Application of Plastic Waste (Polyethylene and Synthetic Polymers) as a Soil Modifier in Subgrades and Shallow Foundations

Morteza H. Eshkiknezhad

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
September 2022
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Prof. Dr. Umut Türker
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Eriş Uygar
Supervisor

Examining Committee

1. Prof. Dr. Zalihe Nalbantoğlu Sezai
2. Assoc. Prof. Dr. Eriş Uygar
3. Asst. Prof. Dr. Abdullah Ekinci

ABSTRACT

Polyethylene terephthalate (PET) is one of if not the most commonly consumed type of plastic in industry and they can be readily spotted as they are used for water, pop bottles, and a few types of packaging. Although alternative recycling solutions can help in the conservation of landfills, they are not a definite solution. In this study, as an alternative solution to the waste problem of PET products, been used to find an alternative solution to further enhance sand properties to make them suitable for construction zones. Despite other studies in this direction, none of them have reached the substantial results that this study has achieved. The reason being is the presence of a novel methodology that creates a remarkable interlocking strength between aggregates using plastics. This method which includes heating both sand and plastic particles up to the melting point of plastics has better effects on unconfined compression and shear strength of sand than plastic strips combined with sand in a solid form. The plastic waste percent used in this study were 2.5, 5, 7.5, and 10 percent of the dry weight of sand in 4 different sample preparation groups (SPM-1, SPM-2, SPM-3, and SPM-4). The results indicated up to 3745kPa compressive strength and 8.6 times improvement in shear strength of sand for SPM-3 in a melted plastic form.

Keywords: Soil, Sand, Waste, Plastic bottle, Polyethylene terephthalate (PET), Shear strength, Compressive strength

ÖZ

Polietilen tereftalat (PET), endüstride en yaygın tüketilen plastik türlerinden biri değilse de, su, pop şişeler ve birkaç ambalaj türü için kullanıldıkları için kolayca fark edilebilirler. Alternatif geri dönüşüm çözümleri, düzenli depolama alanlarının korunmasına yardımcı olsa da kesin bir çözüm değildir. Bu çalışmada, PET ürünlerin atık sorununa alternatif bir çözüm olarak, kum özelliklerini daha da geliştirmek ve inşaat alanlarına uygun hale getirmek için alternatif bir çözüm bulmak için kullanılmıştır. Bu konuda önceki çalışmalar PET'i katı olarak fiber şeklinde kum ile karıştırmak surety ile gerçekleştirilmişti. Bu çalışmada, PET kum tanecikleri arasında dikkate değer bir kenetlenme gücü sağlayan yeni bir yöntem denenmiştir. Hem kumun hem de plastik parçacıkların plastiklerin erime noktasına kadar ısıtılmasını içeren bu yöntem, katı halde kumla karıştırılmış plastik fiberlere göre kumun serbest sıkıştırma ve kesme mukavemeti üzerinde çok daha iyi etkiler elde edilmesine yardım etmiştir. Kullanılan plastik atık yüzdeleri, 4 farklı numune hazırlama grubunda (SPM-1, SPM-2, SPM-3 ve SPM-4) kuru kum ağırlığının yüzde 2,5, 5, 7,5 ve yüzde 10'u kadardır. Sonuçlar, erimiş plastik formda SPM-3 numune grubu için yaklaşık 3745 kPa'ya kadar basınç dayanımı ve kumun kesme dayanımında yaklaşık 8.6 kat iyileşme olduğunu gösterdi.

Anahtar Kelimeler: Toprak, Kum, Atık, Plastik şişe, Polietilen tereftalat (PET), Kesme dayanımı, Basınç dayanımı

DEDICATION

I dedicate this thesis to my mother Mrs Soheyla Khorshidi Eshkiki and my brothers Mostafa and Mojtaba.

ACKNOWLEDGEMENT

I would like to record my gratitude to Assoc. Prof. Dr Eriş Uygar for his great patience, supervision, and guidance for giving me an excellent experience throughout my studies. He provided me with constant encouragement and support in various ways. His ideas and passion have influenced my path greatly and have been inspiring constantly. I am indebted to him for everything he has done for me more than he knows.

I would like to also thank and send my highest regards to Prof. Dr Umut Türker, Prof. Dr Sonuç Zorlu Oğurlu, and Asst. Prof. Dr Arif Akkeleş for their great kindness and love throughout my studies. Nurturing me in any way they possibly could for me to reach success. I will never forget their ethereality.

My thanks go to the academic staff of civil engineering department of Eastern Mediterranean University. Especially my course-related professors for their patience, assistance, advice, and encouragement in all my courses.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AR	Aspect Ratio
CBR	California Bearing Ratio Test
C	Cohesion Value
C°	Degrees Celsius
DSST	Direct Shear Strength Test
e_{max}	Maximum Void Ratio
e_{min}	Minimum Void Ratio
HDPE	High Density Polyethylene
Hz	Hertz
kPa	kilopascal
LDPE	Low Density Polyethylene
MPix	Megapixel
MPa	Megapascal
MSS	Mean Square Slope
PET or PETE	Polyethylene Terephthalate
PP	Polypropylene
SB	Sample Box
SPM-1	Sample Preparation Method 1
SPM-2	Sample Preparation Method 2
SPM-3	Sample Preparation Method 3
SPM-4	Sample Preparation Method 4
UPV	The Ultra-Sonic Pulse Velocity
UCT	Unconfined Compression Test

μm	Micrometers
Φ	Friction Angle
σ'	Effective Normal Stress
τ_{max}	Maximum Shear Strength

Chapter 1

INTRODUCTION

Recently, numerous studies have been conducted on the enhancement of soils using plastic strips in order to generate an alternative way for recycling of waste materials such as plastic bottles (Benson & Khire, 1994; Dutta et al., 2015; Peddaiah et al., 2018; Thorneycroft et al., 2018).

The consuming intentions are normally a single-use application, as repeating the utilization process of these bottles can increase the risk of bacterial and leaching growth. Products made out of PETs are hard to sanitize. Although there are chemical solutions that can help in cleaning the bottles, they can be extremely harmful and haphazard to human health if not properly removed. Plus, they consume more energy regarding recycling rather than production. It also can leach carcinogens. Plastics made out of PET are recyclable and about 25% of them are now being recycled in the US today by shredding and creating small plastic flakes which are used to either create new bottles or turned into polyester fibre. The recycled fibre is used to make textiles namely, carpets, stuffing, pillows, life jackets and fleece garments (Eartheasy, 2020).

While plastic has many valuable uses, single-use or disposable plastic have become a tradition with severe environmental consequences. Around the world, one million plastic drinking bottles are purchased every minute, and 5 trillion single-use plastic bags are used worldwide every year. In total, half of all plastic produced is designed to be used only once and then thrown away. Plastic waste is now so ubiquitous in the natural environment that scientists have even suggested it could serve as a geological indicator of the Anthropocene era, a man-made impact of the earth's crust (Eartheasy, 2020).

Since the last few decades, the amount of plastic waste generated has tripled, and the plastic material production in the early 21st century, has increased more than what it had been for the previous 40 years or so. Nowadays, the annual production of plastic waste globally is approximately 300 million tons (Eartheasy, 2020). That is nearly equivalent of the combined weight of the whole earth population. It has been assessed by the researchers that nearly more than 8.3 billion tons plastic has been artificially manufactured since the early times of 50s decade. An estimation of 60 percent of the manufactured plastic has been located either in a natural environment or a landfill (Eartheasy, 2020).

A staggering number of 99% or more of plastic produced are either derived from petroleum, natural gas or coal, all of which are considered as non-renewable and dirty. If the current trend continues, by the year 2050, shockingly 20% of petroleum consumption can be due to plastic production. The flow of plastic must be slowed at its source. Only 9% of the plastics produced are being recycled, and 12% of them are being burned, resulting in creation of harmful gases, finally 79% of the plastics are accumulated in natural environments or urban areas (Okunola A et al., 2019). The bottom part of cigarettes which have small plastic fibres in them are the most usual suspect of plastic wastes found based on statistics. Plastic bottles, bottle caps, food wrappers, plastic bags and straws were next in line simultaneously (Okunola A et al., 2019).

Rivers carry various plastic wastes from mainland into to the sea, indicating that rivers are major problems to oceans' waste pollution issue (see Figure 1). A shockingly massive number of 8 million tons of plastic wastes are led into the ocean annually. Mainly due to rivers carrying them there. These waste materials generated out of petroleum, can survive in the ocean and land for centuries. As plastics are durable and have high resistance to chemical solutions, these extreme properties also help them thrive in natural world. They are nearly impossible to decomposed thoroughly in nature. Most of them never fully disintegrate. However, they will get smaller as time passes. In many occasions livestock can consume these tiny particles (of microplastics) as they mistake them for food. Thus, making it severely possible that it may end up in our food chain. They can be found in most tap waters of the world as well. Clogging the sewers resulting in an adaptive environment for pests. Plastic wastes and specifically bags which are made out of low-density polyethylene or polypropylene can increase the chance of transmission of vector-borne diseases like malaria.

