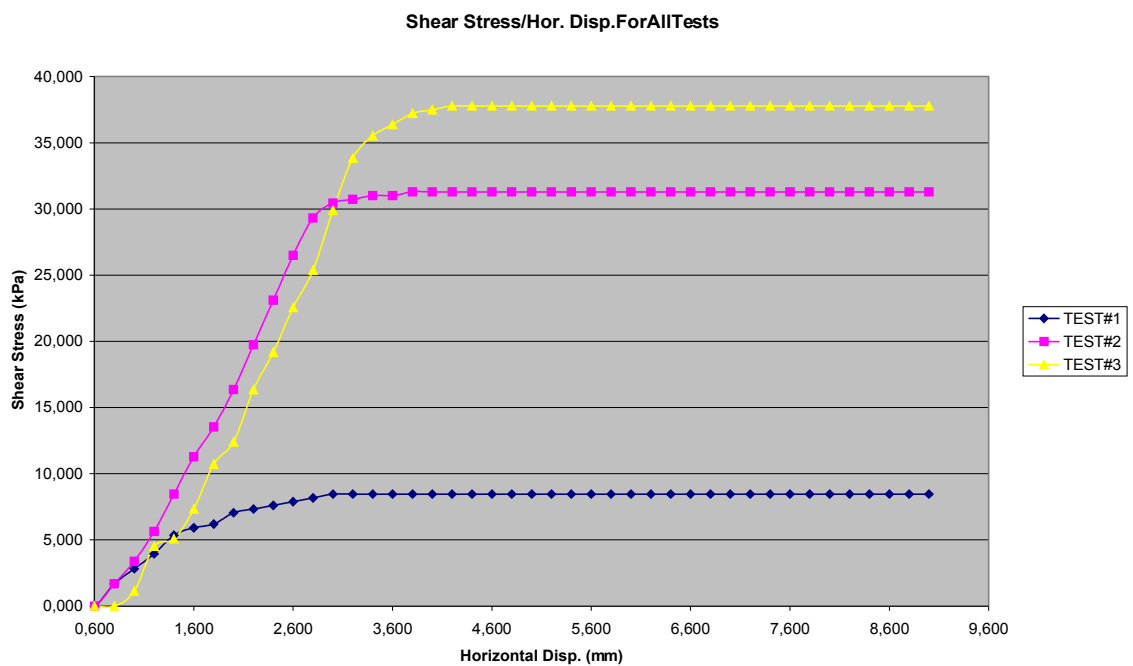


Figure 5.1. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

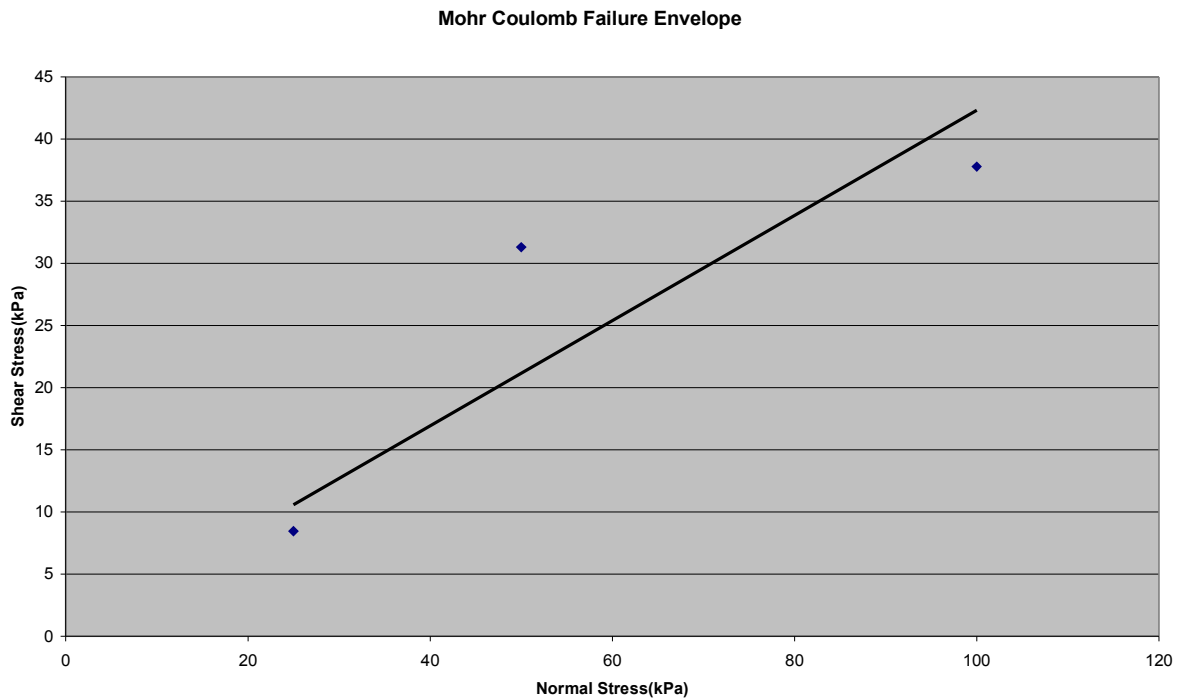


Figure 5.2. Shear Stress vs. Normal Stress graph

The Cohesion value is found as 0 kPa and angle of internal friction is found $22,9^\circ$ for the sand alone. The unit weight of the sample is found as $14,58 \text{ kN/m}^3$

5.1.2. 100 per cent Tire Crumb

The tire crumb sample is prepared and the stress vs strain values are recorded. By the obtained data, the shear vs. strain graph in Figure 5.3. is drawn. The shear stress values increased without reaching any constant value. And the drawn failure envelope (Figure 5.4.) gave results of a cohesion value of 6.06 kPa and internal friction angle of 5.17° . The density of the tire crumb is found as 5.83 kN/m^3 .

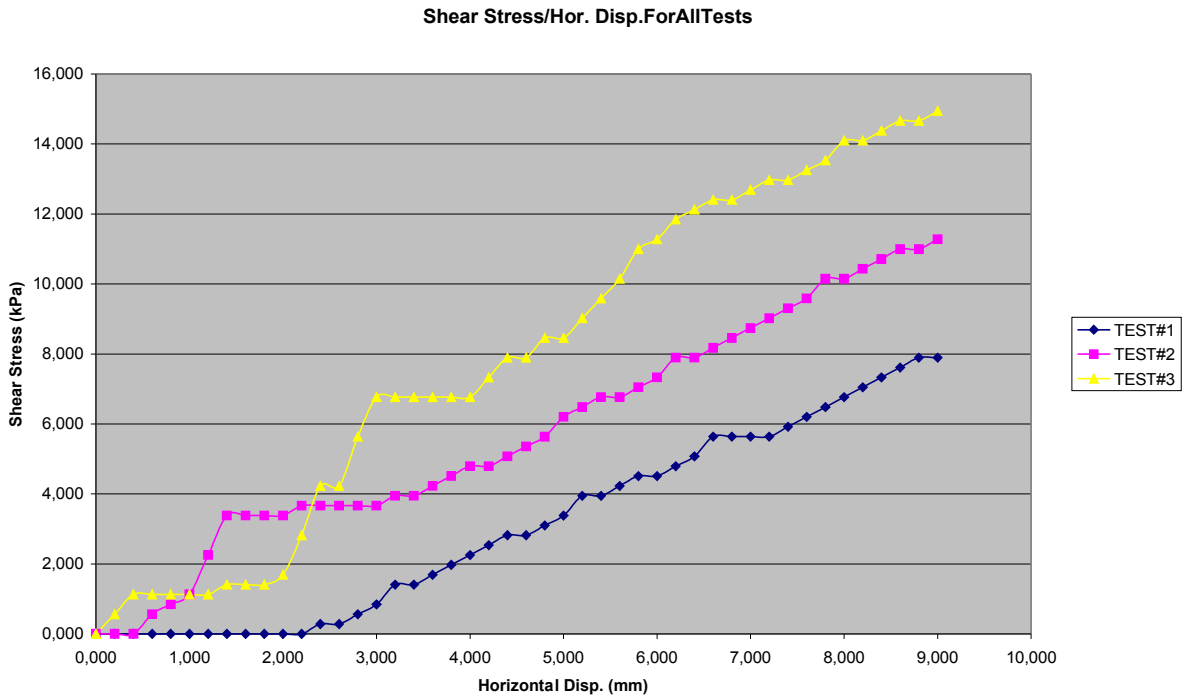


Figure 5.3. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

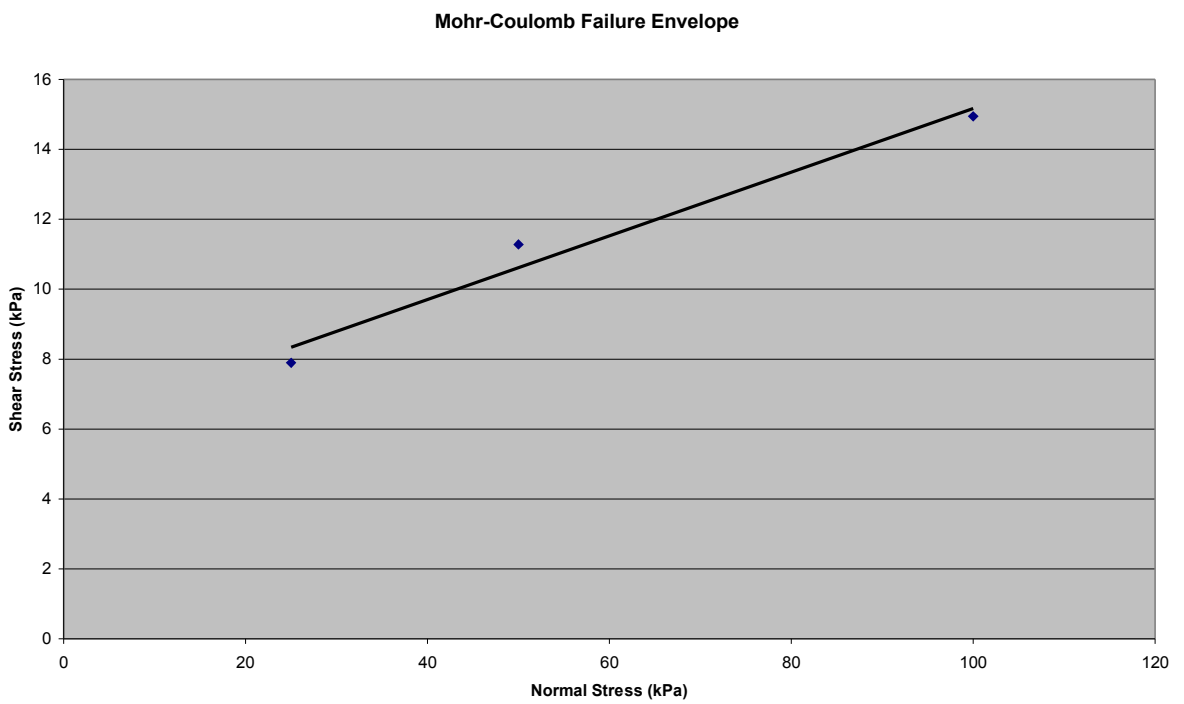


Figure 5.4. Shear Stress vs. Normal Stress graph

5.1.3. 15 per cent Tire Crumb

15 per cent tire crumb by weight is mixed with sand. The density of the sample is found 13.6 kN/m^3 . The shear stress vs. horizontal displacement graph and shear vs. normal stress graph are given in Figure 5.5. and Figure 5.6. The cohesion value is found 0 kPa and angle of internal friction is found $33,06^\circ$. No peak shear stress was obtained.

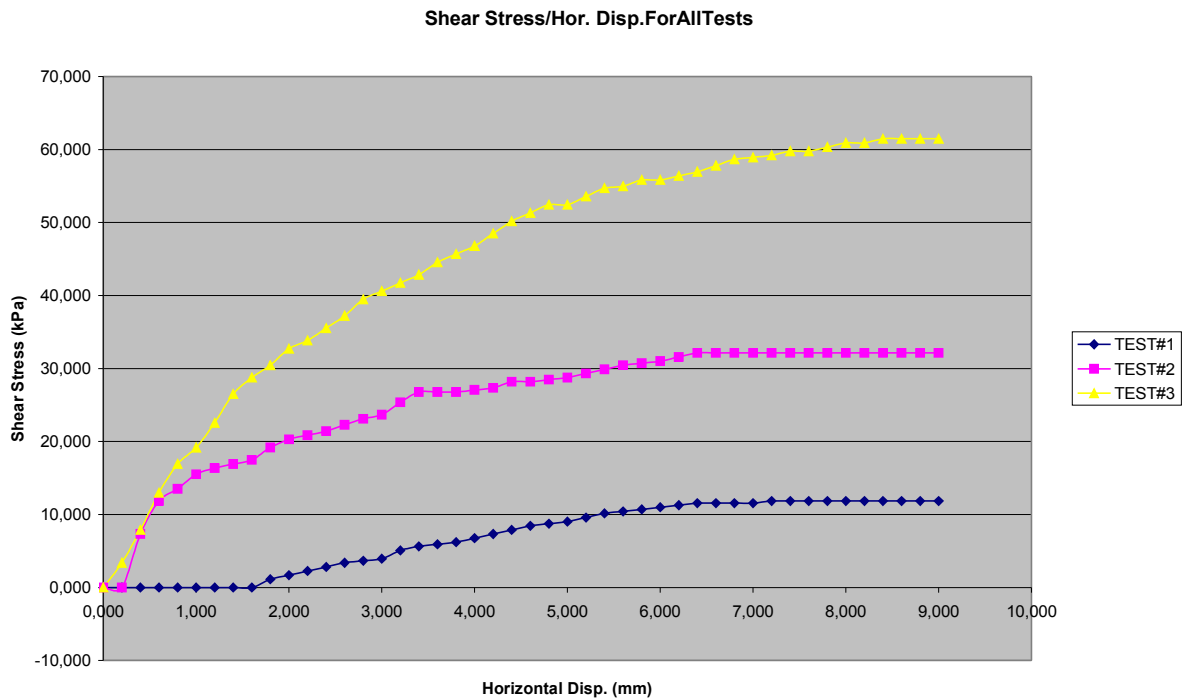


Figure 5.5. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

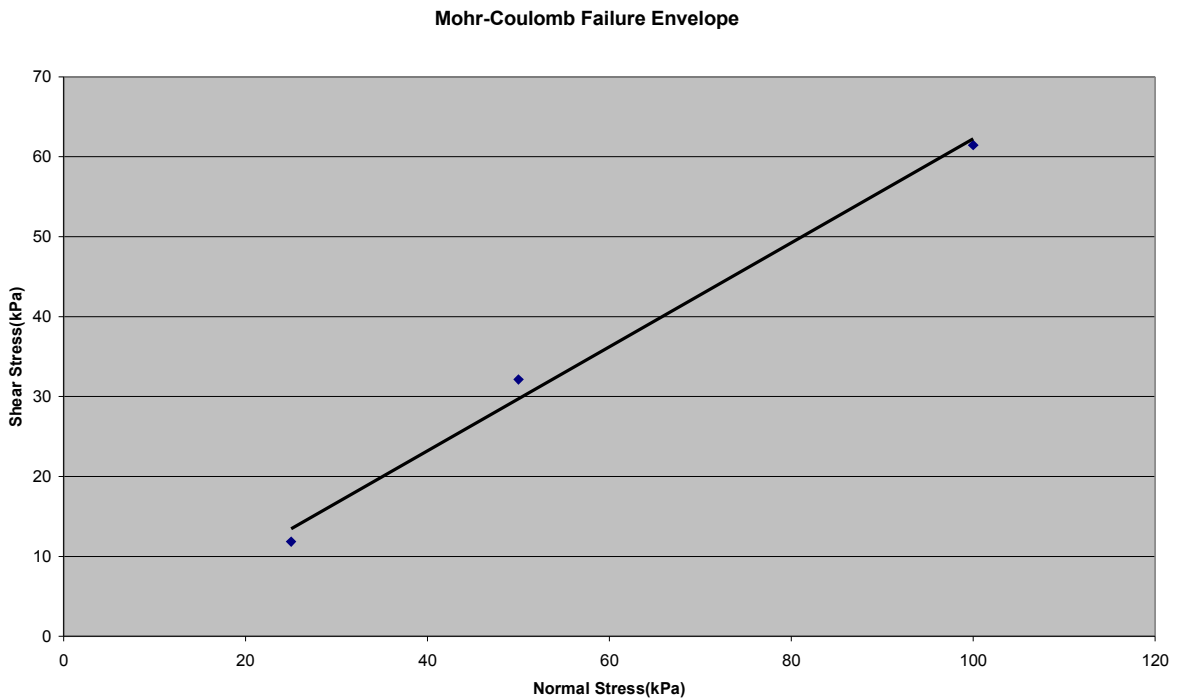


Figure 5.6. Shear Stress vs. Normal Stress graph

5.1.4. 25 per cent Tire Crumb

25 per cent tire crumb by total weight is mixed with sand. The density of the sample is found 11.7 kN/m^3 . The shear stress vs. horizontal displacement graph in Figure 5.7. is drawn and using shear stresses obtained, shear vs. normal stress graph in Figure 5.8. is given. The cohesion value is found 6.9 kPa and angle of internal friction is found $27,31^\circ$. The sample mostly behaved like the previous tests because of the high sand content, but it is observed that the shear strength parameters are better for the mixture than for the sand and tire crumb alone. No peak shear stress was obtained.

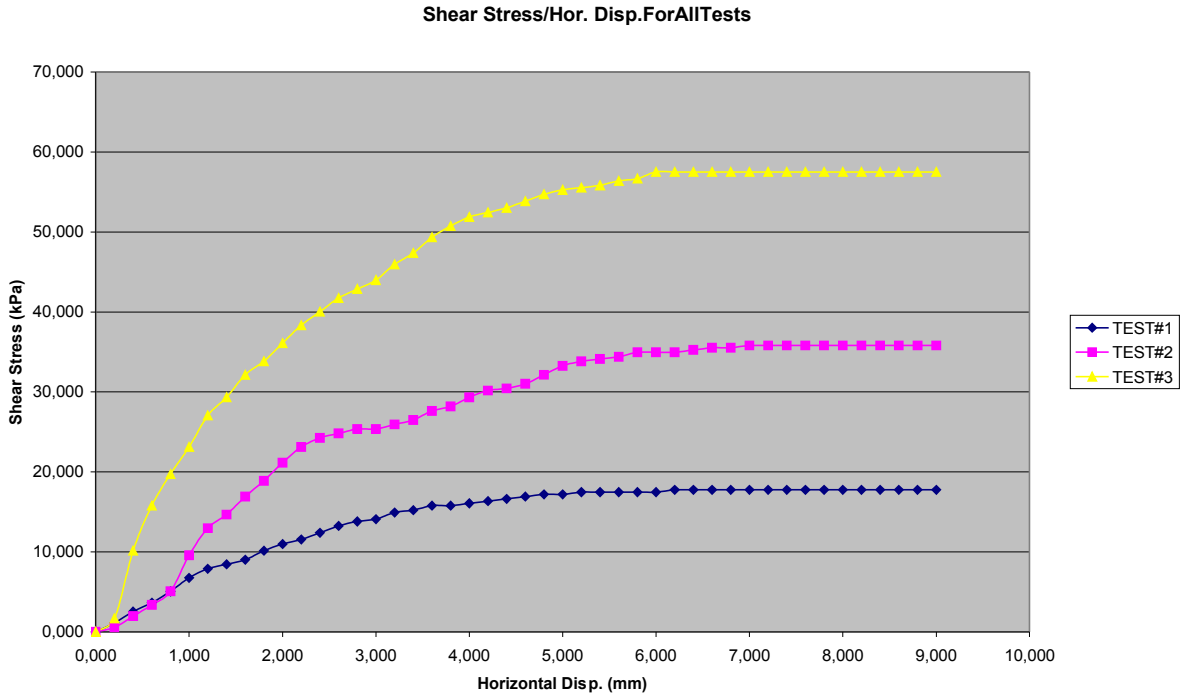


Figure 5.7. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

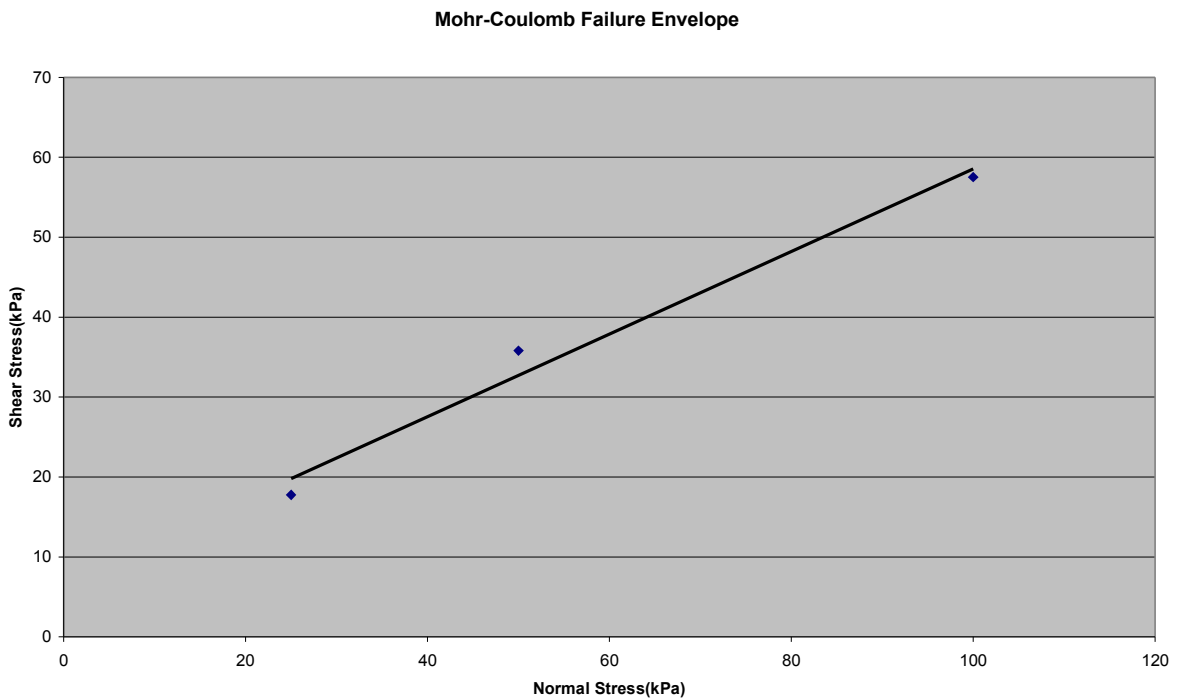


Figure 5.8. Shear Stress vs. Normal Stress graph

5.1.5. 40 per cent Tire Crumb

40 per cent tire crumb by total weight is mixed with sand. The density of the sample is found $9,07 \text{ kN/m}^3$. The shear stress vs. horizontal displacement graph in Figure 5.9. is drawn and using shear stresses obtained, shear vs. normal stress graph in Figure 5.10. is given. The cohesion value is found $1,55 \text{ kPa}$ and angle of internal friction is found as $30,42^\circ$. The sample shows the similar behaviour with tire crumb sample because of the increasing tire crumb content. Almost the constant value is not reached for the higher normal stresses of 50 and 100 kPa. The strength parameters are still ver higher than the tire crumb and sand sample results.