With the current trend of plastic wastes, it is estimated that by the year 2050, there will be more plastic wastes in the ocean rather than fishes (see Figure 2), (Schmidt et al., 2017). Thus, making it extremely important and alarming to create applicable methods to use plastic wastes in various industries as a useful and cheap material to encourage the industry to lean towards recycling plastics.

In this study, as an enhancement to sand soil properties, it was considered to assess and experiment the mechanical properties of sand soil mixed with plastic strips reclaimed from polyethylene terephthalate (PET) to generate an alternative construction material with high availability as an effort to address the ever-increasing plastic waste crisis. As literatures survey presents, in recent years, there has been an positive interest in the field of Civil engineering to use plastic wastes as an alternative material in construction as a replacement or reinforcement of the traditional materials (Schmidt et al., 2017).

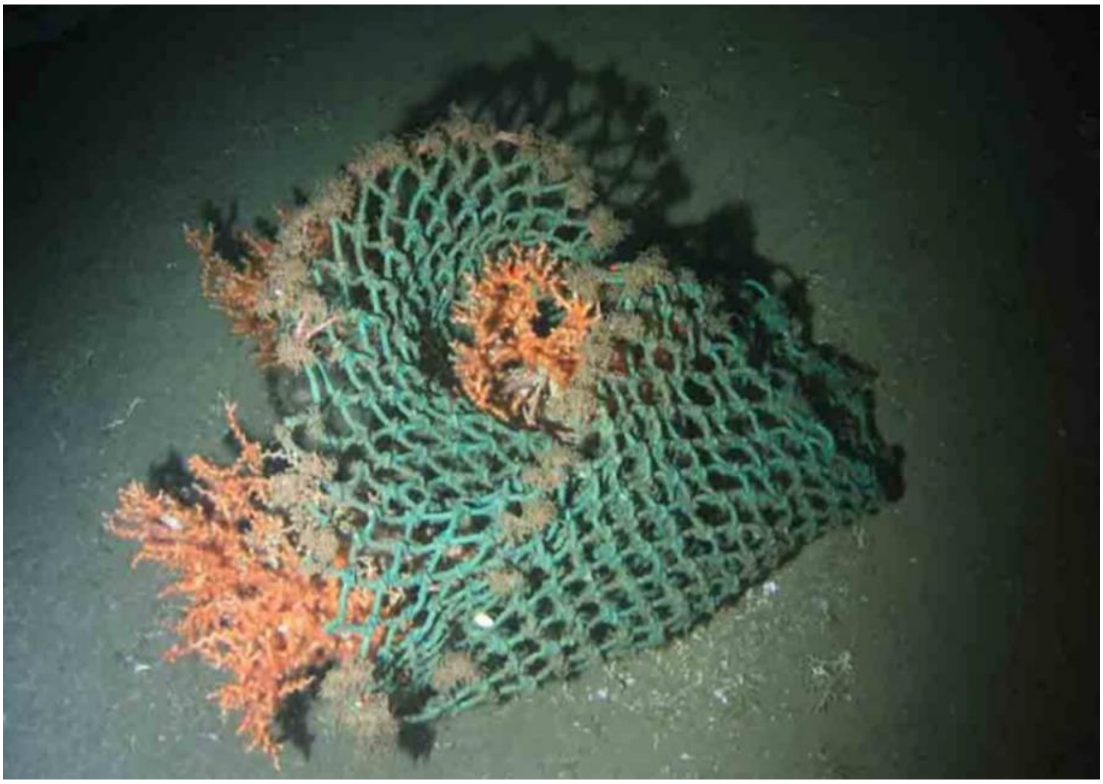


Figure 1: Plastic waste on the ocean floor (Perkins, 2014)

Figure 1, Litter such as this net found entangled in a coral off the Scottish coast in a survey published earlier this year is only the most visible part of the waste that accumulates at the bottom of the sea (Perkins, 2014).

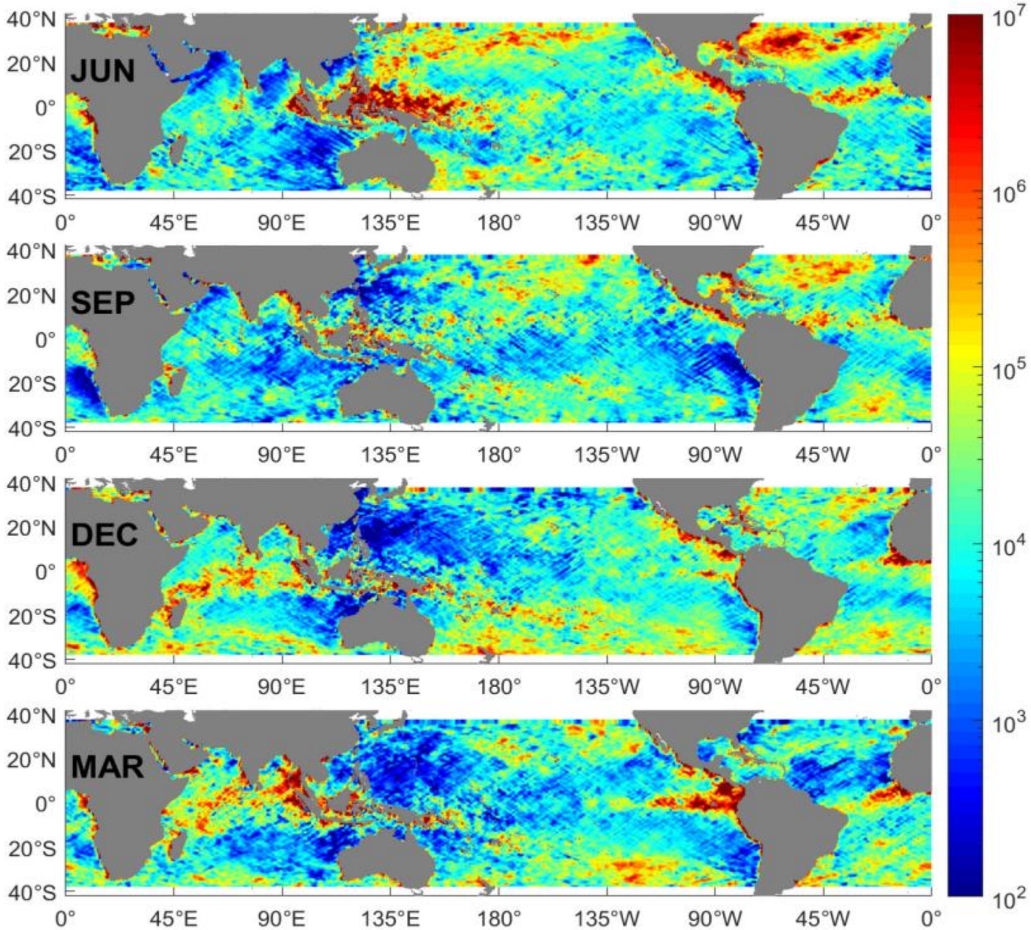


Figure 2: Monthly average microplastic number density concentration (#/km2, log10 scale) for June–September–December 2017 and March 2018. Both Atlantic and Pacific basins have generally higher concentrations in austral and boreal summer. The northern Indian Ocean has highest concentrations in the spring. These seasonal patterns tend to repeat(Evans & Ruf, 2022)

Chapter 2

LITERATURE REVIEW

2.1 Background Studies

The addition of reinforcement changes the sand's properties significantly. The resistance and stability of soil against applied load are derived from its shear strength. The reinforcing methods varies for embankments, retaining structures, subgrade soil stabilization beneath footing, and pavements. While, there aren't many research studies conducted about addition of plastics to soils, It is expected that with the growing volume of waste plastics, it will be one of the candidate materials in the near future.

In this study, the plastic waste materials utilized in all common fields of engineering (such as concrete are considered) as potential reference. In all of the studies conducted about utilization of plastic waste, the direction of research have been towards adding plastic strips (in solid term) with different aspect ratio and plastic strip content percentage and observing behaviour under various tests (CBR, triaxial and direct shear test). Hence, in the present study, a new innovative methodology is presented that highly affects the properties of the product which modern introducing plastic waste be melting to create better bonding and retention between sand particles and plastics.

Gray et. al. (1983), evaluated the mechanics of sand reinforced with fibers. They used variety of fibers and direct shear tests were performed on each sample type. They utilized natural, synthetic and steel fibers. They compared the experimental values with a theoretical prediction based on equilibrium force model of a reinforced sand using fibers. At the end, they concluded that their theoretical prediction correctly predicted a variety of behaviour of mixtures in their shear strength. Aside from that, the minimum effect of aspect ratio on shear strength were 1.7% and the behaviour of shear strength increment had a parallel effect to loose, medium dense and very dense state (Gray & Ohashi, 1983).