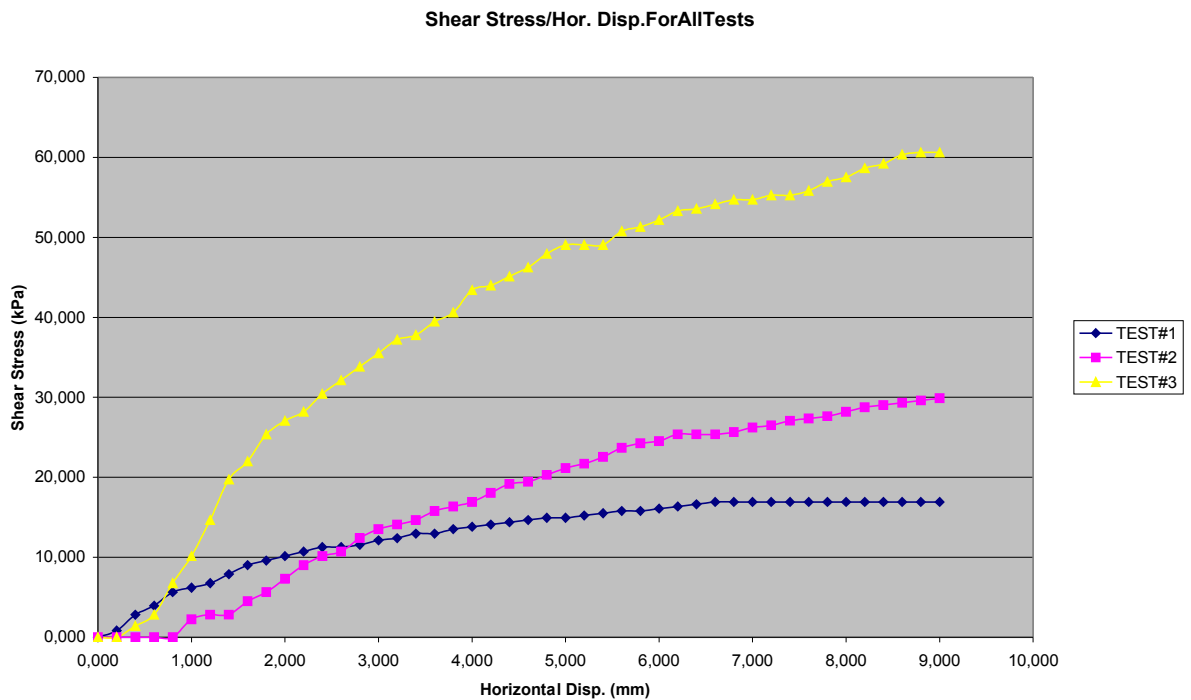


Figure 5.9. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

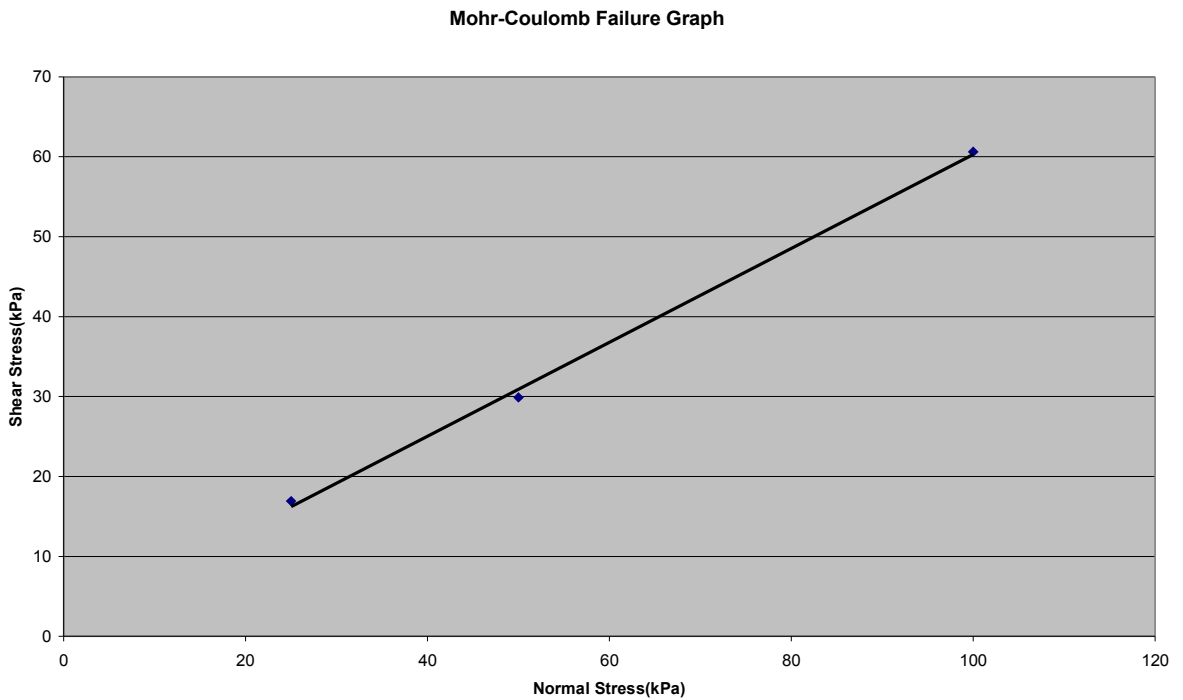


Figure 5.10. Shear Stress vs. Normal Stress graph

5.1.6. 50 per cent Tire Crumb

50 per cent tire crumb by total weight is mixed with sand. The density of the sample is found $8,5 \text{ kN/m}^3$. The shear stress vs. horizontal displacement graph in Figure 5.11. and shear vs. normal stress graph in Figure 5.12. are given. The cohesion value is found $3,8 \text{ kPa}$ and angle of internal friction is found $29,24^\circ$. The shear stress values continued to increase throughout the test. No peak shear stress was observed.

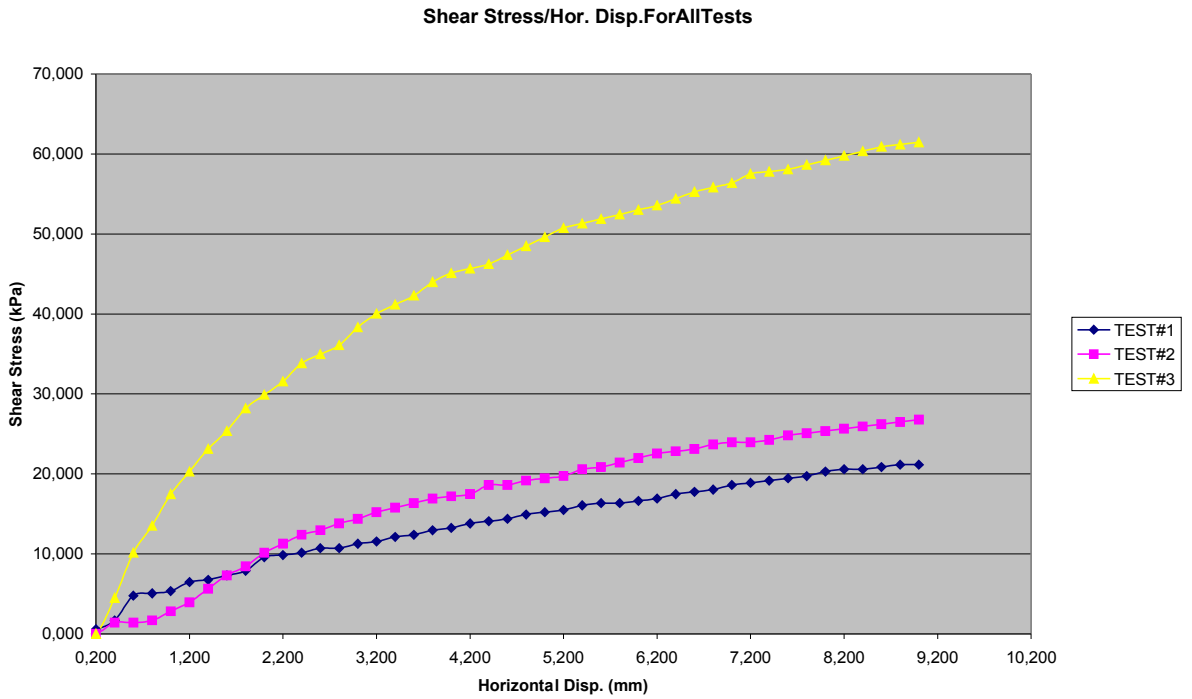


Figure 5.11. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

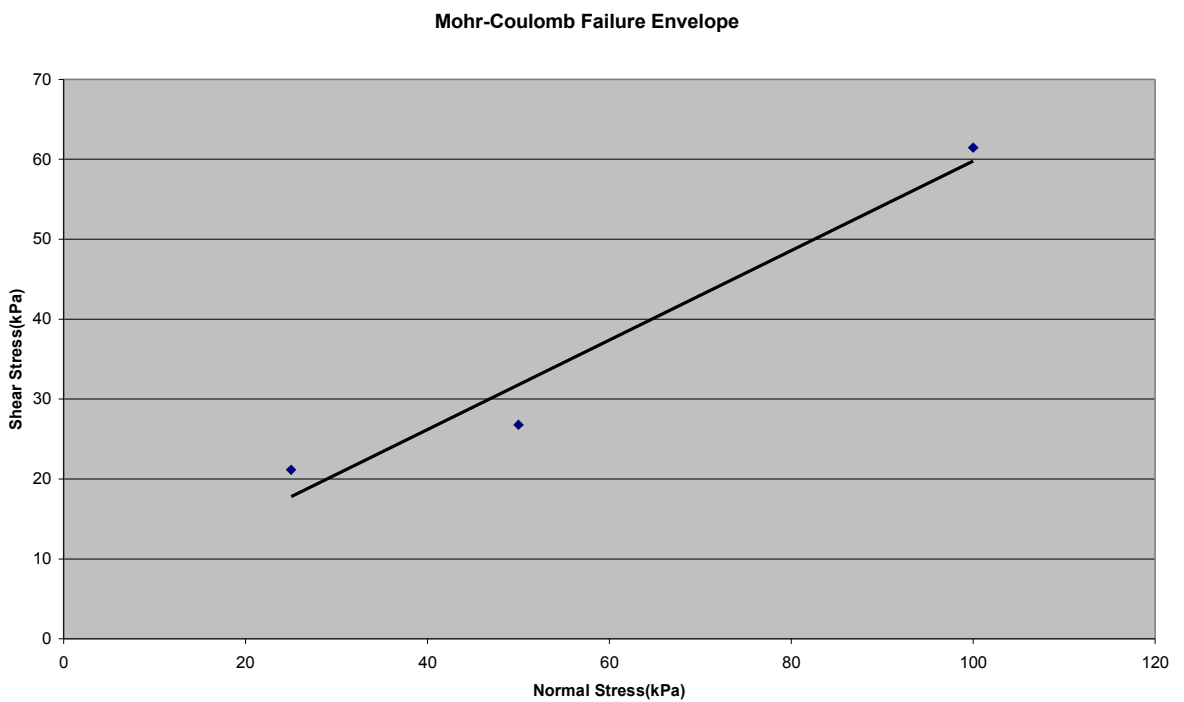


Figure 5.12. Shear Stress vs. Normal Stress graph

5.1.7. 75 per cent Tire crumb

75 per cent tire crumb by total weight is mixed with sand. The density of the sample is found $7,56 \text{ kN/m}^3$. The shear stress vs. horizontal displacement graph in Figure 5.13. is drawn and using shear stresses obtained, shear vs. normal stress graph in Figure 5.14. is given. The cohesion value is found 0 kPa and angle of internal friction is found $29,03^\circ$. The stress values increased rapidly and continued to increase even the maximum strain value of 9mm is reached. If Figure 5.13. is compared with the Figure 5.3., it is clear that the sample achieved nearly the same characteristics as the tire crumb sample. A continuous rise in the shear stress value, as the strain increases, is observed like the tire crumb sample.

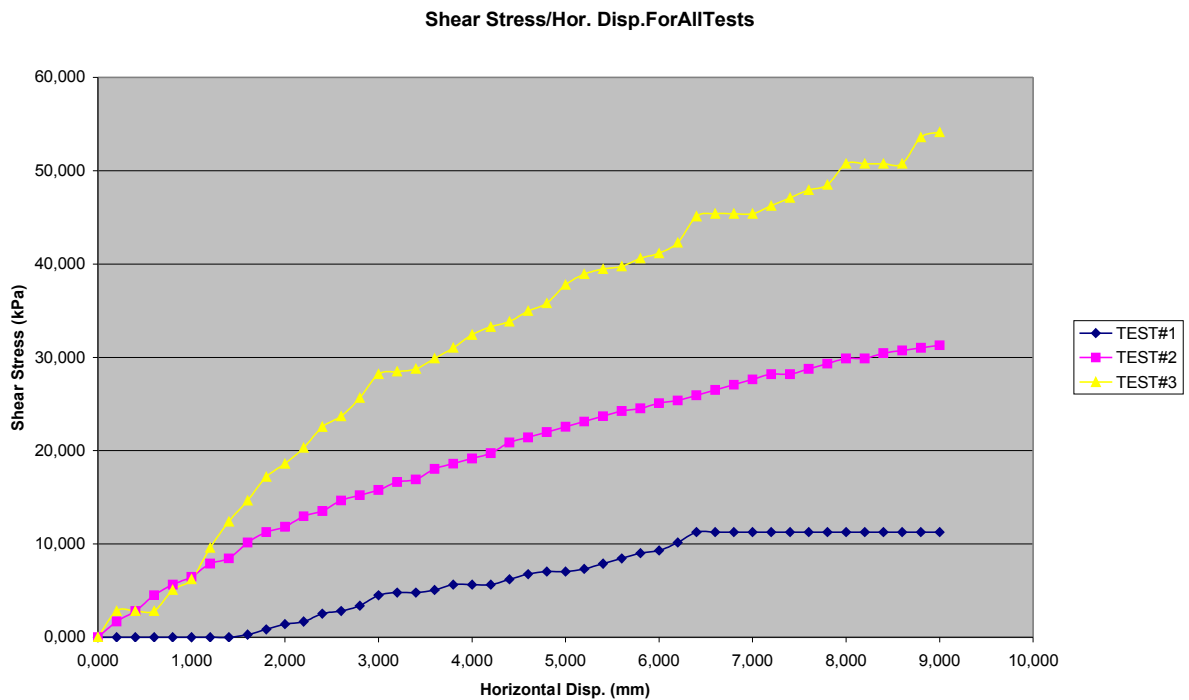


Figure 5.13. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 25, 50 and 100 kPa

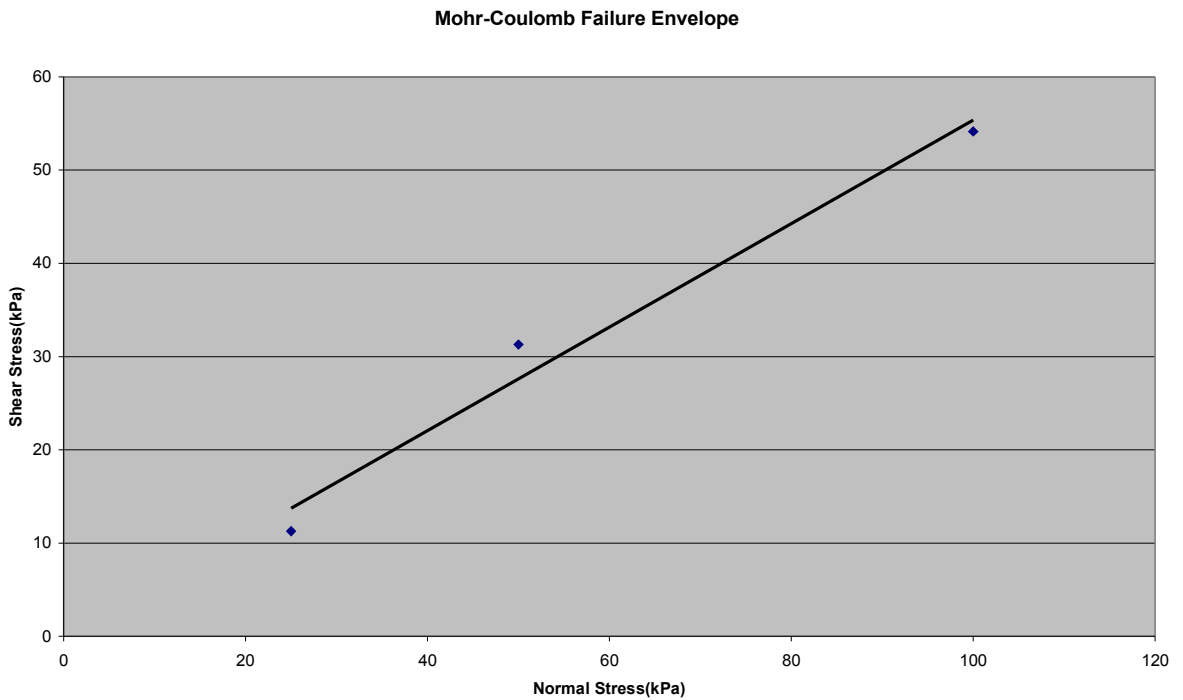


Figure 5.14. Shear Stress vs. Normal Stress graph

5.1.8. Summary of the Direct Shear Test Results

The calculated data for all of the tire crumb+sand mixture samples are shown in the Table 5.1. The values of direct shear test mainly indicated the effects of mixing tire crumb with sand. As seen in the Table, the cohesion values that are found, showed unsteady values. But these values are not the exact values, they are the apparent cohesion values. But the previous test results enlightens the general behaviors of the tire waste and sand mixtures. Due to the test results, it can be generalized that tire waste addition to sand increases the shear strength parameters of sand alone and the higher strength values are observed between the 15 and 40 percentages of tire crumb by weight mixtures. The test results of the direct shear tests are presented in Figure 5.16.