In another study considered by Sobhan and Mashnad (2003), the effect of adding waste material, as HDPE which they recycled by gathering consumed milk and water bottles was investigated. The purpose of study was to assess the compressive, flexural and split tensile strength, in addition, they evaluated the toughness enhancement effect of plastic strips. The dimensions of used plastic strips were 38 or 19 mm. Their study showed that the addition of plastic strips can make the specimen to reach to a maximum compressive strength of 7000 kPa, split tensile strength 1000 kPa, and flexural strength of 1200 KPa. The specimen's strength indicated its merit to be used in a high-quality stabilised base of a highway pavement (Sobhan & Mashnad, 2003).

Dash et. Al., (2004) they investigated a 2 variety of geosynthetic materials' effect in sand foundations. The geosynthetic materials utilized were namely, planar and geocell. Triaxial tests were performed on both material type modified sand. Results indicated that for the geocell material reinforced sand, there was a significant strength increment that not even after 45% increment, failure did not occur. For the planar material reinforced sand however, failure was observed at 15% of the footing width and the load capacity of times the size of unreinforced sand (Dash et al., 2004).

Dutta and Rao, (2004), investigated the effect of utilizing plastic wastes on the mechanical properties of the sand. Triaxial compression tests were performed for samples having various aspect ratio, strip content percentage, plastic waste type, and different confining pressures were used in order to determine the engineering properties of the sand reinforced with plastic waste. Two types of plastic wastes were utilized. One, retrieved from plastic bags called LDPE with thickness of 0.05 mm. They were cut in 12 mm wide strips and later they were cut into 24 mm long strips and 12 mm long strips. The results indicated that the presence of plastic waste strips improves the physical performance of the sand(Dutta & Rao, 2004).

Dutta and Sarda (2007), conducted another study towards plastic wastes and this time they investigated its effects on stone dust/fly ash saturated clay. In their study, they used plastic strip content percentage of 0.25% up to 4%. In addition, three different dimensions of strips were utilized as well. The study showed a significant improve in CBR and secant modulus. The optimization investigation proved that strip length and strip content percentage have a linear effect with sample's strength. However, passing 2% did not increase the CBR value (Dutta & Sarda, 2007).

Choudhary et. al. (2010), investigated the CBR evaluation of soil reinforced with plastic waste strips. The used plastic waste was as the type of high-density polyethylene (HDPE) and were cut into strips in order to improve the mechanical properties of subgrade soil underneath the pavement. They used different strip content percentages and different dimensions. California Bearing Ratio (CBR) test was performed. The results showed that with specific strip content percentage and aspect ratio, the strength of subgrade soil and the deformation behaviour was significantly improved (Choudhary et al., 2010).

Choudhary et. al., (2010), utilized plastic wastes in sub-grade of flexible pavement. CBR test were performed on samples in this study. Plastic waste strip contents varied from 0.25% all the way up to 4%. The study showed that with a specific aspect ratio and strip content percentage, a significant increase in CBR value and secant modulus can be achieved. The sand was classified as a poorly graded sandy soil. The plastic waste utilized in this study was from HDPE type. Plastic strips dimensions were 24 mm × 12 mm and 36 mm × 12 mm with a thickness of 0.4 mm. Details of used strip content include; 0.25%, 0.5%, 1%, 2% and 4% (Choudhary et al., 2010). Babu et. Al. (2011), evaluated the stress-strain of soil with plastic waste additives. They retrieved the plastic wastes out of plastic bottles. The soil type used in this study was red soil and fine sand. Where were mixed with plastic strips cut out of plastic bottles. They concluded that, the unconfined compressive strength of the mixture was reduced due to addition of plastic strips. However, the triaxial compression test indicated an increase in the tensile strength of the soil mixture which can be effective for bearing capacity improvement and in decreasing the settlement (Babu & Chouksey, 2011).

Ahmed, (2012), used a regression model in order to predict the strength of sand with the addition of plastic wastes. A group of splitting tensile and unconfined compression tests were performed on both non-reinforced sand and reinforced sand. It was concluded that plastic strips have a better effect on tensile strength of sand rather than the compressive strength. In addition, it was pointed out that strip content percentage and aspect ratio of plastic strips have a significant effect on the enhancement of sand properties. A cementing agent was utilized as well as plastic strips of polyester type mixed with sand. The soil used was classified as poorly graded sand. A shredder machine was used to cut plastic waste to sizes of 2, 4 and 8 mm (Ahmed, 2012).

Neopaney et. al. (2012), investigated stabilization of soil by adding plastic wastes. They used different aspect ratios as well as different fiber content in their study. Plastic bag strips have been used to conduct this research. CBR tests were performed. The results indicated that, addition of plastic strips, enhanced the strength and deformation behaviour for the soil in subgrade area significantly. In this study, aspect ratios of 10, 20, 30, and 40 mm were used with 0, 0.25, 0.5, and 1 percent plastic strip content were used (Neopaney et al., 2012).

In study conducted by Bhattarai et. al. (2013), the change in characteristics of soil with addition of plastic strips. In this study, different aspect ratios and strip content percentage were considered. The plastic waste used was obtained from plastic shopping bags and other plastic wastes. Various CBR tests were performed. The results indicated that, utilization of plastic strips with appropriate proportion, significantly improves the soil physical properties In this study just like the study by Neopaney et. al. (2012), aspect ratios of 10, 20, 30, and 40 mm were used with 0, 0.25, 0.5, and 1 percent plastic strip content were used (Bhattarai et al., 2013).

Nibudey et. al. (2013), predicted the strength of concrete with plastic fiber addition. In their study, polyethylene terephthalate (PET) with content percentages up to 3% were used and they concluded that the optimum point of compressive strength and split tensile strength were at 1% fiber content percentage where 4.3% increment in compressive strength and 11.21% increment in split tensile strength of concrete was observed (Nibudey et al., 2013).

Muntohar et. Al. (2013), evaluated a silty soil which was rice and lime stabilized and they used plastic waste fibers as an addition to reinforce the soil. The study proved that plastic waste material increased the engineering properties of soil stabilized with rice husk blended with lime in terms of compressive, tensile and shear strength. The plastic waste type used in this study was polypropylene material collected out of plastic bags and were cut into long strips (Muntohar et al., 2013). In another study conducted by Laskar and Pal, (2013), the compaction and consolidation characteristics as well as maximum dry density of a plastic waste reinforced soil were assessed. The plastic type utilized in this study was of the type of plastic bottles. Plastic bottles were used in a strip form with 3 different aspect ratios namely are, 2, 4 and 8 with dimensions of 10 mm × 5 mm, 10 mm × 2.5 mm and 10 mm × 1.25 mm respectively. The soil type used was classified as a sandy-silt soil with clay with contents of 40.15% fine sand, 30.90% silt and 28.95% clay. They have also utilized these different aspect ratios in three strip content percentage variations of 0.25, 0.5 and 1% strip content. They concluded that with an increment in the strip content percentage, the compressive index coefficient of volume change has been decreased. In addition, with increment in plastic strip content, the maximum dry density was reduced (Laskar & Pal, 2013).

Chebet and Kalumba (2014), investigated the usage of plastic bag waste material as a soil additive in order to improve the physical properties of the sandy soil. The plastic waste was used in the shape of strips with dimensions of 15-45 mm× 6-18 mm. Strip content percentage were 0.3%. An improvement of more than 20% was observed regarding the shear strength of the reinforced soil. By using the plate loading test, they have also, measured an increase in the bearing capacity of the soil (Chebet & Kalumba, 2014).

Farah and Nalbantoglu (2015), utilized plastic waste in order to improve the properties of soil. In their study, plastic waste strips were retrieved out of plastic bottles and aside from control group of solid sand, they used a variety of strip content percentages as 0.5, 0.75 and 1%. Direct shear box test and CBR test were performed on the samples. Results indicated that shear strength and CBR number of the soil was increased by an increment in strip content. However, the 0.75% strip content were found as the optimum point. In addition, the shear strength and penetration resistance of reinforced soil was improved by 9% (Farah, 2015).

Dutta et. Al. (2015) also worked on effect of added plastic waste strips to the sandy soil. In their study, they used plastic strip the low-density polyethylene (LDPE) and high-density polyethylene (HDPE) with different dimensions of; 24mm×12mm and 12mm×12mm. They indicated that the tensile strength of the first type of plastic waste strips was 0.011 KN and the length at failure (elongation) was 20%. For the second type, they reached a tensile strength of 0.32KN and the length at failure (elongation) of 25%. Regarding the plastic strip percentages, they used 0.05-0.15% of strips for LDPE and 0.25-2% for HDPE. They used both type of aspect ratios 1 and 2 for each type of plastic waste. In their study, they firstly represented their control group tests with different confining pressures and indicated the deviator stress-axial strain relationship (Dutta et al., 2015).

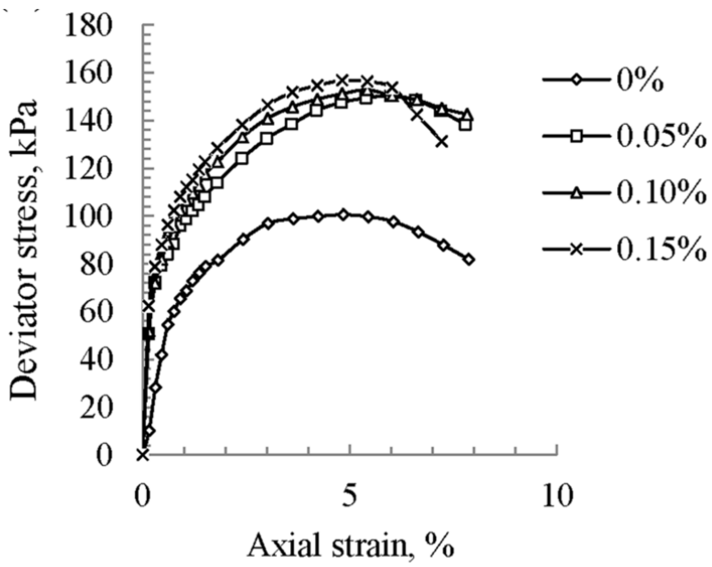


Figure 3: Triaxial test result for sand combined with plastic strips (LDPE) dimensions of 24 × 12 mm (Dutta et al., 2015)

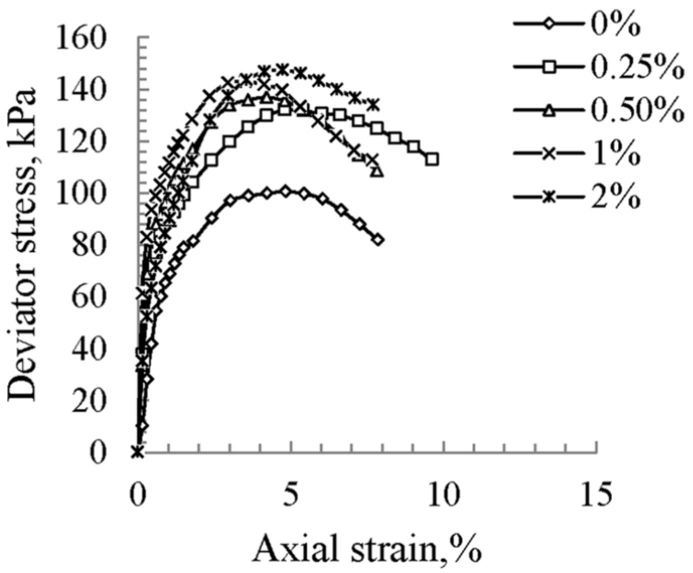


Figure 4: Triaxial test result for sand combined with plastic strips (HDPE) dimensions of 24 × 12 mm (Dutta et al., 2015)

Kalliyath et. al., (2016), investigated the stabilization effects of plastic fibers on soil. The soil type used in this study was silty clay. The plastic waste material used were retrieved out of milk and curd packet covers. Waste materials were shredded into 2 mm thickness, 4 different fiber content percentages namely, 0.25, 0.5, 1 and 1.5% were considered. In addition, the dry density of 0.5% plastic fiber content, increased its dry density value, comparing to normal soil. Standard Proctor and unconfined compressive strength tests were performed on samples. The unconfined compressive strength was found to be improved by 0.5% of its non-plastic contained normal soil. Later, the optimum value of fiber content percentage was presented as 0.5% (Kalliyath et al., 2016).

Kumar et. al., (2016), investigated utilization of plastic waste strips in stabilizing dune sand in order to design flexible pavement. The plastic type was LDPE. And strip content percentages of 0.5, 0.6, 0.7, 0.8, 0.9 and 1% were used with aspect ratio of 1 and dimensions of 5 mm × 5 mm. CBR tests and constant head permeability tests were performed. The results indicated that the utilization of LDPE in dune sand can significantly help improve the strength of dune sand (Kumar et al., 2016).

Kumar et. al, (2018), have also conducted a very similar study on subgrade. Unsoaked CBR test as well as standard proctor test were performed on the samples. Soil type utilized were a local clayey soil. Their goal was to analyse the optimum strip content percentage and aspect ratio regarding soil characteristic improvement (Kumar et al., 2018).

Peddaiah et. Al., (2018), they investigated the soil's mechanical enhancement while adding waste plastic bottle strips. The results indicated that addition of plastic strips was effective towards stabilization and were resembled to work as a fiber reinforced soil material. Soil utilized in this study was silty sand. The tests performed were namely, compaction, California bearing ratio (CBR) and direct shear. Plastic strips were used in the form of different aspect ratios and strip content percentages. An increment in shear strength of the soil as well as CBR value was observed. The optimum enhancement of soil physical properties happened at 0.4% strip content with aspect ratio of 1 and related dimensions of 15 mm × 15 mm (Peddaiah et al., 2018).

Fadhil et. al., (2020), focused on improving the mechanical properties of a clay-sand soil with addition of plastic waste strips. Different plastic strip content percentages of 0.25, 0.5, 0.75 and 1% were used. In addition, a variety of different aspect ratios and dimensions were used. However, the width of the strips were kept constant at 15 mm. Findings indicated a significant increment in unconfined compressive strength of the soil when the strips content were in 1% and 15 mm dimension condition. Evaluations have also shown that with the increase in the dimension of plastic strips, reduction in unconfined compressive strength was observed in each stage of the study (Fadhil et al., 2020).

In another study performed by Sayi and Eren (2021), the durability and physical properties the reinforced concrete using plastic waste material namely, Polyethylene terephthalate (PETE or PET) was investigated. In their study, they measured the physical properties effects of PET material with consideration of durability, acoustic properties and temperature durability of this mixture and they used different dimensions and different content percentages of PET material. Furthermore, they concluded that, addition of plastic fibers reduced the bulk density and increased the void ratio of the concrete mixture. In addition, they reached to a conclusion that since the ultra-sonic pulse velocity (UPV) of concrete had decreased, surely, there is possible formation of porosity within the mixture. The water permeability increased comparing to a mixture without PET material. Also, they heated the samples to control the temperature durability of the mixtures and results had shown that only slightly the compressive strength of mixture was reduced. However, the flexural strength had significant amount of increment in high temperature of between 100-200 C° (Sayı & Eren, 2021).

Vismaya et. al. (2021), assessed the mechanical strength of subgrade soil with addition of plastic bag wastes. In their study, the effects of change in aspect ratio and the thickness of plastic bags on unconfined compressive strength of the cohesive soil were evaluated. Plastic waste strips were used with various thicknesses of 15, 30 and 45 µm. The conclusion was that with increment of thickness, the unconfined compressive strength and tensile strength increases (Vismaya et al., 2021). Abdulrahman et. al. (2021), observed the effect of plastic fiber on mechanical properties of Gypseous soil. In their study, 1% plastic fiber content were used in order to enhance the shear strength of the soil and improve the collapsibility of the soil at the saturated state or wet type of soil. Tests such as direct shear test and collapse test were performed on the samples. They concluded that the cohesion value of the soil had an increment from 2 MPa to 11MPa with addition of plastic fiber. The plastic fiber used in the study was polypropylene (PP) (see Figure 5 and 6), (Abdulrahman et al., 2021).

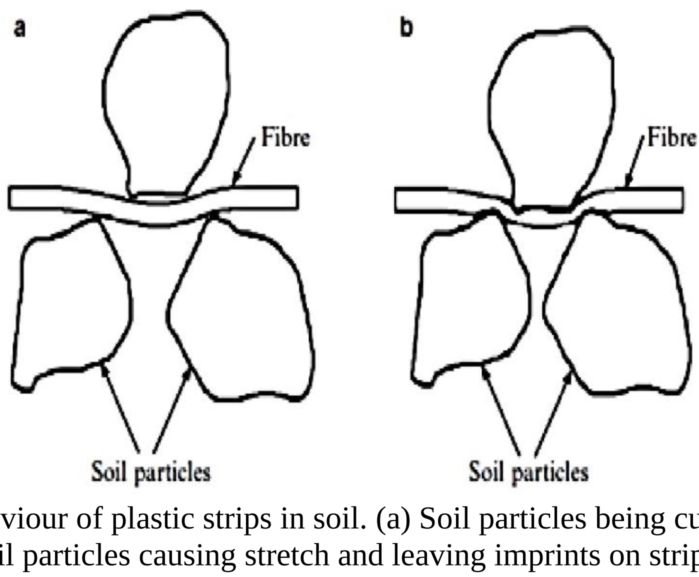


Figure 5: Behaviour of plastic strips in soil. (a) Soil particles being curbed by plastic strips. (b) Soil particles causing stretch and leaving imprints on strips resulting in creation of adhesion (Abdulrahman et al., 2021)