Table 5.1. Summary of direct shear tests results

	Normal Stresses (kPa)	Shear Stresses (kPa)						
		SAND	15 per cent tire crumb	25 per cent tire crumb	40 per cent tire crumb	50 per cent tire crumb	75 per cent tire crumb	100 per cent tire crumb
#1	25	8,45	11,81	17,76	16,91	21,14	11,27	7,89
#2	50	31,29	32,14	35,80	29,88	26,78	31,29	11,27
#3	100	37,78	61,45	57,51	60,618	61,46	54,13	14,94

tan values	0,42	0,65	0,51	0,58	0,55	0,55	0,09
friction angle	22,9	33,06	27,31	30,42	29,24	29,03	5,19
Cohesion	0	0	6,9076	1,55	3,8062	0	6,06
density(kN/m3)	14,58	13,61	11,66	9,07	8,5	7,56	5,83

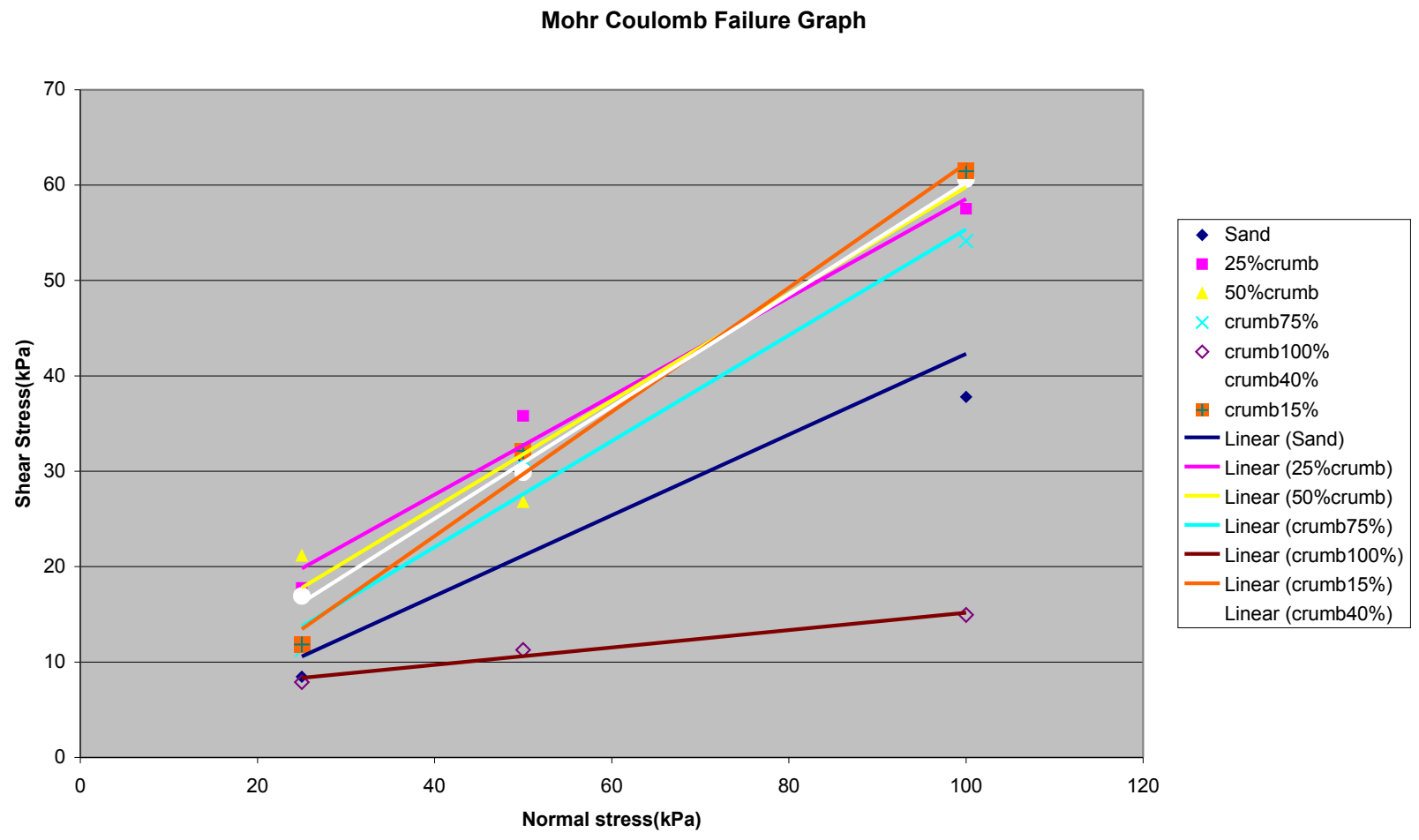


Figure 5.15. Shear stress vs. Normal Stress graph for all tests

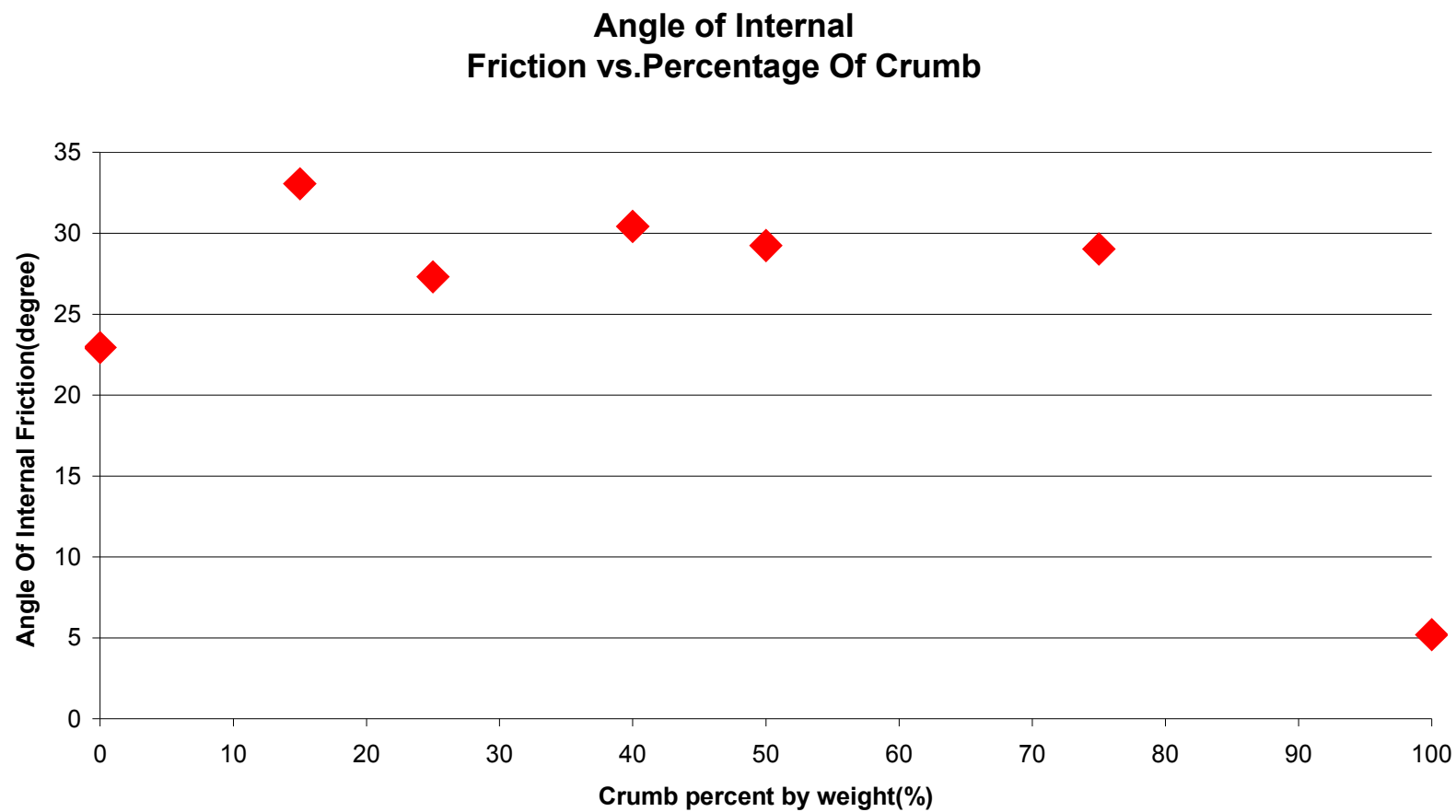


Figure 5.16. Angle of internal friction vs. Percentage of tire crumb

5.2. Large Scale Direct Shear Test Results

For the large scale direct shear tests, the previous calculations of relative densities are used to obtain the required weights of samples that will be placed in the shear box. The samples are prepared in the required weights and they are compacted in the shear box by the help of a hammer while they are poured into the box, thus the desired densities are achieved by the previously known volumes and weights. The direct shear test are done for both the samples of sand, tire crumb, TB1, TB2 and the mixtures of sand with these lightweight materials in various proportions. During the test, 20kPa, 40kPa and 80kPa of normal stresses are applied to each samples respectively. Test#1, Test#2 and Test#3 represents tests for normal stress 20kPa, 40kPa and 80kPa respectively.

5.2.1. 100 per cent Sand

Before the mixtures are tested, first, the sand (Figure 5.17.) is tested alone. As seen in Figure 5.18., the sand sample shear stress increased rapidly and stopped as the strain value reached 10mm. The obtained data is used for determining the failure envelope (Figure 5.19.) and strength parameters are calculated. Cohesion is found 0 kPa, angle of internal friction is found $34,22^\circ$. The determined unit weight is 14 kN/m^3 for sand. Figure 5.20. represents a view of the test sample during testing.



Figure 5.17. Sand Sample placed in the shear box

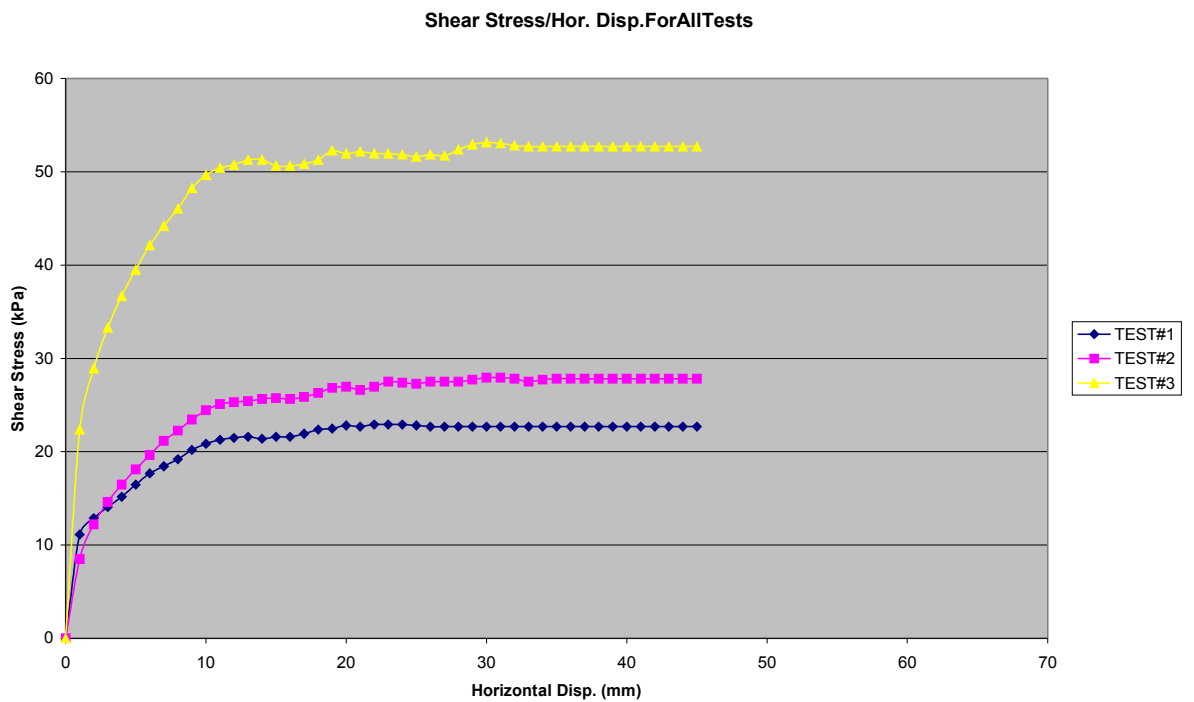


Figure 5.18. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

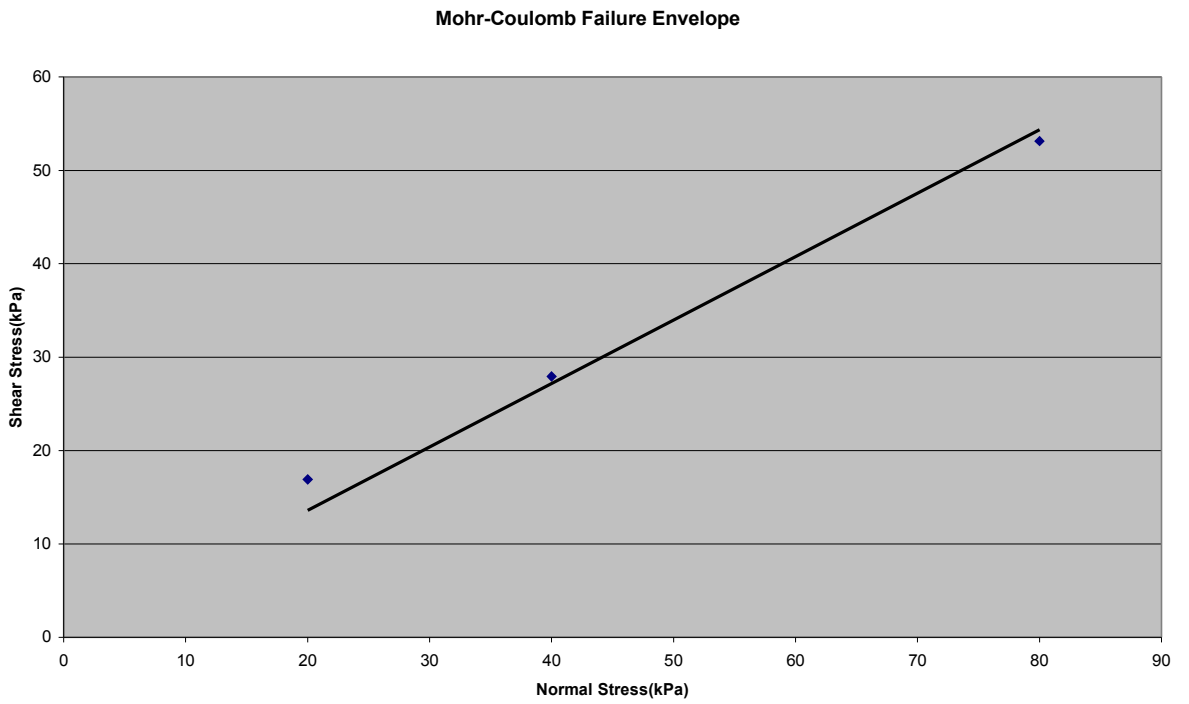


Figure 5.19. Shear Stress vs. Normal Stress graph



Figure 5.20. Horizontally loaded Sand

5.2.2. 100 per cent Tire crumb

The tire waste, tire crumb (Figure 5.21.) is tested alone without mixing for the strength parameters and it is observed that shear stress values increased as the shear box is moved laterally until even the horizontal displacement exceeds the 45mm (Figure 5.22.). So the test is continued until the shear stress value is fixed at a constant volume. The obtained data is used for determining the failure envelope (Figure 5.23.) and strength parameters are calculated. Cohesion is found 5,4kPa, angle of internal friction is found 16,39°. The determined unit weight for the tire crumb is 5,5 kN/m³.



Figure 5.21. 100 per cent Tire crumb placed in the shear box

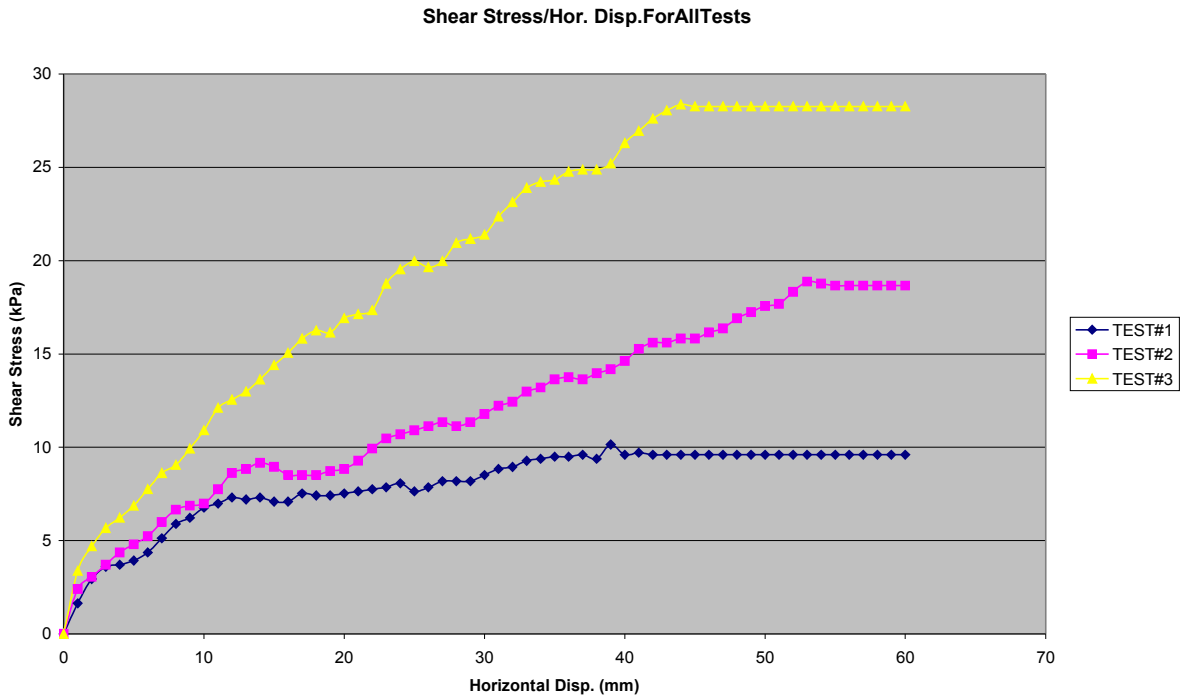


Figure 5.22. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

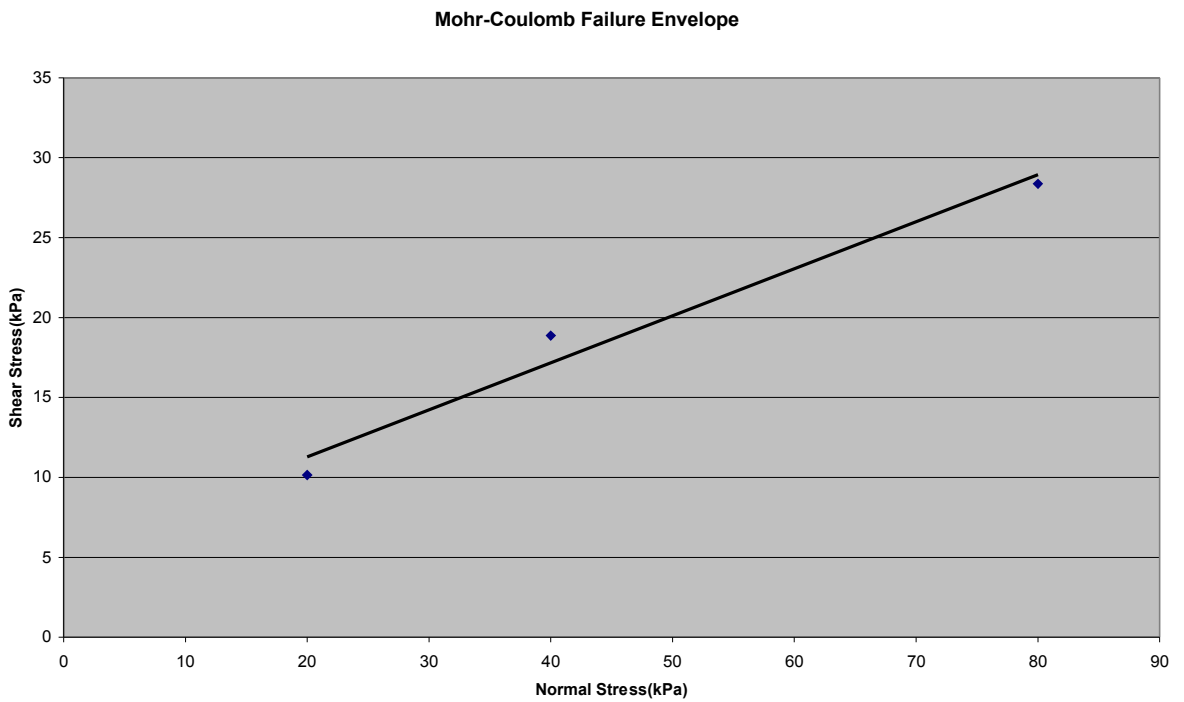


Figure 5.23. Shear Stress vs. Normal Stress graph

5.2.3. 100 per cent TB1

The tire buffings, TB1 (Figure 5.24.) are tested alone without mixing for the strength parameters and it is observed that shear stress values increased so closely under different normal loads. As represented in the Figure 5.25., the values for the 20 and 40 kPa normally loaded samples were nearly same until displacement was 25mm. The tests are continued until the shear stress values are fixed at a constant volume. The obtained data is used for determining the failure envelope (Figure 5.26.) and strength parameters are calculated. Cohesion is found 7,58kPa, angle of internal friction is found 11,56°. The determined unit weight is 3,5 kN/m³ for TB1.