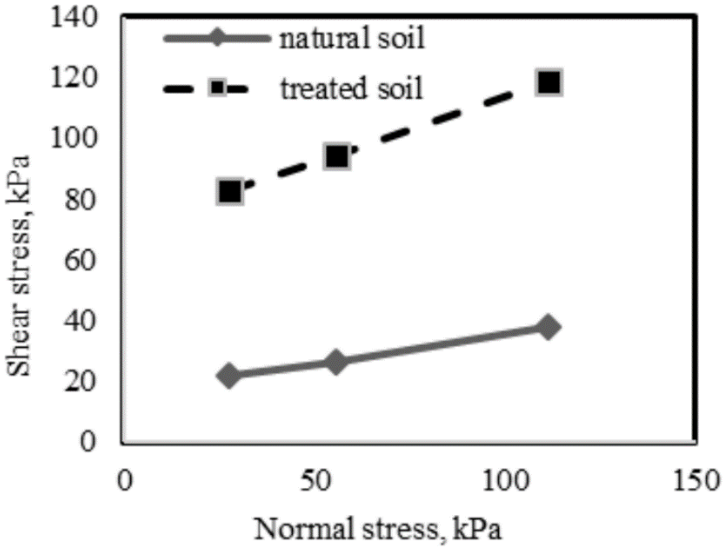


Figure 6: Direct shear test results and the relationship between shear and normal stress (Abdulrahman et al., 2021)

Fathi et. al., (2021), assessed a large-scale direct shear experiment and considered the cyclic and monotonic behaviour of plastic waste treated sand. In their study, they used polyethylene terephthalate (PET) obtained from cutting plastic bottles which were cut into strips with dimensions of 10 mm × 10 mm, 25 mm × 10 mm and 50 mm × 10 mm with associated aspect ratios of 1, 2.5 and 5 respectively. The strip content percentage used were namely, 0.5, 0.75 and 1% of the dry sand total mass. Results indicated that, addition of plastic strips increased the cyclic shear strength. An increment in the aspect ratio, could cause in an increase in the shear strength of the sample (Fathi et al., 2021).

Chapter 3

MATERIALS AND METHODS

3.1 Materials

The materials used in this study consist of sand and plastic bottle strips. The beach sand present widely at Famagusta Bay, has poor shear strength and is susceptible for particle crushing and liquefaction (Saeed et al., 2021; Uygar & Doven, 2005). PET was chosen as the plastic waste for this study, not only because does it pollute the environment, but it also constitutes most of the wastes among the materials dumped in the nature (as much as 29.1%, EPA, 2021).

3.1.1 Soil

Fine sand utilized in this study was attained from Silver Beach located at Famagusta Bay, Cyprus. Figure 7 shows aerial view of the location of sampling with approximate coordination on: X= 582835, Y= 3891992 (Google, 2022).

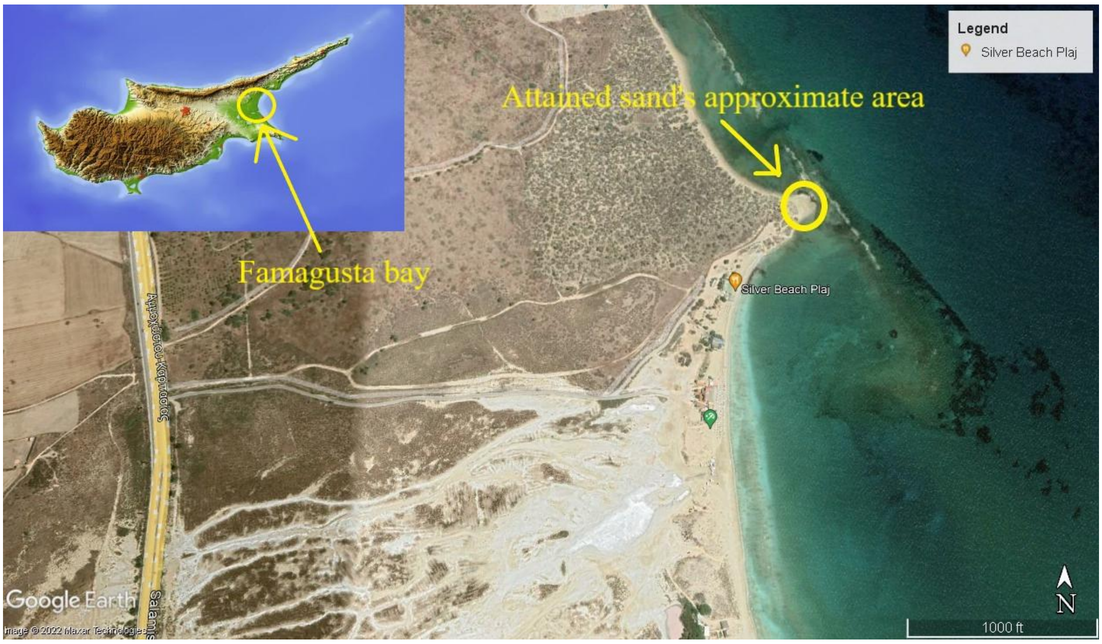


Figure 7: Aerial view of the fine sand's location obtained from Google Earth, (2022)

3.1.2 Plastic strips

Each plastic bottle and container have a production number on them usually located at the bottom side, indicating their full chemical compound. For this study, the production number of plastic bottles is shown in Figure 8.

Figure 8: The production number hatched on the bottle showing the chemical component to be polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is one of, if not the most generally consumed type of plastic and it can be recognized easily as they are used for water and pop bottles, and a few other types of packaging. The consuming intentions are normally a single use application, as repeating the utilization process of these bottles can increase the risk of bacterial and leaching growth. Products made out of PETs are hard to sanitize. Although, there are chemical solutions that can help in cleaning the bottles, they can be extremely harmful and form a haphazard to human health if not properly removed. In addition, they require more energy when recycling compared to their production. Clearing process can cause leaching of carcinogens (Ackah, 2019; Singh et al., 2018).The molecular structure of polyethylene terephthalate (PET) is:

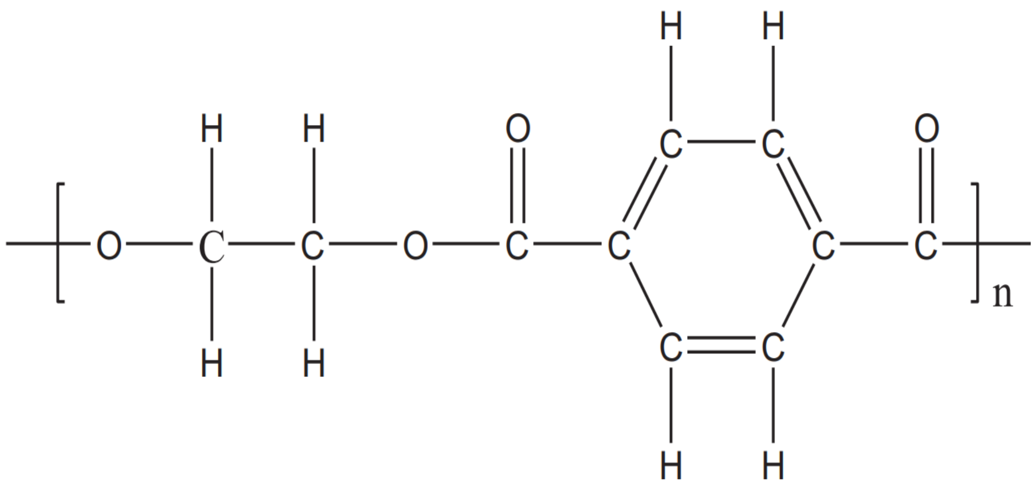


Figure 9: Molecular structure of PET

And the molecular formula of PET is: $(C_{10}H_8O_4)_n$ or $C_5H_4O_2$. The density of this material also is 1.397 g/cm3 (Guo et al., 2020).

According to the research conducted by (Bamford & Jenkins, 1955; Guo et al., 2020), polyethylene terephthalate (PET) is possible to be melt-spun and hot-drawn, and its amorphous density is 1.335-1.337 gm/cm^2, with a unit-cell density of crystallite of 1.455 gm/cm^2. Therefore, it is convenient to use PET as an additive to sand, for which density usually varies in the range of 1.3–1.7 g/cm^3 (Bamford & Jenkins, 1955)

3.2 Plastic Strip Preparation

The strips used in this study are 12mm×4mm with the aspect ratio of 3 as they were more convenient to produce in this dimension, as well as literature review proving that as the length of strips increase, engineering properties of soil was improved more greatly (Bhattarai et al., 2013; Choudhary, Jha, et al., 2010; Neopaney et al., 2012).

Sample preparation process includes of firstly removing the commercial label wrapped around the bottle and then heating the plastic bottles by holding them on top of a heater with 200C° temperature to a point where the air inside the bottle starts to expand and push the walls resulting in a smooth surface on bottle walls and become easy to work on. Afterwards, using a bottle cap and a razor knife, a cutting tool has been manufactured which can generate long plastic strips out of plastic bottles in a constant thickness of 4mm. The photo of the tool manufactured is shown in Figure 10.

Figure 10: The tool used in order to cut the bottles into long strips

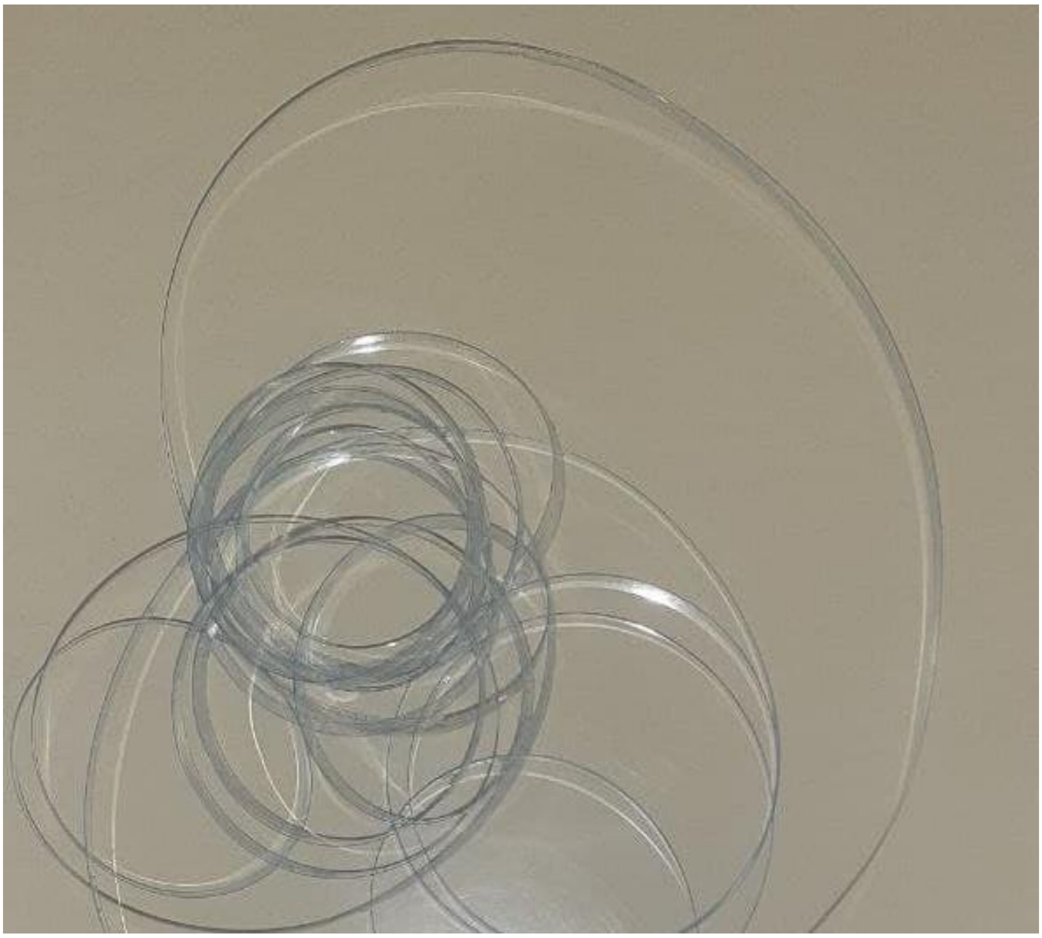


Figure 11: Long plastic strips with thickness of 4mm generated by cutting plastic bottles

After cutting the plastics in long strips, they were held in 20+ groups in palm of hand and using a scissors they were cut into 12mm long strips. Strips were held in 20+ groups to achieve time efficiency and accuracy of aspect ratio of plastic strips. A demonstration of the process can be seen in Figure 11.

In order to keep the aspect ratio constant, the bottle cap installed on manufactured tool shown in Figure 10, was carefully drilled at a distinctive distance of 4mm from each side.

Figure 12: The hand-technique used to create 12mm×4mm long strips

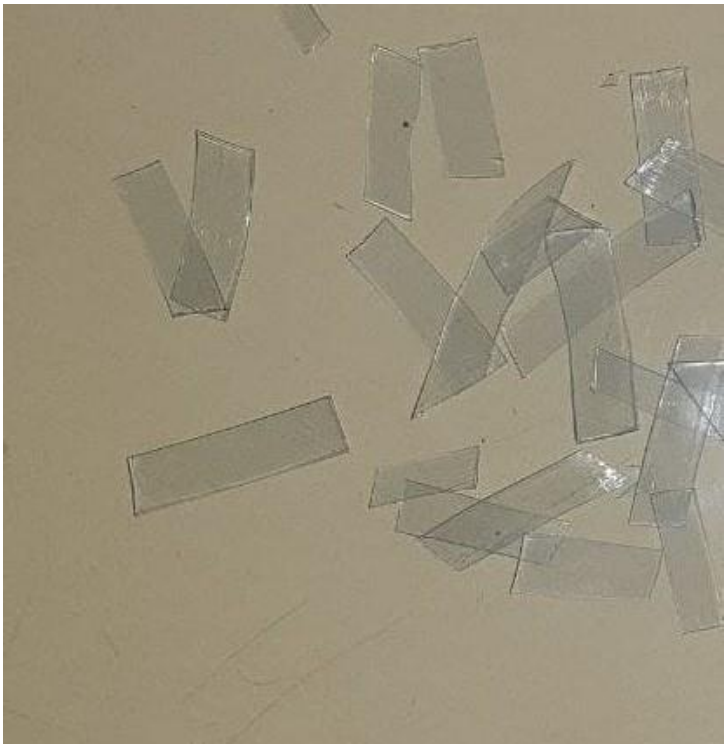


Figure 13: The plastic strips generated in this technique

3.3 Sample Preparation

In the previous studies on the use of plastics in soil stabilization, plastic strips combined with sand in solid form (Benson & Khire, 1994; Dutta et al., 2015; Farah, 2015; Peddaiah et al., 2018). However, in this study, three newly developed sample preparation methods have been presented, which consist of heating the samples up to the melting point of plastics, with respect to time. When plastic melts and the reduction in viscosity occurs, plastics start to move between the sand particles and create an interlocking behaviour with a strong bonding when it solidifies upon losing heat. A sample box (SB) 70mm × 34mm was designed to maintain a uniform temperature throughout the sand and plastics while heating. The SB manufactured is presented in Figure 16.

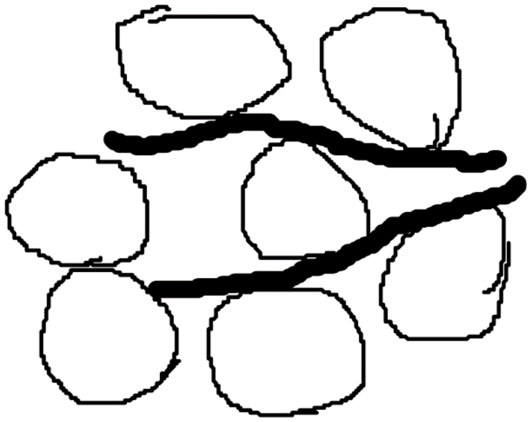


Figure 14: Plastic strips added to sand in a solid form

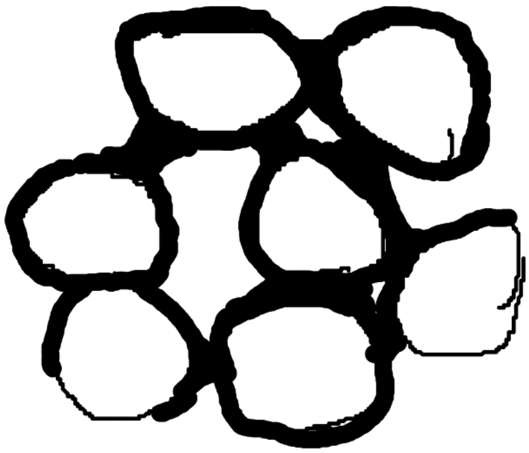


Figure 15: Sand particles coated with melted plastic and the bonding created by melted plastic in between particles

Minor emissions can be seen while melting in SPM-2, SPM-3, and SPM-4. Controlling the temperature at the melting point of plastic will reduce emissions and will be negligible.