Figure 5.24. 100 per cent TB1 placed in the shear box

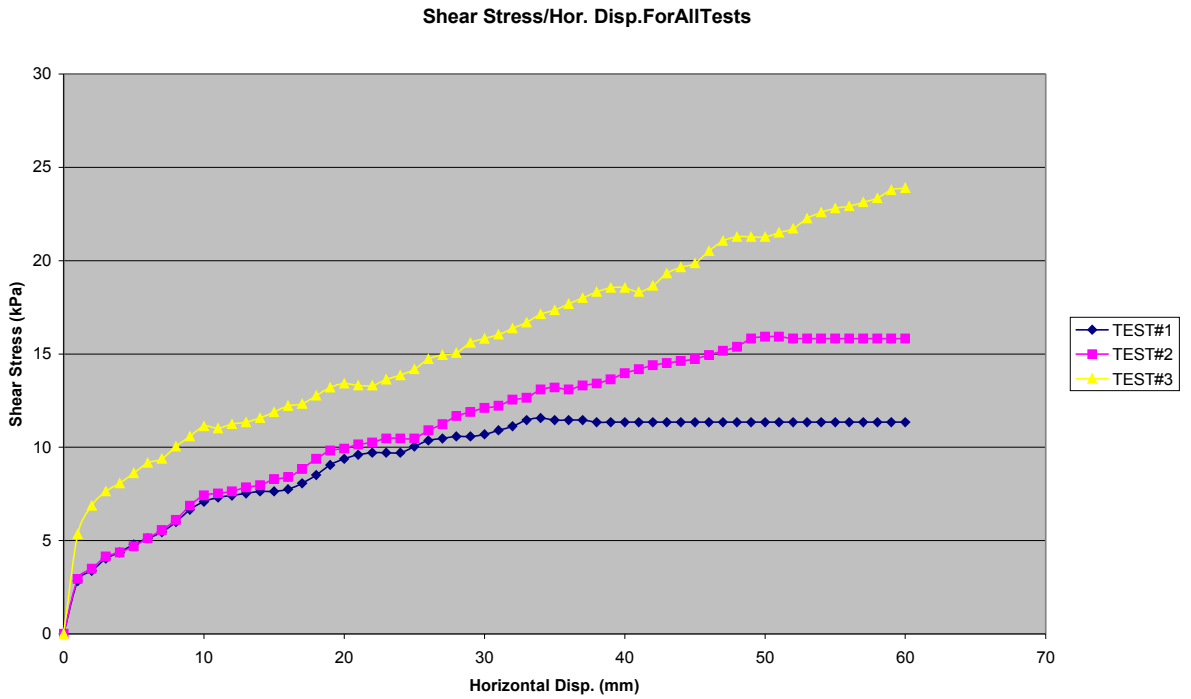


Figure 5.25. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

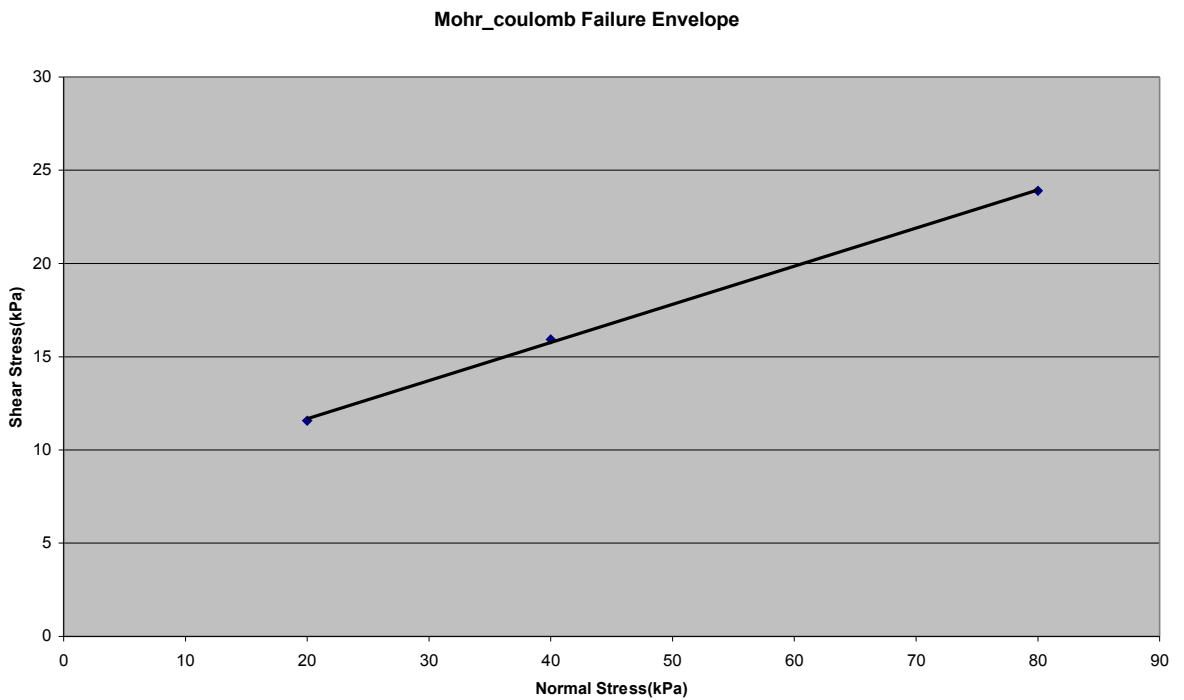


Figure 5.26. Shear Stress vs. Normal Stress graph

5.2.4. 100 per cent TB2

The tire buffings, TB2 are tested alone and it is observed that shear stress values increased under different normal stresses. As represented in the Figure 5.27., the values for the 20 and 40 kPa normally loaded samples are nearly same until displacement was 25mm, just like it was observed in the test results of TB1. The tests are continued until the shear stress values are fixed at a constant volume. The obtained data is used for determining the failure envelope (Figure 5.28.) and strength parameters are calculated. Cohesion is found 12,44kPa, angle of internal friction is found 7,37°. The determined unit weight is 3,5 kN/m³ for TB2. The Figure 5.29. represents a view of the test sample during testing.

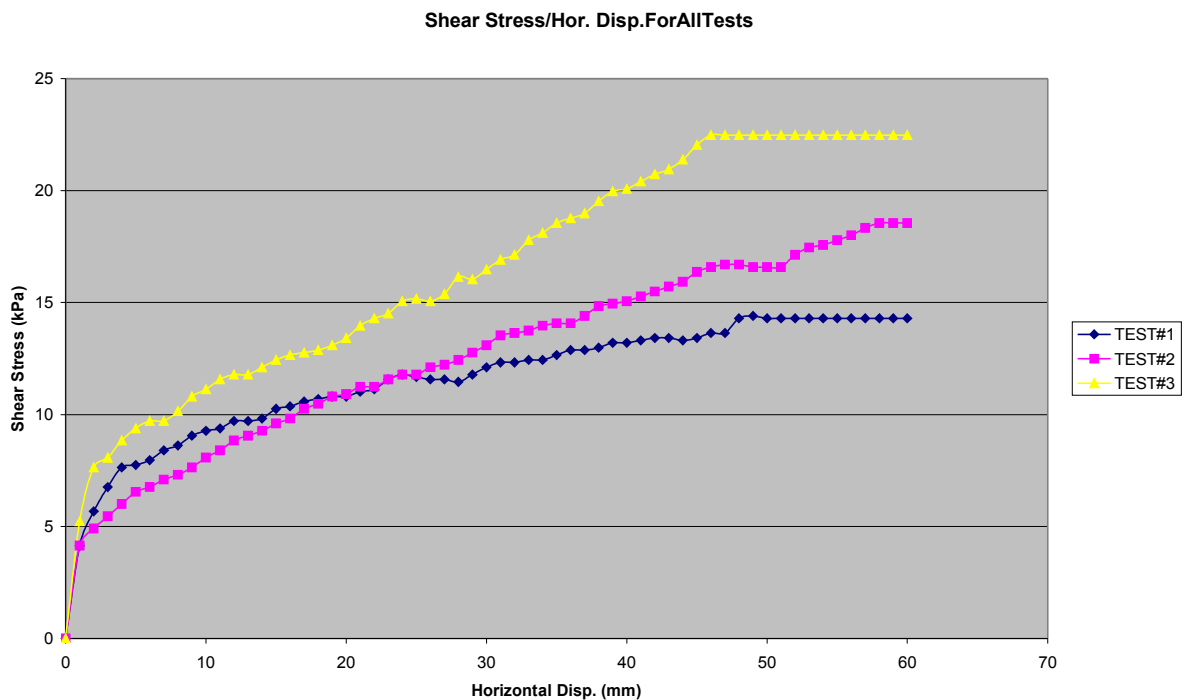


Figure 5.27. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

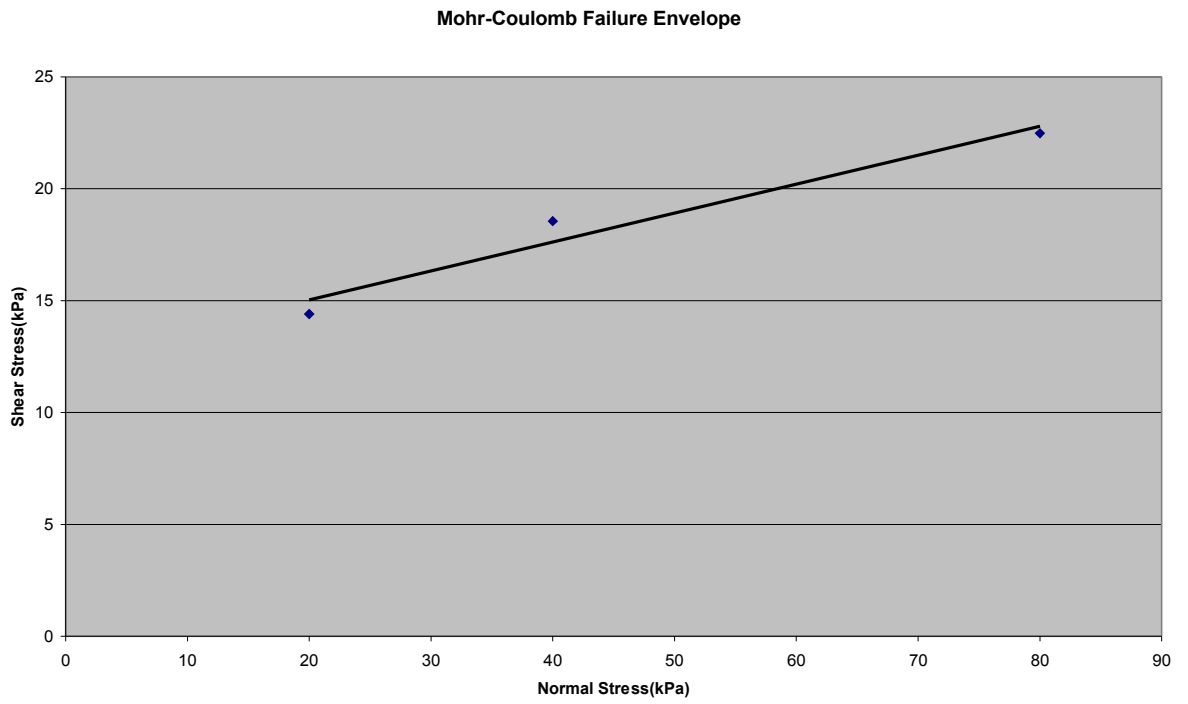


Figure 5.28. Shear Stress vs. Normal Stress graph



Figure 5.29. Horizontally loaded TB2

5.2.5. 10 per cent Tire crumb

Samples are prepared by adding tire crumb to the sand in a proportion of 10 per cent of the total weight. Then they are tested in the shear box (Figure 5.30.).

As the Figure 5.31. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 20mm, all of the test results of 20, 40 and 80kPa normally loaded samples reach peak values and then starts to decrease. This indicates that the mixture is mostly dominated by the sand. The obtained data is used for determining the failure envelope (Figure 5.32.) and strength parameters are calculated. Cohesion is found 5,46kPa, angle of internal friction is found 38,32°. The determined unit weight is 13,5 kN/m³ for 10 per cent tire crumb sample.

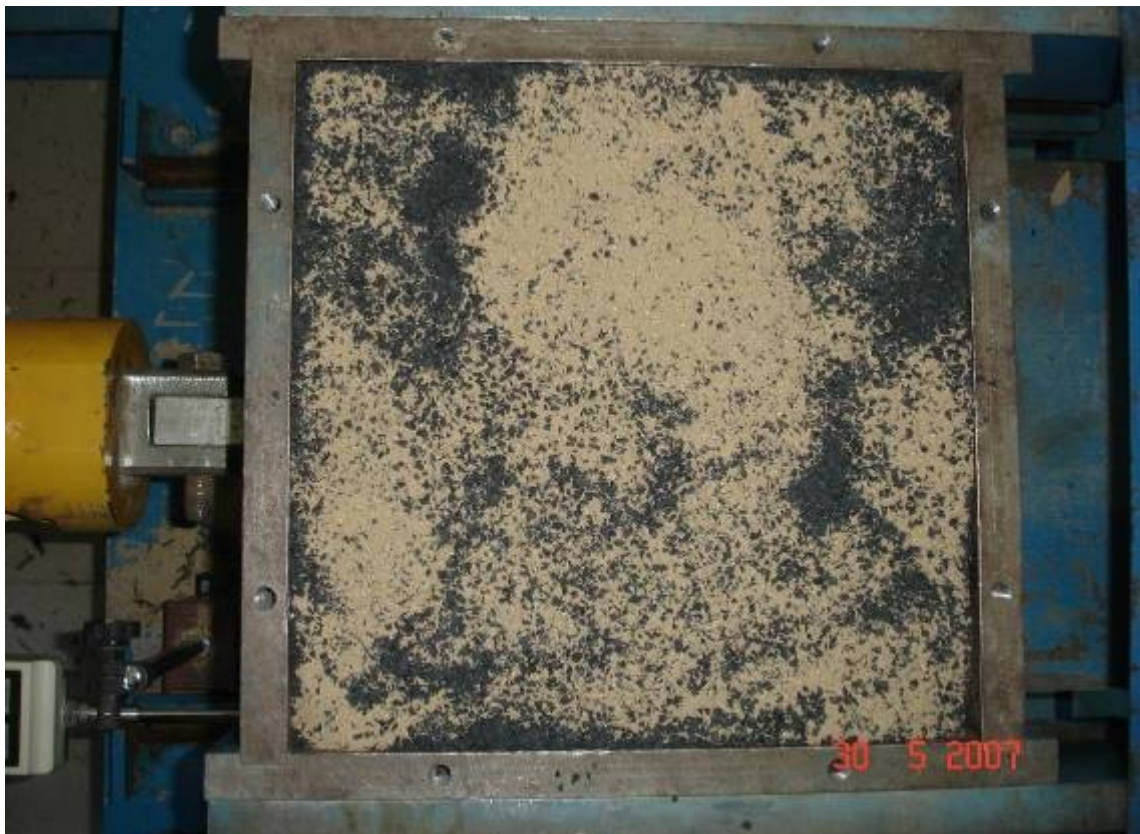


Figure 5.30. 10 per cent Tire crumb placed in the shear box

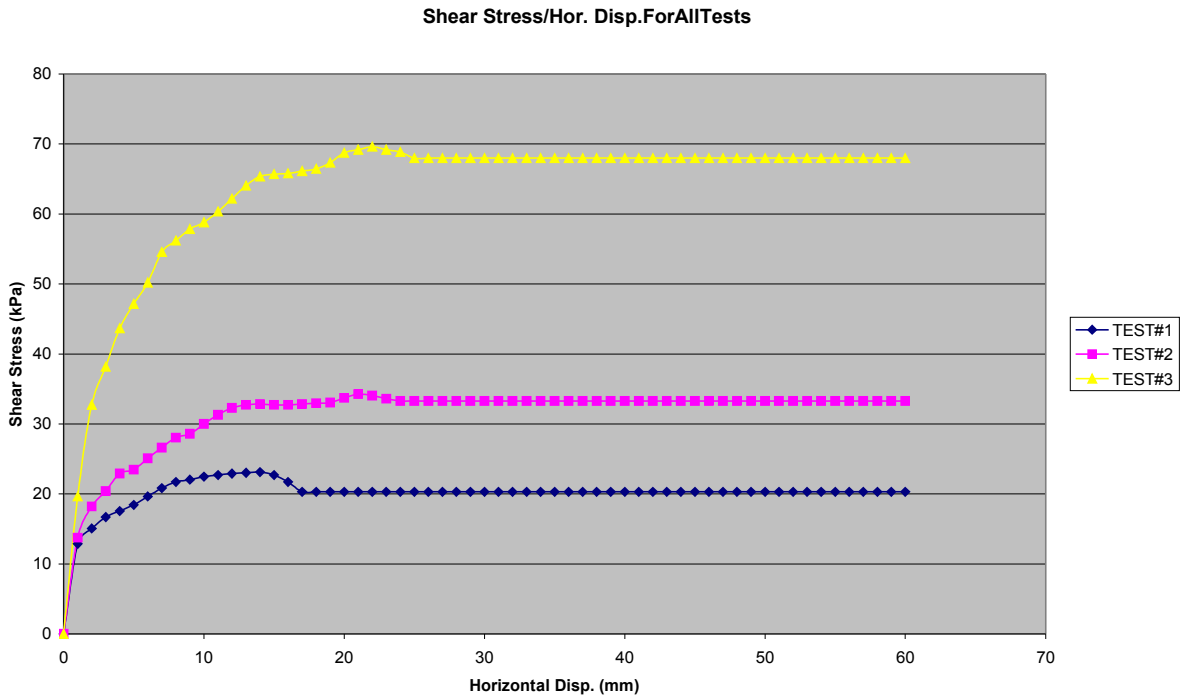


Figure 5.31. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

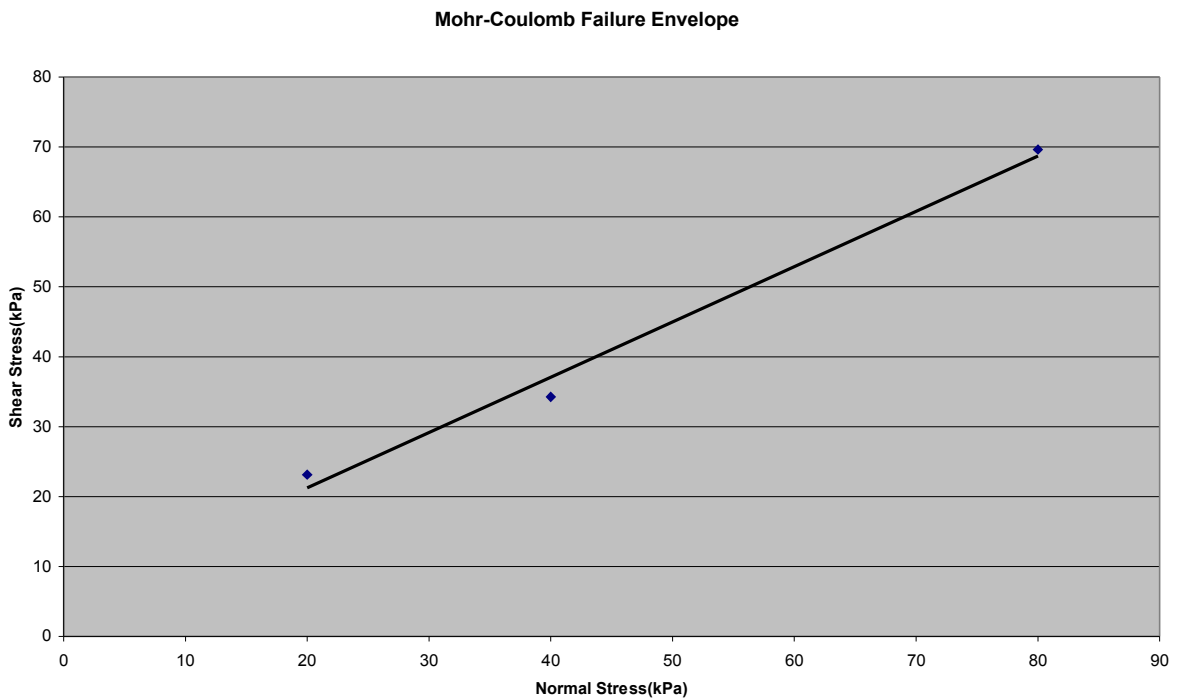


Figure 5.32. Shear Stress vs. Normal Stress graph

5.2.6. 20 per cent Tire crumb

Samples are prepared by adding tire crumb to the sand in a proportion of 20 per cent of the total weight. Then they are tested in the shear box (Figure 5.33.).