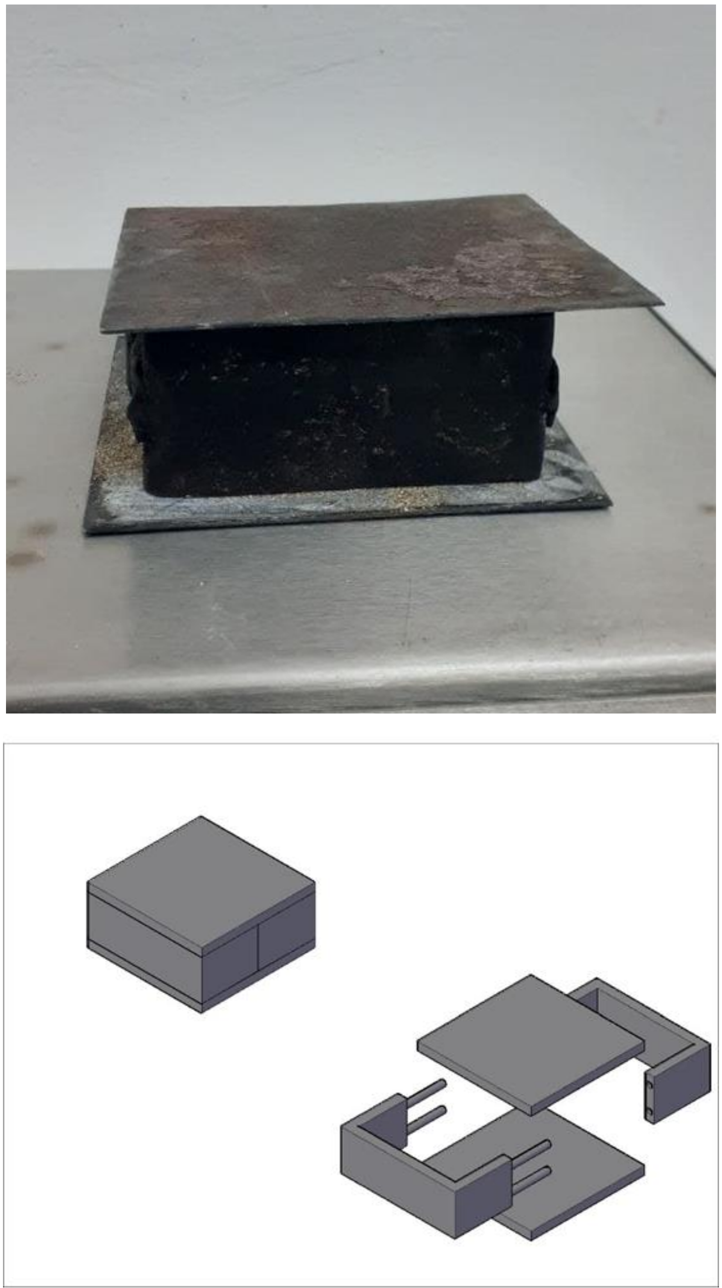


Figure 16: Sample box made out of metallic sheet used on hotplate, with dimensions of 70 mm×70 mm and height of 34 mm.

3.3.1 Sample Preparation Method 1

In SPM-1 the plastic strips which are cut into 12 mm×4 mm sizes were mixed with soil in different percentages ranging from 2.5, 5, 7.5 and 10 percent by dry weight in groups of three and were tested using direct shear test without any sub-preparations.

3.3.2 Sample Preparation Method 2

Firstly, the weighed sand and plastic strips 12 mm×4 mm were placed inside a container and mixed up thoroughly using a spoon. Later, using a spoon the mix was slowly added into the SB to keep the sand-plastic proportion approximately constant. The SB was kept at the top of the hotplate with a gap between the heater and the SB using a cylinder with the height of 78 mm. The cylinder's thickness was 1mm, maintaining contact with the SB. Thus, adding only a negligible amount of induction energy directly from the hotplate to the SB. Sample box and cylinder were covered with a steel mold to prevent heat loss and to keep the heat constant between the upper part and lower part of the sample. Hotplate, cylinder and steel mold were heated up to the required temperature which is 250 C°. While placing the SB, the big mold was removed and the SB quickly placed on top of cylinder with the big mold on top, in order to prevent the heat loss during the process. The SBs were heated up to 40 minutes and were quickly removed and stirred while still being hot to let the melted plastic strips have better bonding with sand particles. Afterwards, the samples were left to cool down prior to slicing them into required dimensions in direct shear box, which was 60 mm×60 mm×32 mm in size. A layer of sand was placed underneath the sample and on top inside the shear box prior to testing to provide uniform surface for the application of normal stress. The second sample preparation method was taken into consideration in order to compare the effect of heat loss on shear strength and bonding strength of the samples.

3.3.2 Sample Preparation Method 3

The procedure has high resemblance with first type of sample preparation. After 40 minutes of heat exposure on top of hotplate in 250 C° inside the steal mold and on top of cylinder, sample was stirred in order to create the optimum amount of bonding between particles and plastic. The shear box was placed inside the oven with hammer for 5 minutes to increase their temperature. The sample was poured directly from sample box to shear box in three different layers and was hammered in each layer to induce compaction. Finally, the samples were left to cool down to the room temperature prior to testing. In this method, it was expected that due to temperature loss in the procedure of adding the hot-mixture directly to shear box, there would be a weaker bonding between particles. Thus, this sample preparation method was considered to evaluate the change in behaviour due to temperature loss, and to control the temperature for finding optimum condition).

The temperature inside samples at the post-heating stage were maintained at 250C°, as higher temperature would change the soil and plastic chemical properties.

3.3.3 Sample Preparation Method 4

The procedure has high resemblance with first type of sample preparation. After 40 minutes of heat exposure on top of hotplate in 250 C° inside the steal mold and on top of cylinder, sample was stirred in order to create the optimum amount of bonding between particles and plastic. Afterwards, the sample was added to a cylinder with 3.3cm dimension and 8 cm length using a spoon and with a with weight of 168g hammered in 3 different stages in clockwise direction and starting from 10 up to 25 times drops to achieve compaction. Then the samples were carefully cut into 6.6 cm length in accordance to ASTM standard on sample ratio for unconfined compression tests.

3.4 Microscopic Photos

In order to better understand the interlocking behaviour and bonding between sand and plastic waste particles, numerous microscopic photos from each sample group with 2 different magnifications using an optical microscope mounted with 20MPix digital camera were obtained and are presented in Figure 17 to Figure 26.