As the Figure 5.34. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 20mm, all of the test results of 20, 40 and 80kPa normally loaded samples reach peak values and then starts to decrease. But the decrease is not rapid as the 10 per cent sample does. This indicates that the mixture is not dominated by the sand as the 10 per cent does. But it is still dominated mostly by the sand. The obtained data is used for determining the failure envelope (Figure 5.35.) and strength parameters are calculated. Cohesion is found 10,86kPa, angle of internal friction is found 29,52°. The determined unit weight is 13 kN/m³ for 20 per cent tire crumb sample.



Figure 5.33. 20 per cent Tire crumb placed in the shear box

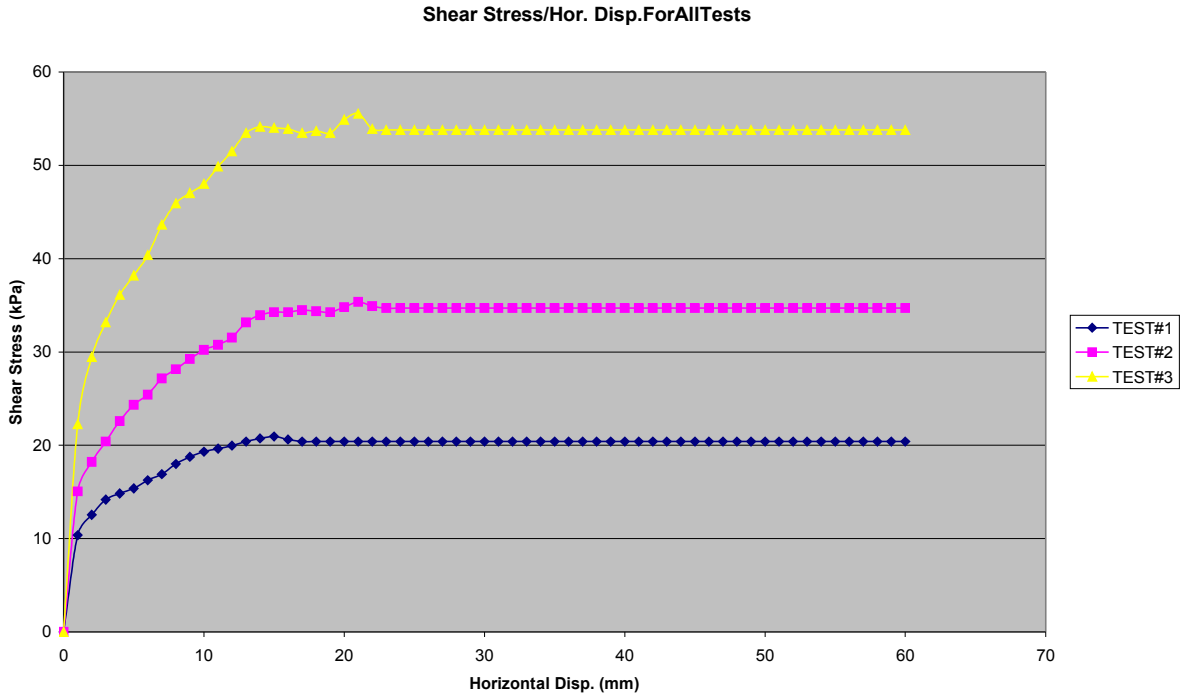


Figure 5.34. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

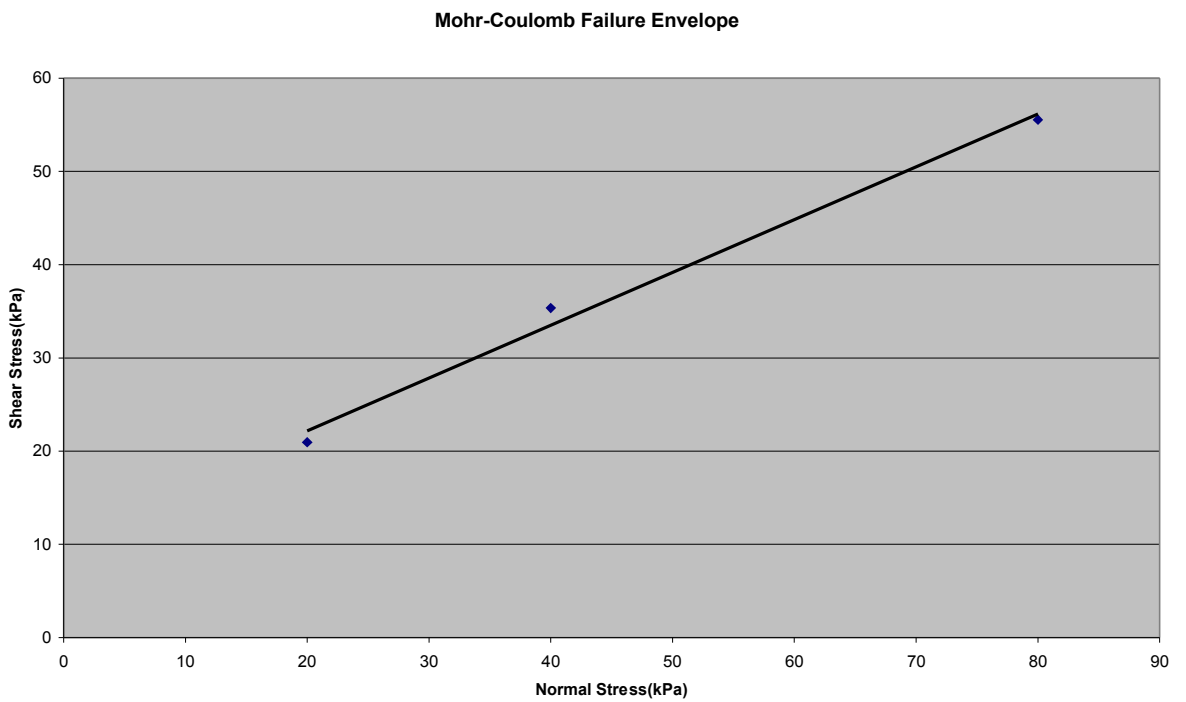


Figure 5.35. Shear stress vs. Normal Stress graph

5.2.7. 30 per cent Tire crumb

Samples are prepared by adding tire crumb to the sand in a proportion of 30 per cent of the total weight. Then they are tested in the shear box (Figure 5.36.).

As the Figure 5.37. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 25mm, all of the test results of 20, 40 and 80kPa normally loaded samples reach peak values and becomes constant. The tire waste characteristics becomes more pronounced. But it is still dominated mostly by the sand. The obtained data is used for determining the failure envelope (Figure 5.38.) and strength parameters are calculated. Cohesion is found 12,77kPa, angle of internal friction is found 28,13°. The determined unit weight is 12 kN/m³ for 30 per cent tire crumb sample.



Figure 5.36. 30 per cent Tire crumb placed in the shear box

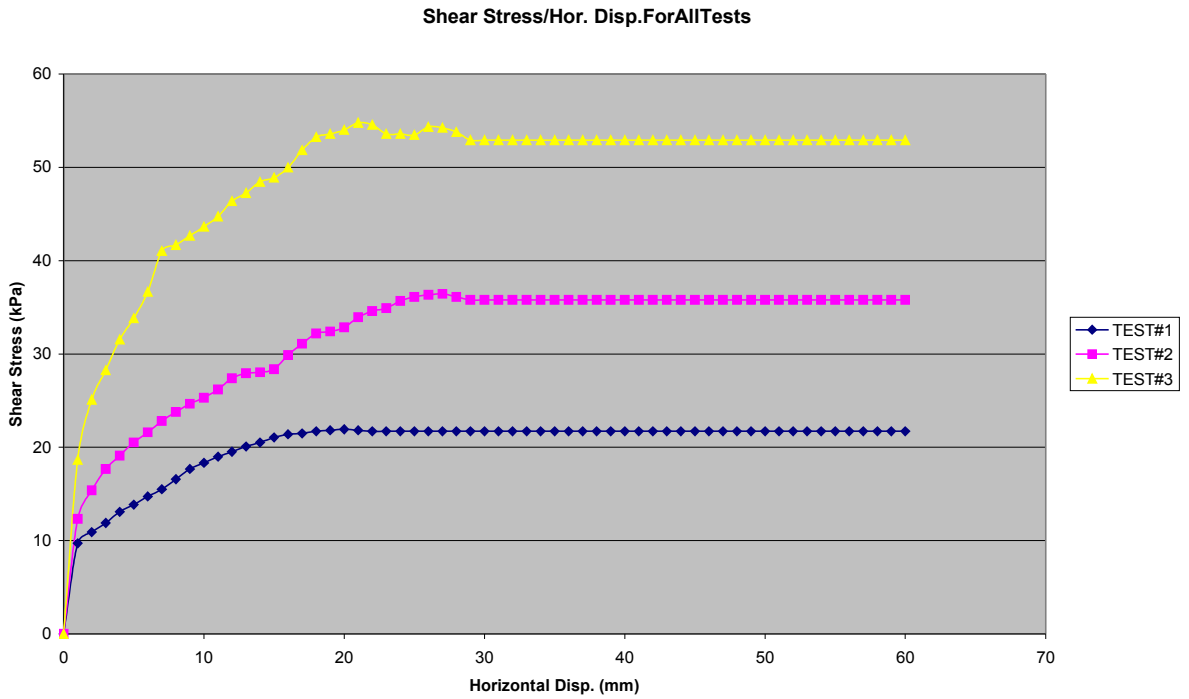


Figure 5.37. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

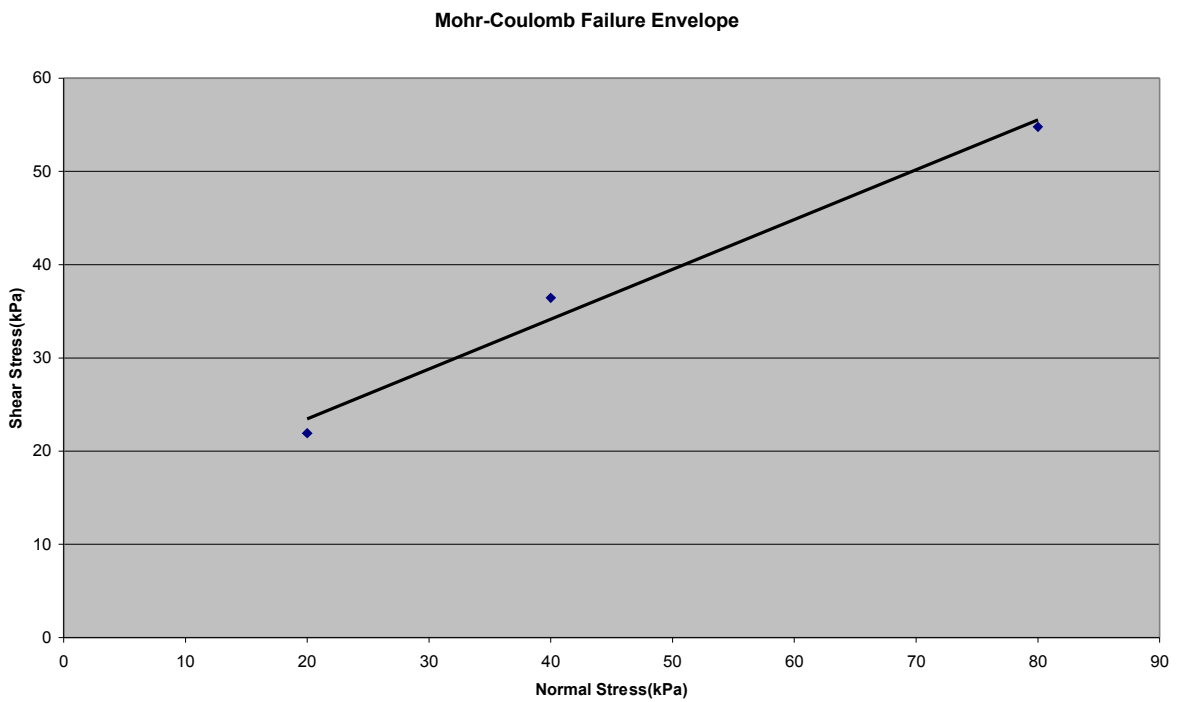


Figure 5.38. Shear Stress vs. Normal Stress graph

5.2.8. 10 per cent TB1

Samples are prepared by adding tire buffings, TB1 to the sand in a proportion of 10 per cent of the total weight. Then they are tested in the shear box (Figure 5.39.).

As the Figure 5.40. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 15mm, all of the test results of 20, 40 and 80kPa normally loaded samples reach peak values and then starts to decrease. This indicates that the mixture is mostly dominated by the sand. The obtained data is used for determining the failure envelope (Figure 5.41.) and strength parameters are calculated. Cohesion is found 16.53kPa, angle of internal friction is found $29,79^\circ$. The determined unit weight is $13,5 \text{ kN/m}^3$ for 10 per cent TB1 sample. The Figure 5.42. represents a view of the test sample during testing.



Figure 5.39. 10 per cent TB1 placed in the shear box

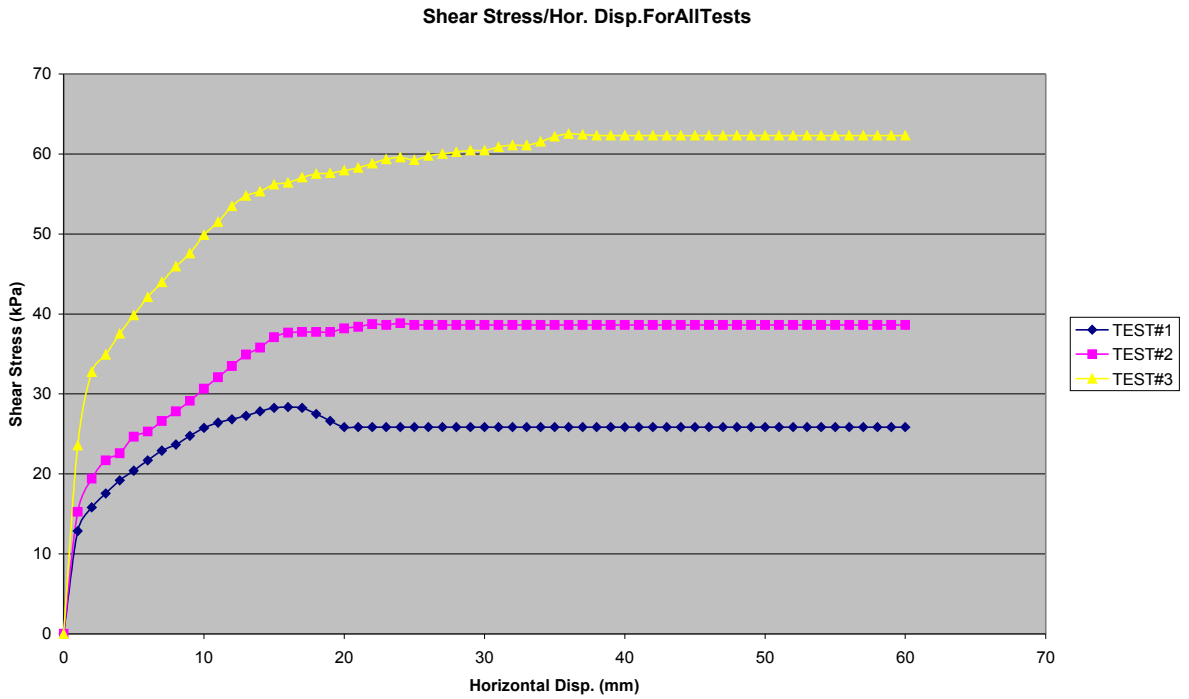


Figure 5.40. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

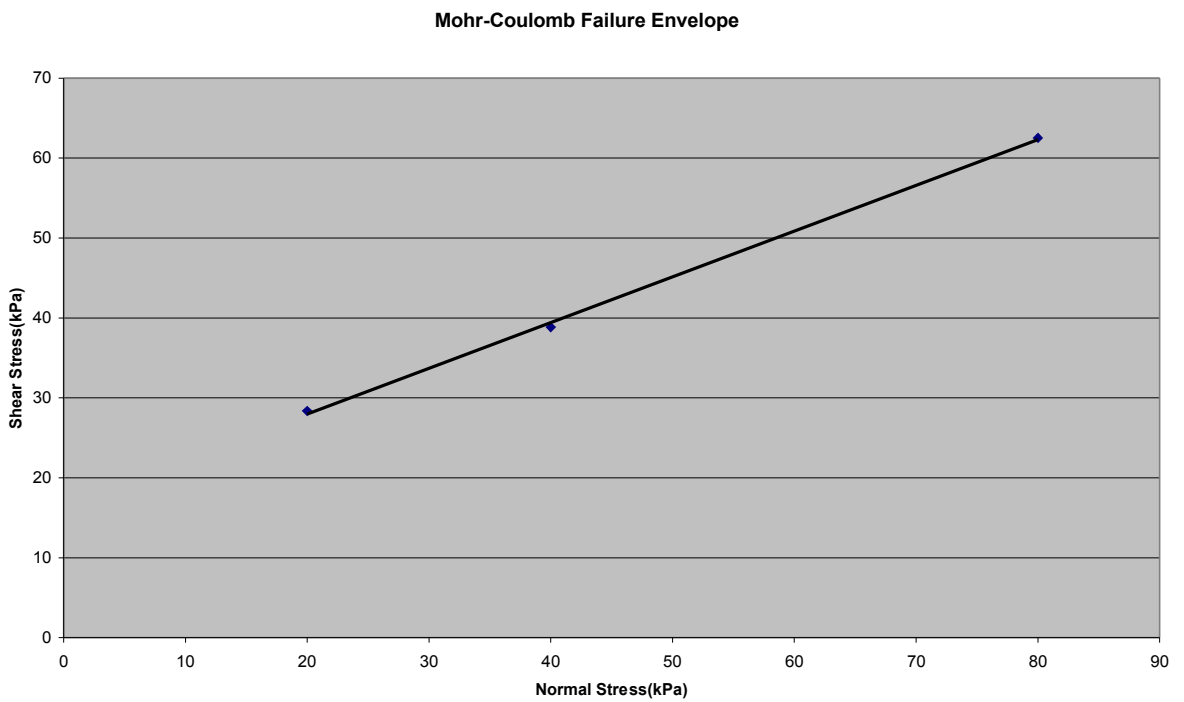


Figure 5.41. Shear Stress vs. Normal Stress graph



Figure 5.42. Horizontally loaded 10 per cent TB1

5.2.9. 20 per cent TB1

Samples are prepared by adding tire buffings, TB1 to the sand in a proportion of 20 per cent of the total weight. Then they are tested in the shear box (Figure 5.43.).

As the Figure 5.44. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 15mm, all of the test results of 20, 40 and 80kPa normally loaded samples starts to increase slightly after a rapid increase.. This indicates that the mixture is not dominated by the sand as the 10 per cent does. But it is still dominated mostly by the sand. The obtained data is used for determining the failure envelope (Figure 5.45.) and strength parameters are calculated. Cohesion is found 13,91kPa, angle of internal friction is found 32,37°. The determined unit weight is 12 kN/m³ for 20 per cent TB1 sample. The Figure 5.46. represents a view of the test sample during testing.



Figure 5.43. 20 per cent TB1 placed in the shear box

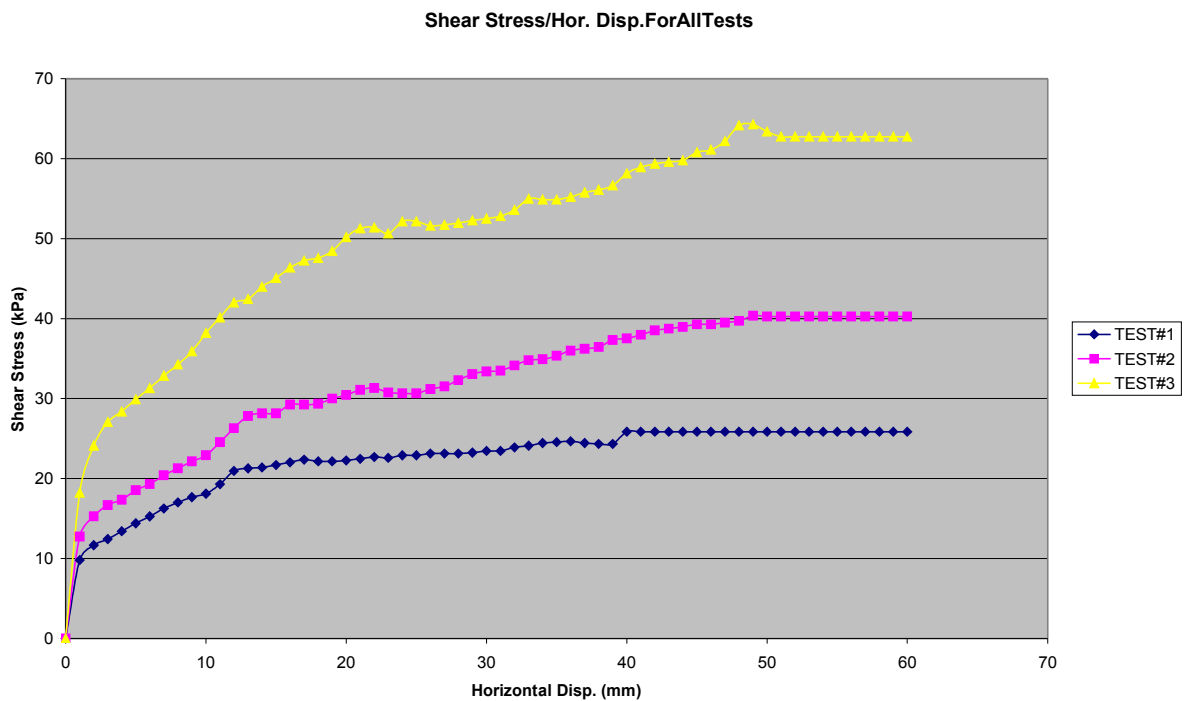


Figure 5.44. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

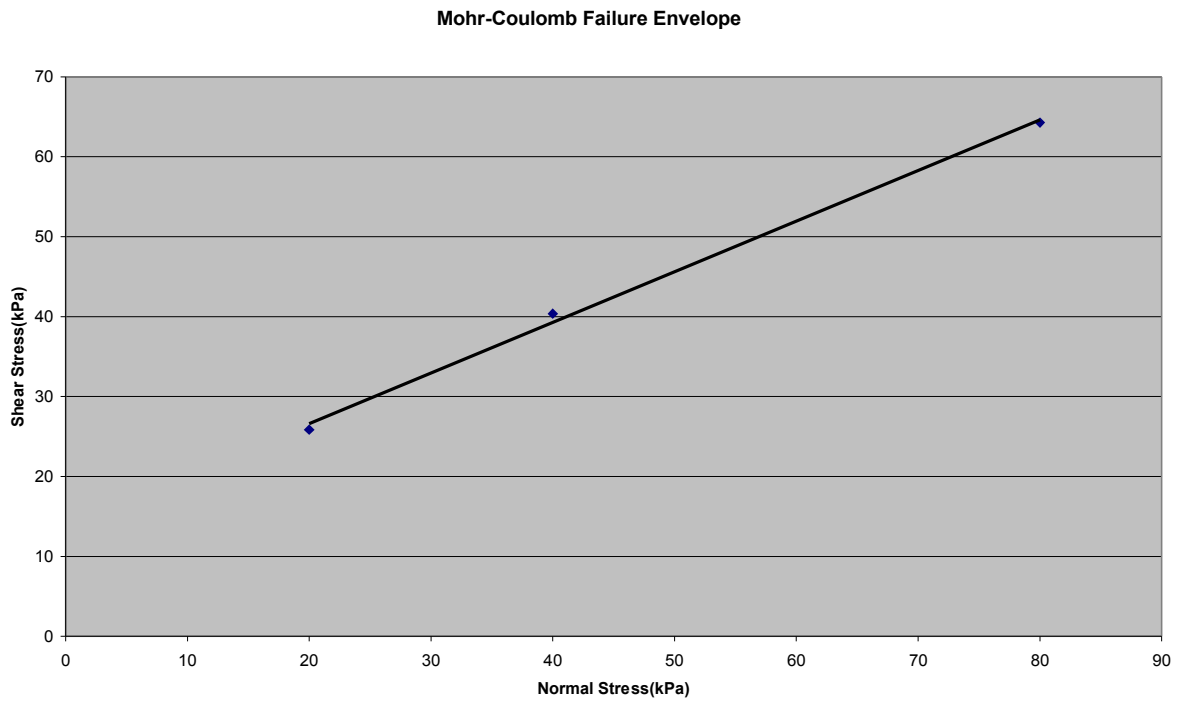


Figure 5.45. Shear Stress vs. Normal Stress graph



Figure 5.46. Horizontally loaded 20 per cent TB1

5.2.10. 30 per cent TB1

Samples are prepared by adding tire buffings, TB1 to the sand in a proportion of 30 per cent of the total weight. Then they are tested in the shear box (Figure 5.47.).

As the Figure 5.48. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 25mm, all of the test results of 20, 40 and 80kPa normally loaded samples become to rise slightly. So, it can be stated that the tire waste characteristics becomes more pronounced. But it is still dominated mostly by the sand. The obtained data is used for determining the failure envelope (Figure 5.49.) and strength parameters are calculated. Cohesion is found 17,73kPa, angle of internal friction is found 25,19°. The determined unit weight is 10 kN/m³ for 30 per cent TB1 sample.

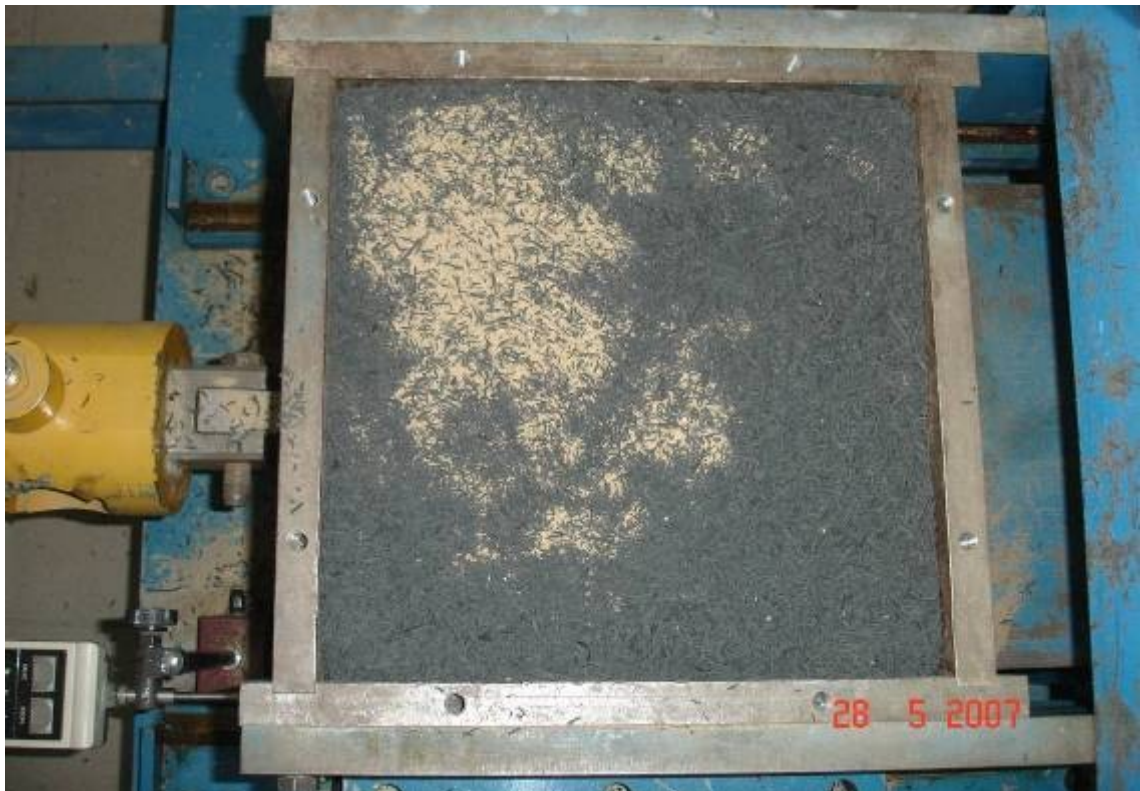


Figure 5.47. 30 per cent TB1 placed in the shear box

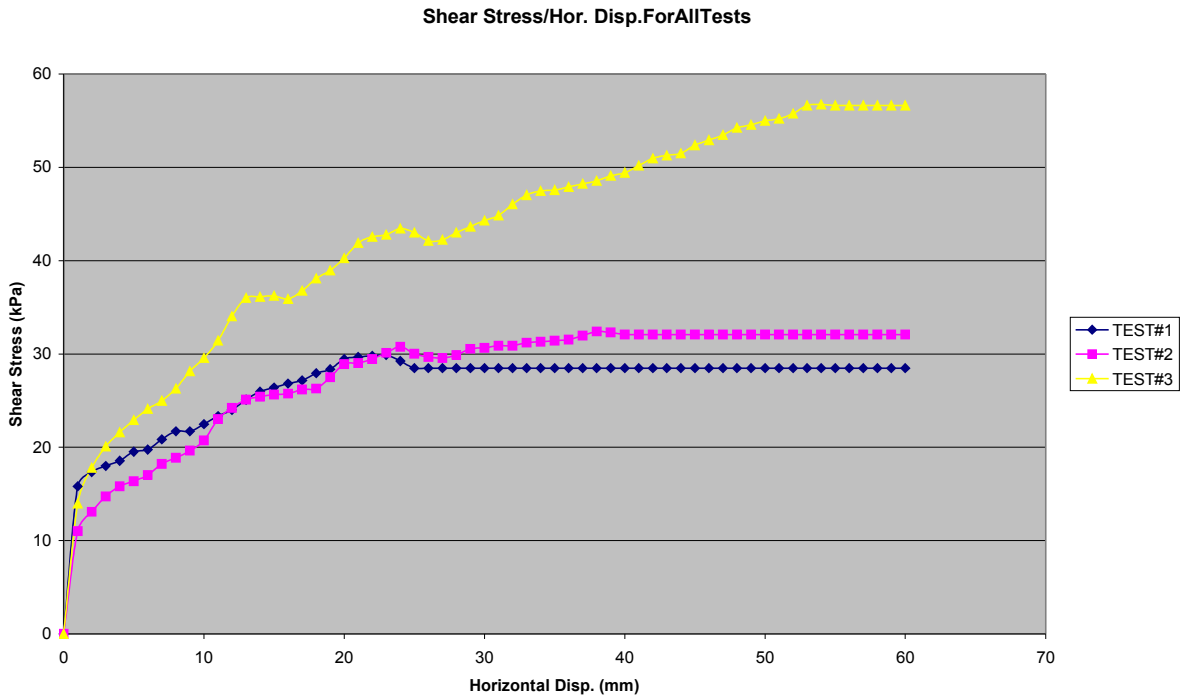


Figure 5.48. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

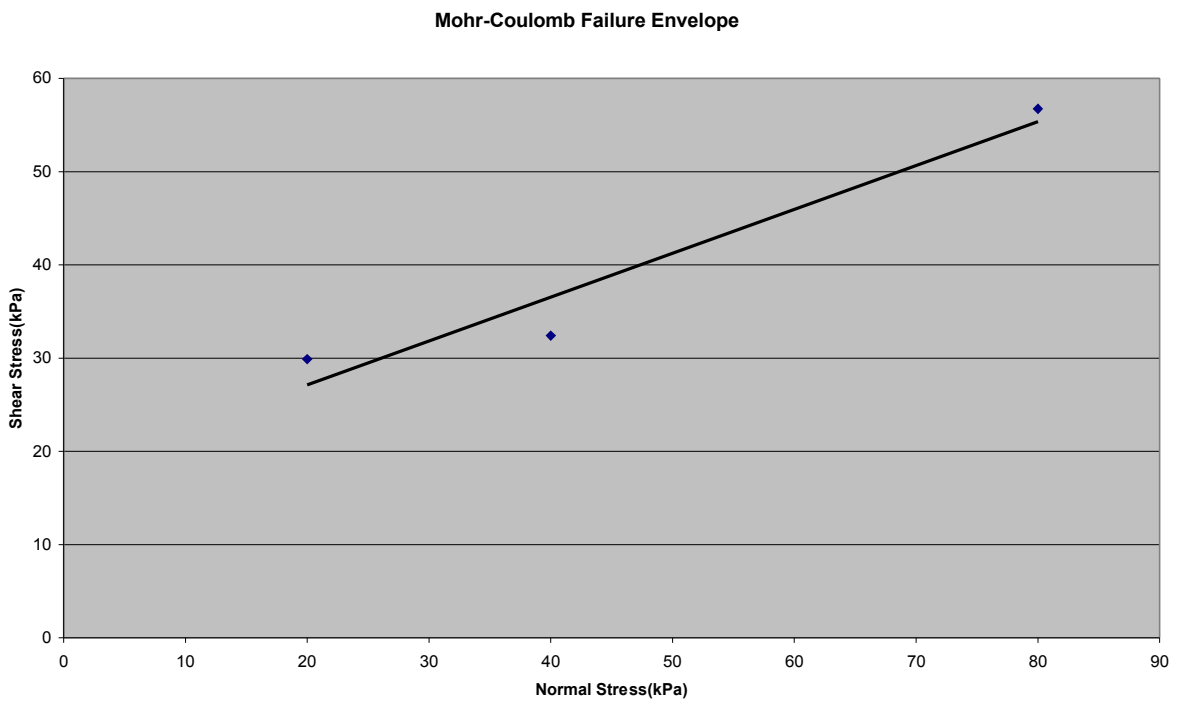


Figure 5.49. Shear Stress vs. Normal Stress graph

5.2.11. 10 per cent TB2

Samples are prepared by adding 10 percent tire buffings (TB2) by weight to the sand. Then they are tested in the shear box (Figure 5.50.).

As the Figure 5.51. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 10mm, all of the test results at 20, 40 and 80kPa normal stresses to reach maksimum values. Until 40mm, shear stress values slightly increase after 10mm of horizontal displacement. The obtained data is used for determining the failure envelope (Figure 5.52.) and strength parameters are calculated. Cohesion is found 11.46kPa, angle of internal friction is found $37,40^\circ$. The determined unit weight is $13,5 \text{ kN/m}^3$. The Figure 5.53. represents a view of the test sample during testing.



Figure 5.50. 10 per cent TB2 placed in the shear box

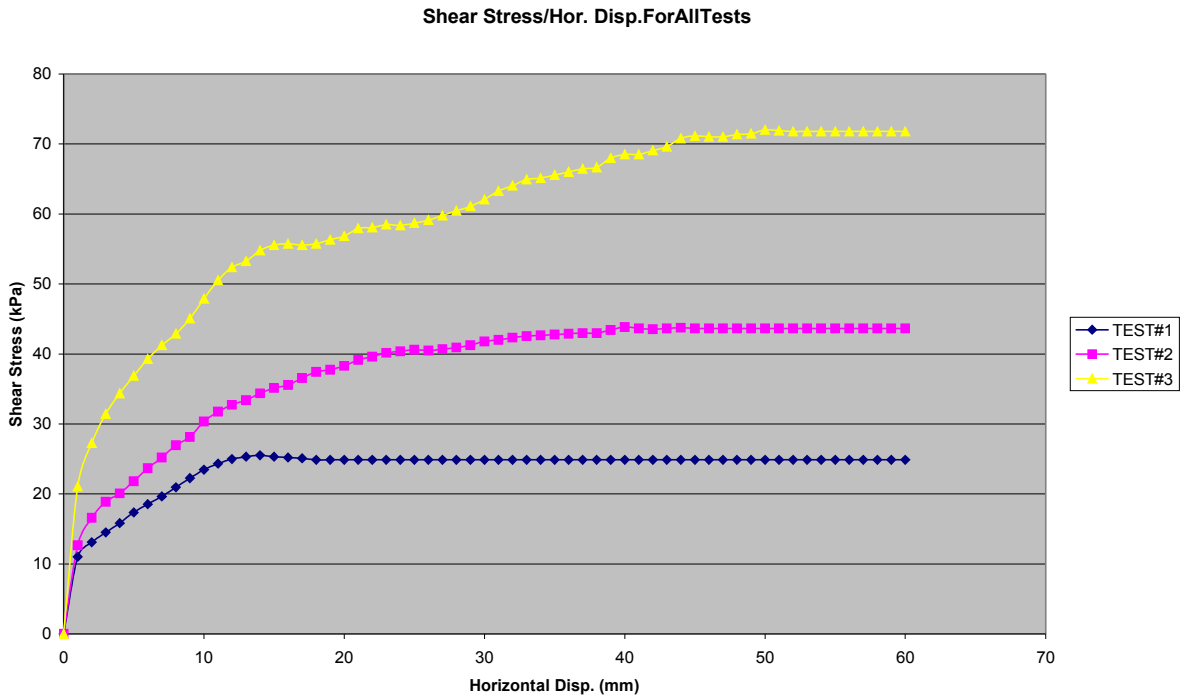


Figure 5.51. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

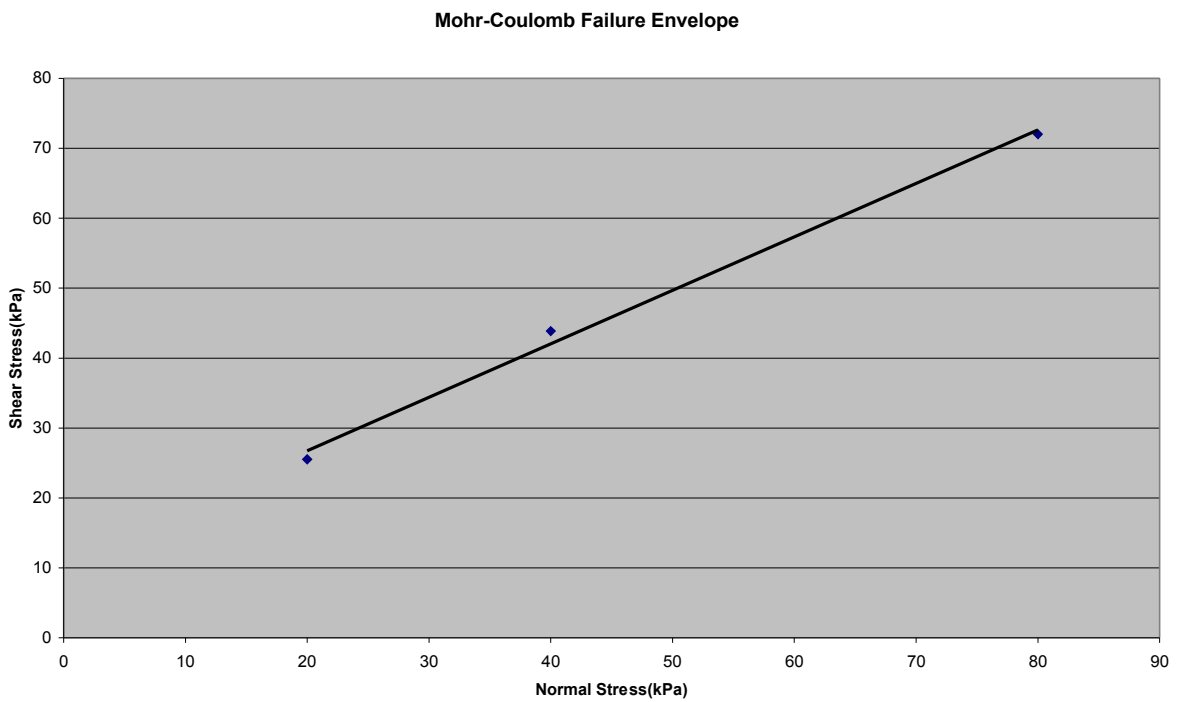


Figure 5.52. Shear Stress vs. Normal Stress graph



Figure 5.53. Horizontally loaded 10 per cent TB2

5.2.12. 20 per cent TB2

Samples are prepared by adding 20 percent tire buffings (TB2) by weight to the sand. Then they are tested in the shear box (Figure 5.54.).

As the Figure 5.55. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 20mm, the test results at the 20, and 40kPa normal stresses reaches a constant value, but at the 80kPa normal stress shear stress value increases slightly until 40mm. The obtained data is used for determining the failure envelope (Figure 5.56.) and strength parameters are calculated. Cohesion is found 0,11kPa, angle of internal friction is found 51,13°. Compared to the other tests, the highest strength parameters found are the 20 per cent TB2 samples. This is a result of the both the fiber structure of the material and effect of using larger fiber sizes. The determined unit weight is 12 kN/m³. The Figure 5.57. represents a view of the test sample during testing



Figure 5.54. 20 per cent TB2 placed in the shear box

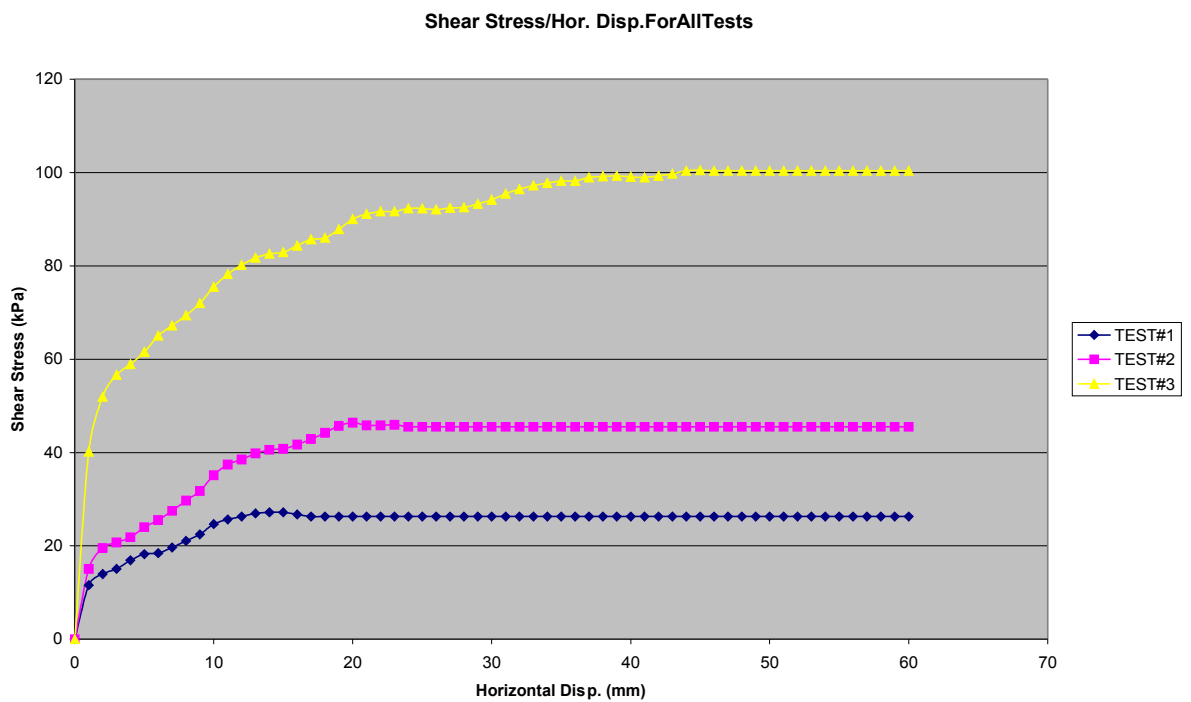


Figure 5.55. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

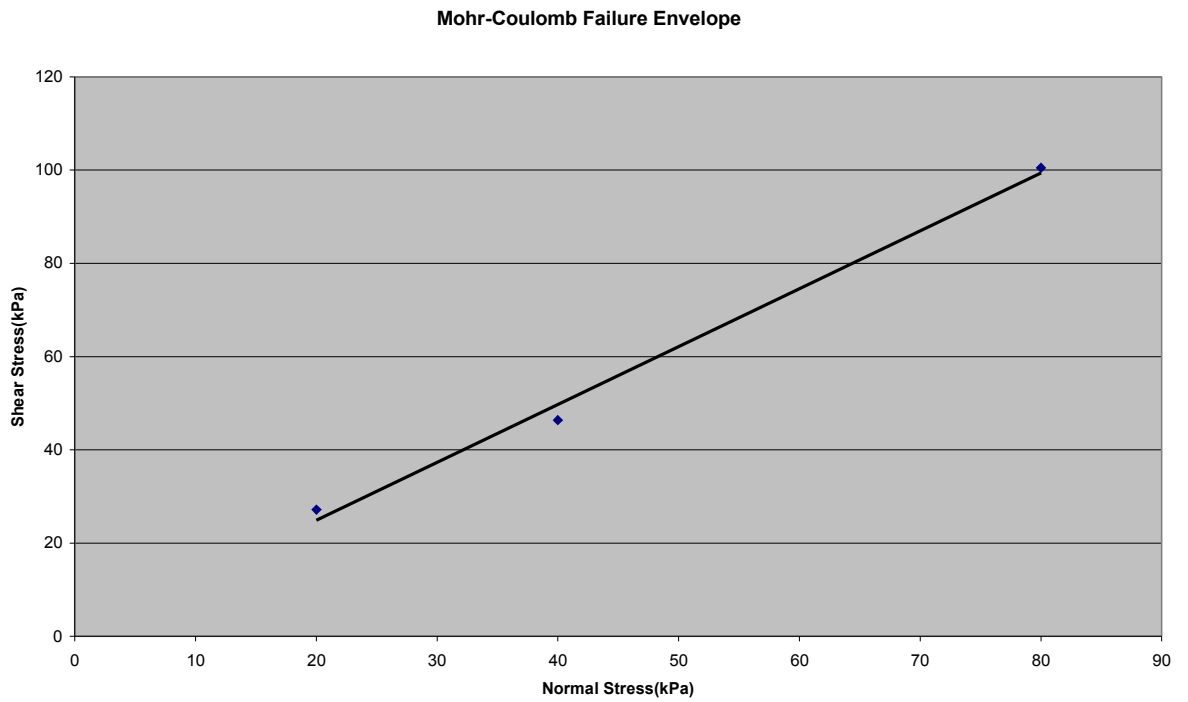


Figure 5.56. Shear Stress vs. Normal Stress graph



Figure 5.57. Horizontally loaded 20 per cent TB2

5.2.13. 30 per cent TB2

Samples are prepared by adding 30 percent tire buffings (TB2) by weight to the sand. Then they are tested in the shear box (Figure 5.58.).

As the Figure 5.59. illustrates, the shear stress increases rapidly as the horizontal displacement increases. In an average displacement value of 20mm, shear stresses at the 20, 40 and 80kPa normal stresses continued to rise slightly. The obtained data is used for determining the failure envelope (Figure 5.60.) and strength parameters are calculated. Cohesion is found 13,69kPa, angle of internal friction is found 32,02°. The determined unit weight is 10 kN/m³ for 30 per cent TB2 sample. The Figure 5.61. represents a view of the test sample during testing.

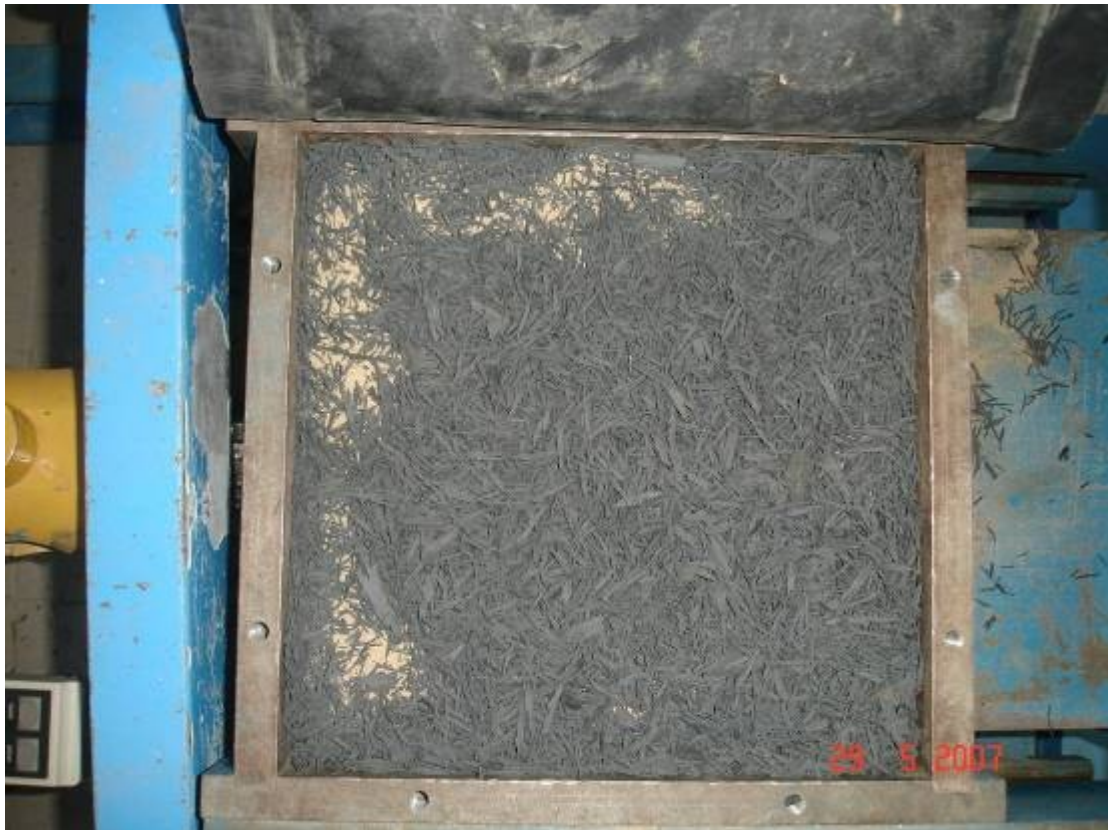


Figure 5.58. 30 per cent TB2 placed in the shear box

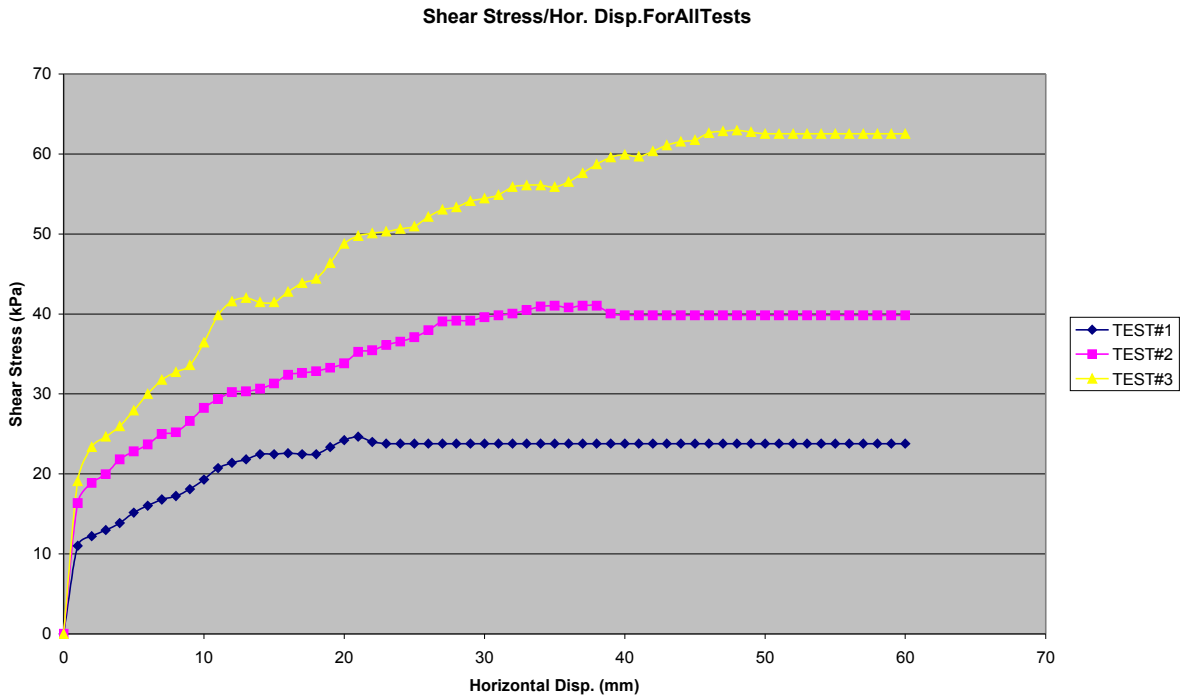


Figure 5.59. Shear Stress vs. Horizontal Displacement Graph for Normal Stresses of 20, 40 and 80 kPa

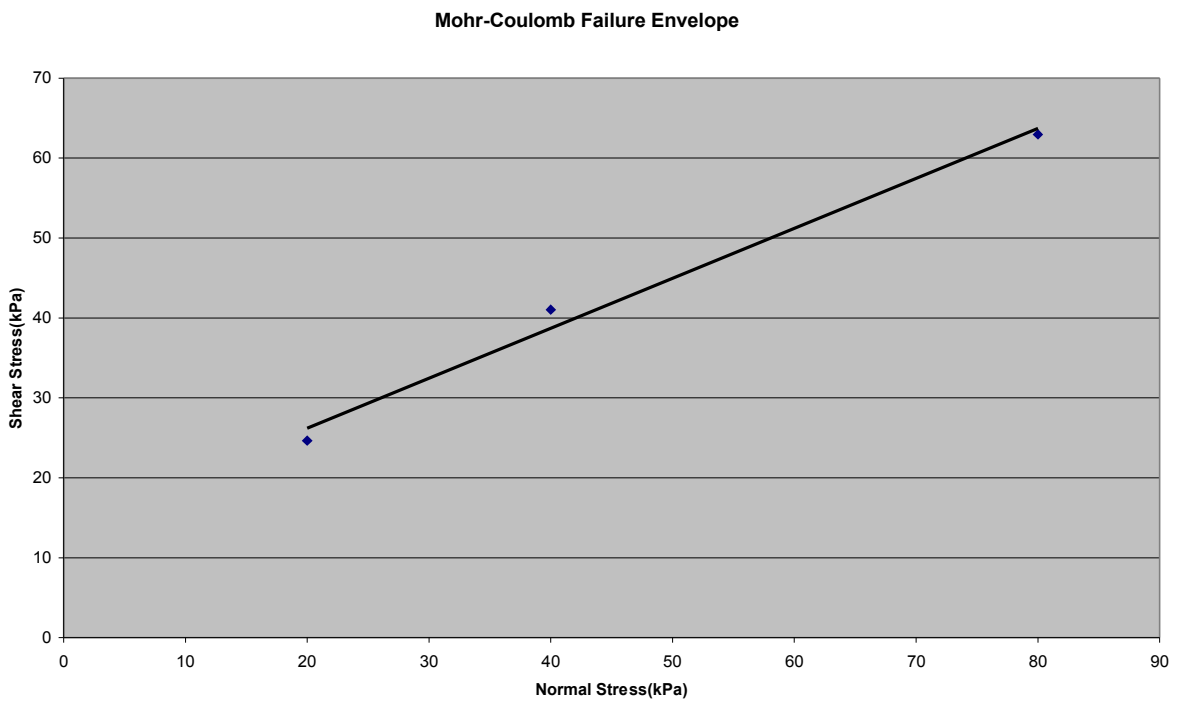


Figure 5.60. Shear Stress vs. Normal Stress graph



Figure 5.61. Horizontally loaded 30 per cent TB2

5.2.14. Summary Of The Large Scale Direct Shear Test Results

The calculated data for all of the samples are represented together in the Table 5.2. The effects of percentage increase, different sized material and different shaped material are said to be dominant for the tire waste - sand mixtures. The maximum shear strength value is obtained in larger horizontal displacements of the shear test. TB2 gives the highest shear strength values for the 20 per cent tire buffings addition to the sand and also the other tests by TB2 have the highest values than the tests performed by crumb and TB1 – sand mixtures. It is observed that the fiber shape and the fiber size dominates over percentages of 10 to 30. In figure 5.62., the failure envelopes for all samples obtained by the test results are given. The lowest shear strength values are for the tire waste materials used alone. And it is also obvious that any tire waste addition improves the shear strength values of the sand. The test results are represented together in Figures 5.63. and Figure 5.64.

Table 5.2. Summary of the large scale direct shear tests

	Normal Stress (kPa)	Shear Stresses (kPa)												
		SAND	TB1	TB2	C	10 per centTB1	20 per centTB1	30 per centTB1	10 per centTB2	20 per centTB2	30 per centTB2	10 per centC	20 per centC	30 per centC
#1	20,00	22,91	11,57	14,40	10,15	28,37	25,86	29,90	25,53	27,17	24,66	23,13	20,95	21,93
#2	40,00	27,93	15,93	18,55	18,88	38,84	40,37	32,41	43,86	46,37	41,03	34,26	35,35	36,44
#3	80,00	53,14	23,90	22,48	28,37	62,52	64,27	56,74	72,01	100,49	62,96	69,61	55,54	54,77

tan values	0,68	0,20	0,13	0,29	0,57	0,63	0,47	0,76	1,24	0,63	0,79	0,57	0,53
friction angle	34,22	11,56	7,37	16,39	29,79	32,37	25,19	37,40	51,13	32,02	38,32	29,52	28,13
Cohesion(kPa)	0	7,58	12,44	5,40	16,53	13,91	17,73	11,46	0,11	13,69	5,46	10,86	12,77
density(kN/m³)	14,00	3,50	3,50	5,50	13,50	12,00	10,00	13,50	12,00	10,00	13,50	13,00	12,00

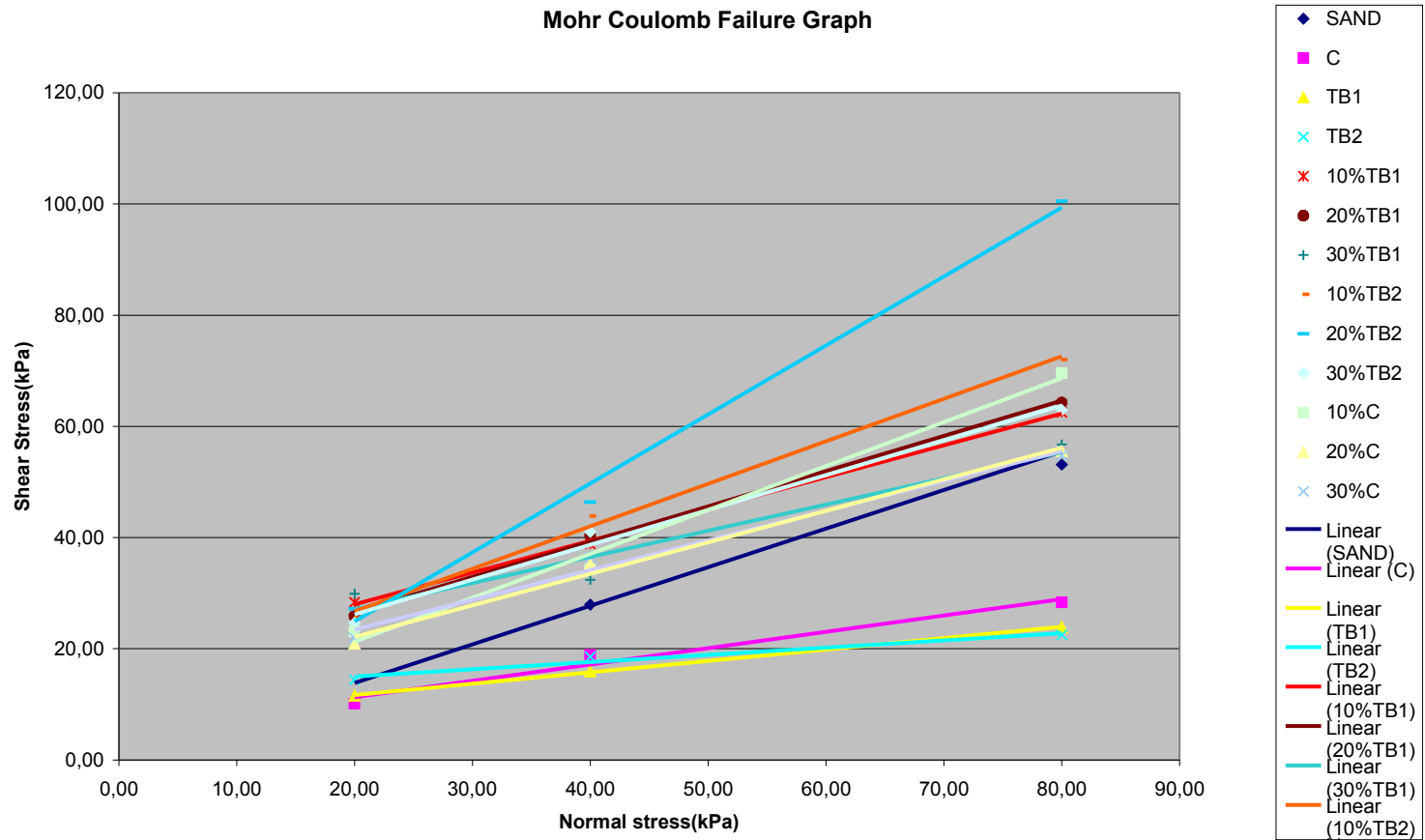


Figure 5.62. Shear Stress vs. Normal Stress graph for all tests

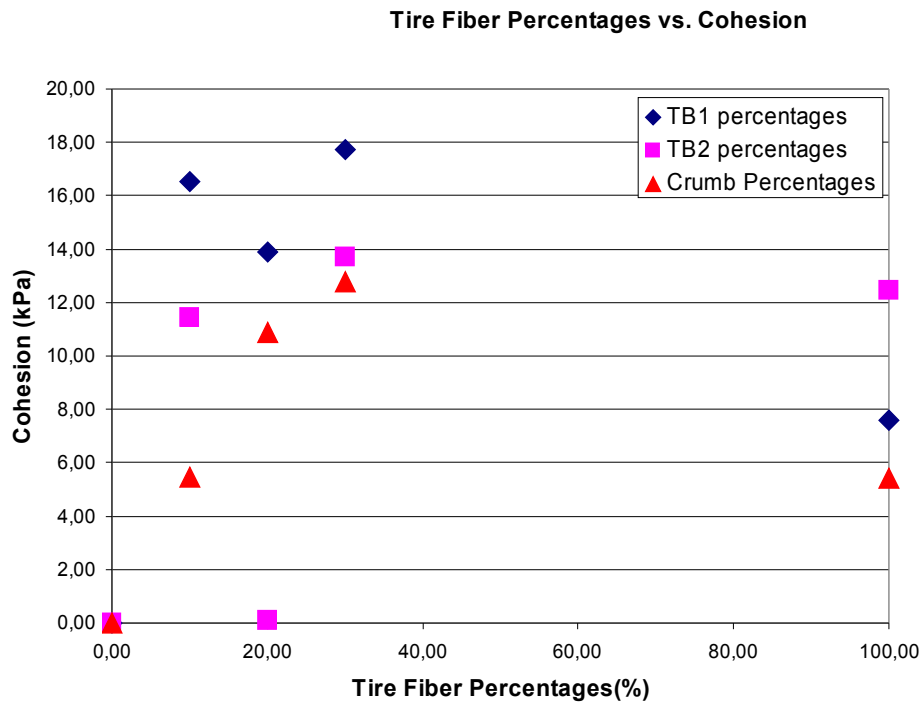


Figure 5.63. Tire Waste Percentages vs. Cohesion

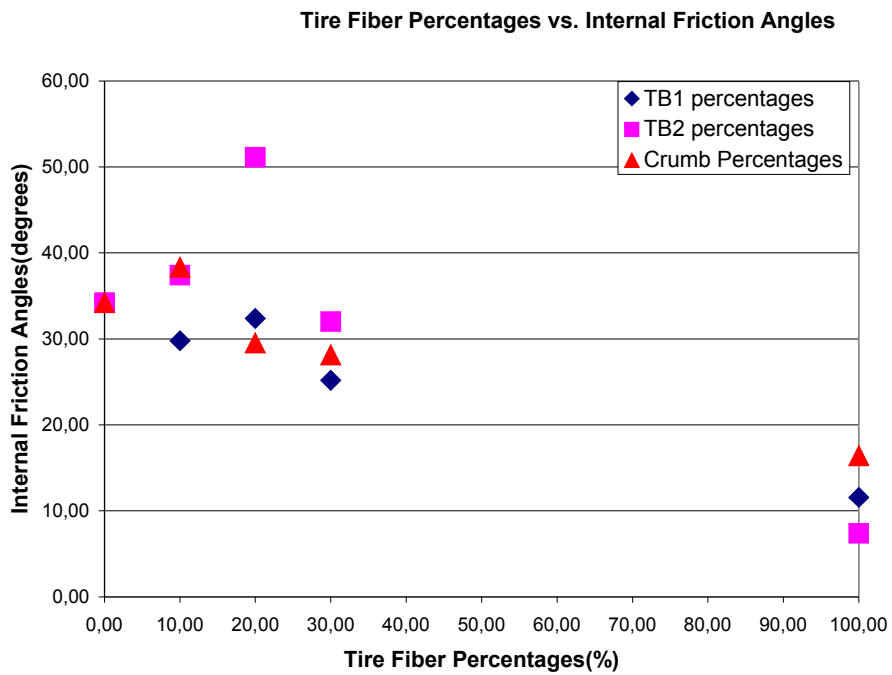


Figure 5.64. Tire Waste Percentages vs. Angle of internal frictions of TB1, TB2 and Tire crumb

Table 5.3. Summary Of Shear Strength Data Compared With The Previous Studies

Reference	Testing Method	Material	Unit Weight (kN/m ³)	Shear Strength Parameters	
				c(kPa)	$\Phi(^{\circ})$
Edinçliler et al. (2004)	Large Scale Direct Shear (300mm*300mm) Tire buffings<4mm	Tire buffings	5,1	3,1	2,2
		sand	15,3	6,91	33
		5 per cent TireBuffings +95 per centSand	15,19	10,4	28,19
		10 per cent TireBuffings +90 per centSand	14,89	8,7	29
		20 per cent TireBuffings +80 per centSand	14,22	15,45	5,31
		30 per cent TireBuffings +70 per centSand	13,56	10,7	8,34
Attom (2004)	Large Scale Direct Shear (300mm*300mm) Sand A	10 per cent TireShreds +90 per centSand	14	0	30
		20 per cent TireShreds +80 per centSand	15	0	37
		30 per cent TireShreds +70 per centSand	15,5	0	41
	Large Scale Direct Shear (300mm*300mm) Sand B	10 per cent TireShreds +90 per centSand	14	0	28
		20 per cent TireShreds +80 per centSand	15	0	35
		30 per cent TireShreds +70 per centSand	15,9	0	42
	Large Scale Direct Shear (300mm*300mm) Sand C	10 per cent TireShreds +90 per centSand	15	0	42
		20 per cent TireShreds +80 per centSand	16	0	45
		30 per cent TireShreds +70 per centSand	16,6	0	48
	Large Scale Direct Shear (300mm*300mm) All Sands	sand A	15,5	0	25
		sand B	15,9	0	28
		sand C	16,6	0	36

This study	Large Scale Direct Shear (300mm*300mm) Tire crumb continued	sand	14	0	34,2
		tire crumb	3,5	5,4	16,39
		10 per cent tire crumb +90 per cent sand	13,5	5,46	38,32
		20 per cent tire crumb +80 per cent sand	13	10,86	29,52
		30 per cent tire crumb +70 per cent sand	12	12,77	28,13
	Large Scale Direct Shear (300mm*300mm) 2mm<Tire buffings<4mm	Tire buffings	5,5	7,58	11,56
		10 per cent tire buffing+90 per cent sand	13,5	16,53	29,79
		20 per cent tire buffings+80 per cent sand	12	13,91	32,37
		30 per cent tire buffings +70 per cent sand	10	17,73	25,19
	Large Scale Direct Shear (300mm*300mm) tire buffings>4mm	Tire buffings	3,5	12,44	7,37
		10 per cent tire buffing+90 per cent sand	13,5	11,46	37,4
		20 per cent tire buffings+80 per cent sand	12	0,11	51,13
		30 per cent tire buffings +70 per cent sand	10	13,39	32,02

*the percentages are by weight

The cohesion values that are found in this study are apparent values and these values are presented on the table. Previous studies like the study of Humphrey et al. (1993) show these apparent values.

The two types of fibers used in this study, showed that the size of the fibers and amount of the fibers have an important effect on the shear strength parameters of the reinforced soil. The shear strength parameters of the soil increases as the fiber content reaches an optimum value. Also it is seen that, increasing size of the fibers, increases the shear strength parameters of the mixture. The longer fibers have longer contacts with the soil particles and so they have more contact areas with the soil particles. These fibers that are found in the shear zone, may be imagined like little anchors which resist against the shear forces.

6. CONCLUSION

In many cases, waste tires are used to reinforce sand. The aim of this study is to determine the effect of tire waste shape and dimensions on shear strength parameters of tire wastes – sand mixtures. Direct shear tests and large scale direct shear tests were performed to evaluate the shear strength parameters. Tire buffings are used as a reinforcement in sand. This application will provide extra means for utilization of waste tires.

In the first part of the experimental program, direct shear test apparatus is used to determine the shear strength parameters of tire crumb+sand mixtures. Tire crumb added to sand at various compositions were tested. Tire crumb+sand samples of 0 per cent, 20 per cent, 25 per cent, 40 per cent, 50 per cent, 75 per cent and 100 per cent tire crumb by weight are tested. It is seen that tire wastes and sand together improves the strength parameters of the materials alone and the maximum values are observed between by weight percentages closer to sand values for tire crumb-sand mixtures.

In the second part of the experimental program where large scale direct shear apparatus is used, two different sized tire buffings (TB1, TB2) and tire crumb are added to sand in 10 per cent, 20 per cent and 30 per cent by total weight and tested to evaluate how the material shape and the percentage by weight affect the shear strength parameters of the composite materials. As a result of the tests, it is observed that the shear strength parameters of 30 per cent tire waste addition are better for the composite materials. Especially, the angle of internal friction values obtained tend to maximize in samples with the 20 per cent tire buffings addition to the sand. However the cohesion values of the composite materials do not show any significant changes as the percentage changes. The cohesion values mainly range between 8 kPa and 14 kPa and the internal friction angles were between 25° and 40°.

Due to the test results of the large scale direct shear tests, angle of internal friction values of composite material including TB2 is observed to have higher values compared to the samples including tire crumb and TB1. The cohesion values are not affected by the

type of tire waste material used in composite materials. All of the composite materials show better shear strength characteristics than the sand alone. The angle of internal friction values did not tend to increase much for the TB1 and tire crumb compared to sand, but increasing cohesion values resulted in a strengthening soil.

It is observed that as the tire waste size increases, the improvement in shear strength characteristics are greater. This can be explained by the increasing amount and length of the intact fiber in the shear zone. However, TB1 and tire crumb, which have nearly the same sizes (approximately 30mm) but having different shapes, nearly showed the same values of the shear strength parameters. So, it is observed that as the tire wastes having sizes smaller than 30mm, the shape alone does not affect the overall shear strength characteristics of the composite material.

As a summary, on the basis of experimental results the following conclusions are made.

- tire buffings and mixtures of sand and tire buffings may be useful as soil reinforcement in embankment construction:
- Three factors were found to significantly affect the shear strength values; normal stress, tire waste shape, and tire waste content.
- In all cases, sand containing tire wastes had higher shear strength than sand alone.
- Several conclusions are made based on the test results. Addition of tire buffings to sand increased its shear strength. Initial friction angle as large as 51° were obtained. The friction angle for unreinforced sand is 34° .

REFERENCES

- Ahmed, I., 1993, *Laboratory study on properties on rubber soils*. Report No. FHWA/IN/JHRP-93/4, Joint Highway Research Project, Indiana Department of Transportation.
- Ahmed, I. and C. W. Lovell, 1993, Rubber soil as lightweight geomaterial. *Transportation Research Record No. 1422.*, National Research Council, Washington D.C. 61–70.
- ASTM, 1998, *ASTM standard practise for use of scrap tires in civil engineering applications*, D 6270-98, American Society for testing and materials, West Conshohocken.
- ASTM D 3080-98, 1998, “Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions,” American Society for Testing and Materials.
- Attom, M.F., 2004, The use of shredded waste tires to improve the geotechnical engineering properties of sands, *Environmental Geology* 49: 497-503.
- Baykal, G., *Development of a Model Unit for Pellet Aggregate Production Using Fly Ash and Optimization of the Pelletization Process*, TÜBİTAK Construction Technology Research Group Project No: INTAG 627, 1997.
- Bosscher, P. J., T. B. Edil, and S.Kuraoka, 1997, “Design of highway embankments using tire chips.” *J. Geotechnical and Geoenvironmental Engineering*, 123(4), 295-304.
- Cecich, V., L.Gonzales, , A.Hoisater, , J.Williams, and K Reddy., 1996, “Use of Tires as Lightweight Backfill Material for Retaining Structures.” *Waste Management & Research*, 14, 433-451.
- Collins, K. J., A. C Jensen,., J. J Mallinson,., V.Roenelle, ,and I. P.Smith, 2002, “Environmental impact assessment of a scrap tyre artificial reef.” *J. Marine Sciences.*, 59, S243-S249.
- Day, K. E., K. E.Holtze , J. L. Metcalfe-Smith, , C. T.Bishop and B. J.Dutka, 1993, “Toxicity of leachate from automobile tires to aquatic biota.” *Chemosphere*, 27(4), 665- 675.
- Downs, L. A., D. N. Humphrey, L. E.Katz, and Rock, C. A., 1996, *Water quality effects of using tire chips below the ground water table*. Technical paper, August 26 1996, Department of Civil and Environmental Engineering, University of Maine, Orono. *Use of tyre shreds in civil engineering applications.*
- Duffy, D. P., 1995, “The potential for use of shredded tire chips as a leachate drainage and collection medium: design, construction and performance considerations.” *Proc. Seminar on landfill design using tire shreds*, Texas Resources Conservation Commission, Austin, 115-132.

- Edil, T. B. and P. J. Bosscher, 1992, *Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications*. Report No. WI 14-92, Department of Civil and Environmental Engineering, University of Wisconsin, Madison.
- Edinçliler, A., G. Baykal and K. Dengili, 2004, "Determination of static and dynamic behaviour of recycled materials for highways." *Resources, Conservation and Recycling*, 42, 223-237.
- ETRMA, 2006, *End of Life tyres – A valuable resource with a wealth of potential*. Report 2006. European Tyre & Rubber Manufacturers association. Brussel.
- Evans, J. J., 1997, "Rubber tire leachates in the aquatic environment." *Reviews of environmental contamination and toxicology*, 151, 69-115.
- Foose G.J., C.H. Benson and P.J. Bosscher, 1996, Sand reinforced with shredded waste tires. *Journal of Geotechnical Engineering*, 122 (9): 760-767.
- Gray, D. H. and H. Ohashi, 1983, "Mechanics of fiber reinforcement in sand." *J. Geotech. Engrg.*, ASCE, 109(3), 335-353.
- Gray, D. H. and T. Al-Refeai, 1986, "Behavior of fabric versus fiber-reinforced sand." *J. Geotech. Engrg.*, ASCE, 112(8), 804-820.
- Gray, D. H. and M. H. Maher, 1989, "Admixture stabilization of sands with discrete, randomly distributed fibers." *Proc., XIIth Int. Conf. on Soil Mech. And Found. Engrg.*, Vol. 2, Rio de Janeiro, Brazil, 1363-1366.
- Maher, M. H. and R. D. Woods, 1990, "Dynamic response of sands reinforced with randomly distributed fibers." *J. Geotech. Engrg.*, ASCE, 116(7), 1661-1667.
- Maher, M. H. and D. H. Gray, 1990, "Static response of sands reinforced with randomly distributed fibers." *J. Geotech. Engrg.*, ASCE, 116(11), 1661-1677.
- Heimdahl, T. C. and A. Drescher, 1998, "Deformability parameters of shredded tire lightweight fills." *Proc. 9th int. conf. on cold regions engineering*, American Society of Civil Engineers, ed D. E. Newcomb, Reston, 524-535.
- Hoppe, E. J., 1994, "Field study of a shredded tire embankment", Report VTRC 94-IR1, Virginia Transportation Research Council, Springfield.
- Humphrey, D. N., L. H. Chen, and R. Eaton, 1997, "Laboratory and field measurements of tire chips for use as subgrade insulation", *Transportation Research Board*, 76th Annual Meeting, Washington D.C.
- Humphrey, D. N., T. Cosgrove, N. L. Whetten, and R. Hebert, 1997, Tire chips reduce lateral earth pressure against the walls of a rigid frame bridge, *Seminar on rehabilitation and upgrades in civil and environmental engineering*, ASCE.

- Humphrey, D. N. and R. A. Eaton, 1993, "Tire chips as insulation beneath gravel surfaced roads", *Proc. Frost in Geotechnical Engineering*, ed. Phukan, Balkema, Rotterdam.
- Humphrey, D. N. and W. L. Nickels, 1997, "Effect of tire chips as lightweight fill on pavement performance", *Proc. XIV international conference on soil mechanics and foundation engineering*, Balkema, Rotterdam.
- Humphrey, D. N. and T. C. Sandford, 1993, Tire chips as lightweight subgrade fill and retaining wall backfill. *Proc. Recycling ahead*. October 19-22, Denver. Lawrence, B. A.M., Humphrey D. N., and Chen, L. I., (1999). "Field trial of tire shreds as insulation of paved roads", *Proc. 10th int. conf. on cold regions engineering*, Lincoln, 428-439.
- Leclerq, B., M. Schaeffner, P. Delmas, J. C. Blivet and Y. Matichard, 1990, "Durability of geotextiles: Pragmatic approach used in France." *Geotextiles, Geomembranes and Related Products*, Ed. Hoedt, D., Balkema, Rotterdam, 679-684.
- Lee, K-M., B. K. W. Cheung, and L. Y. Carol, 2002, "Lightly cemented scrap rubber tire chips as lightweight geomaterials." *Proc. International workshop on lightweight geo-materials*, The Japanese Geotechnical Society, Tokyo, 245-252.
- Manion, W. and D. N. Humphrey, 1992, *Use of tyre chips as lightweight and conventional embankment fill, Phase I –laboratory*. Dept. Civil Engineering, University of Maine, Orno.
- Masad, E., R. Taha, C. Ho and T. Papagiannakis, 1997, "Engineering properties of tire/soil mixtures as a lighthweighth fill material." *Geotechnical testing J.*, 19(3), 297-304.
- Moo-Young, H., K. Sellasie, D. Zeroka, and G. Sabnis, 2003, "Physical and chemical properties of recycled tire shreds for use in construction." *J.Environmental Engineering*, 129(10), 921-929.
- MPCA, 1990, *Waste tires in sub-grade road beds. A report on the environmental study of the use of shredded waste tires for roadway sub-grade support*. February 19 1990. Minnesota Pollution Control Agency, St. Paul.
- Newcomb, D. E., and A. Drescher, 1994, "Engineering properties of shredded tires in lightweight fill applications." Transportation Research record 1437, TRB, National Research Council, Washington D.C., 1-7.
- Ranjan G., R. M. Vasan and H. D. Charan, 1996, "Probabilistic Analysis Of Randomly Distributed Fiber-Reinforced Soil." *Journal Of Geotechnical Engineering*, ASCE, 419-426
- Reddy, K. R. and R. E. Saichek, 1998, "Characterization and performance assessment of shredded scrap tires as leachate drainage material in landfills." *Proc. the fourteenth international conference on solid waste technology and management*, Philadelphia.

- Reddy, K. R. and R. E. Saichek, 1998, "Assessment of damage to geomembrane liners by shredded scrap tires." *Geotechnical Testing J.*, 21(4), 307-316.
- Santoni R.L., J.S. Tingle and S. Webster, 2001, "Engineering properties of sand fiber mixtures for road construction." *Journal of Geotechnical and Geoenvironmental Engineering-ASCE* 2001;127:258–68.
- Shao, J. and J. P. Zarling, 1995, *Thermal conductivity of recycled tire rubber to be used as insulating fill beneath roadways*, Report N. INE/TRC 94.12, Alaska Dept. Of Transportation and Public Facilities, Juneau.
- Tatliso, N., T. B. Edil and C. H. Benson, 1998, "Interaction between reinforcing geosynthetics and soil-tire chip mixtures." *J. Geotechnical and Geoenvironmental engineering*, 124(11), 1109-1119.
- Tweedie, J. J., D. N. Humphrey and T. C. Sandford, 1998, "Tire shreds as lightweight retaining wall backfill: Active conditions." *J. Geotechnical and Geoenvironmental Engineering*, 124(11), 1061-1070.
- UNEP, 2002, *Technical Guidelines on the Identification and Management of Used Tyres.*, Basel Convention Series/SBC No. 02/10, Secretariat of the Basel Convention, Châtelaine.
- Upton, R. J. and G. Machan, 1993, "Use of shredded tires for lightweight fill." *Transportation Research record*, 1422, TRB, National Research Council, Washington D.C, 36-45.
- USEPA, (2006a). *Management of scrap tires*. The U.S. Environmental Protection Agency, Warith, M. A., Evgin, E., and Benson, P. A. S., 2004, "Suitability of shredded tires for use in leachate collection systems." *Waste Management*, 24, 967-979.
- Wik, A., and Dave, G., 2005, "Environmental labelling of car tires – toxicity to *Daphnia Magna* can be used as screening method." *Chemosphere*, 58, 645-651.
- Wu, W. Y., C. C. Benda and R. F. Cauley, 1997, "Triaxial determination of shear strength of tire chips," *J. Geotechnical and geoenvironmental engineering*, 123 (5), 479-482.
- Yang, S., R. A. Lohnes, B. H. Kjartanson, 2002, "Mechanical Properties of Shredded Tires." *Geotechnical Testing Journal*, 25(1), 44-52.