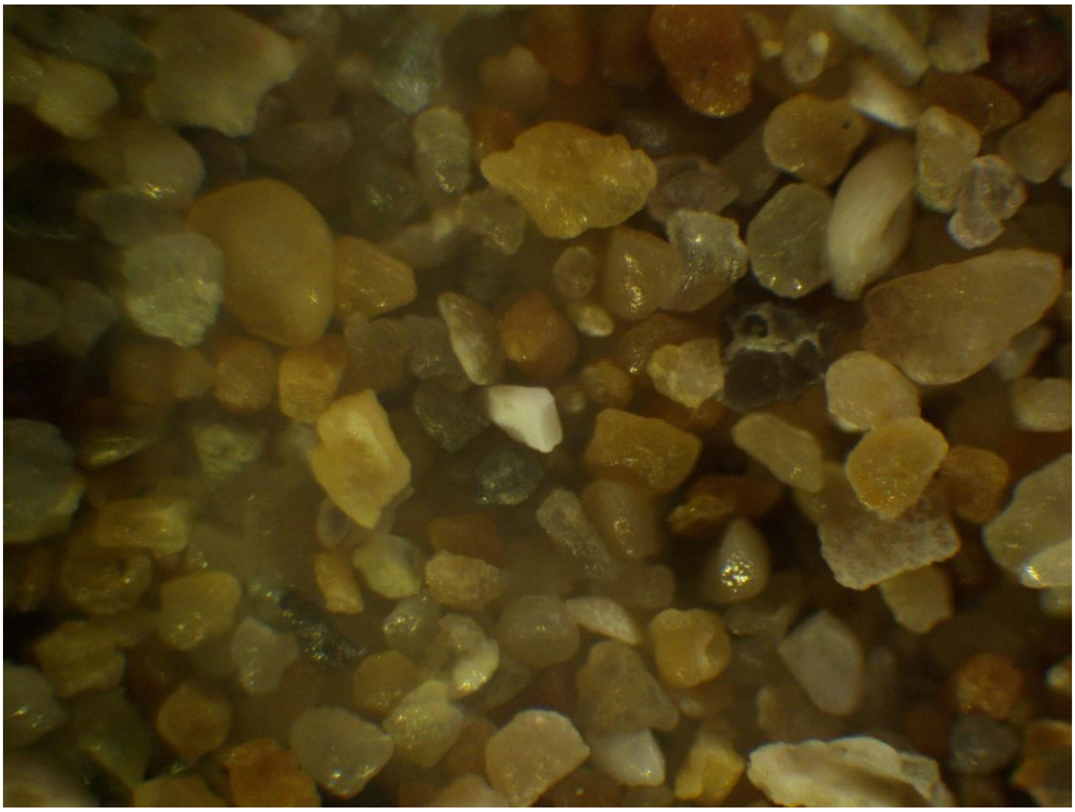


Figure 17: Pure fine sand

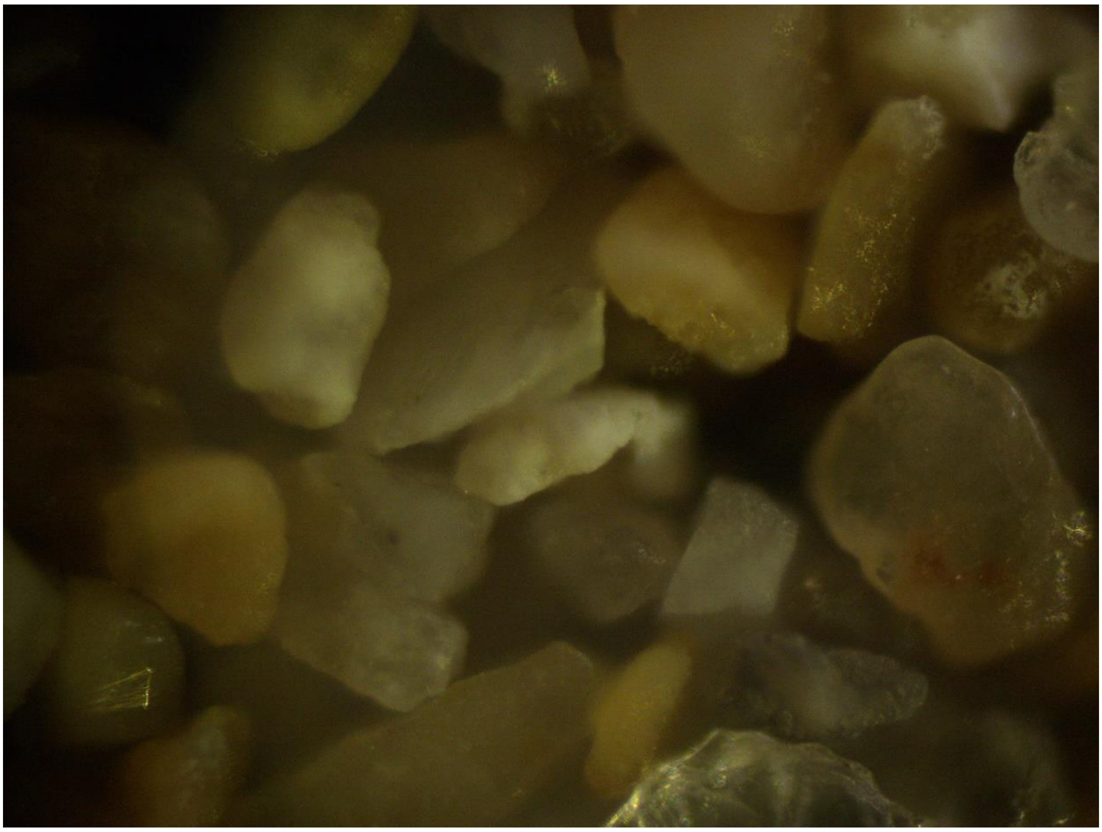


Figure 18: Pure fine sand

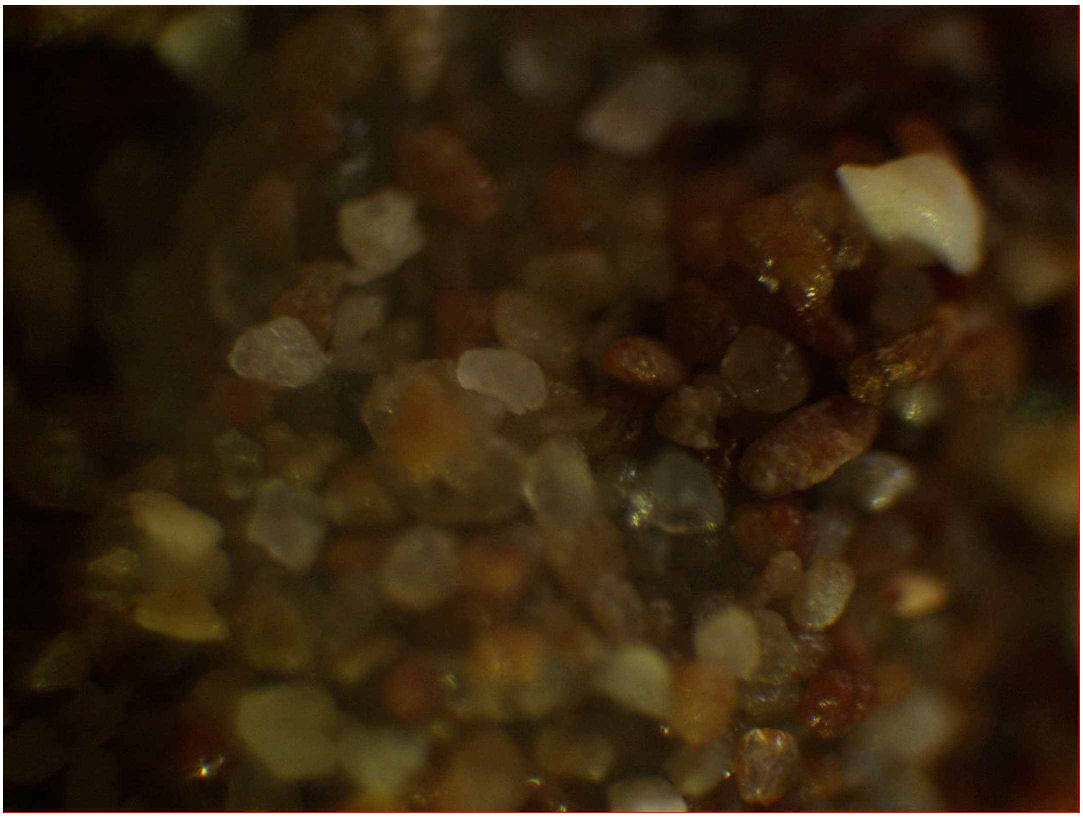


Figure 19: Sand with 2.5% plastic strip content

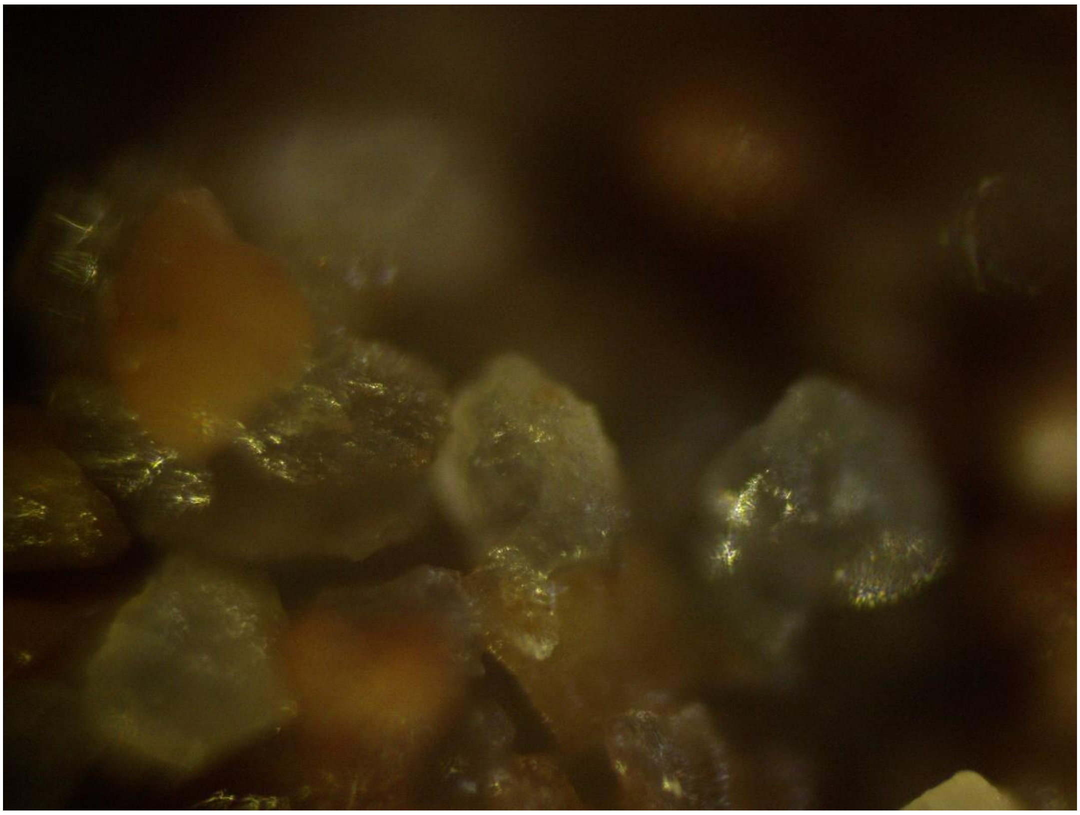


Figure 20: Sand with 2.5% plastic strip content

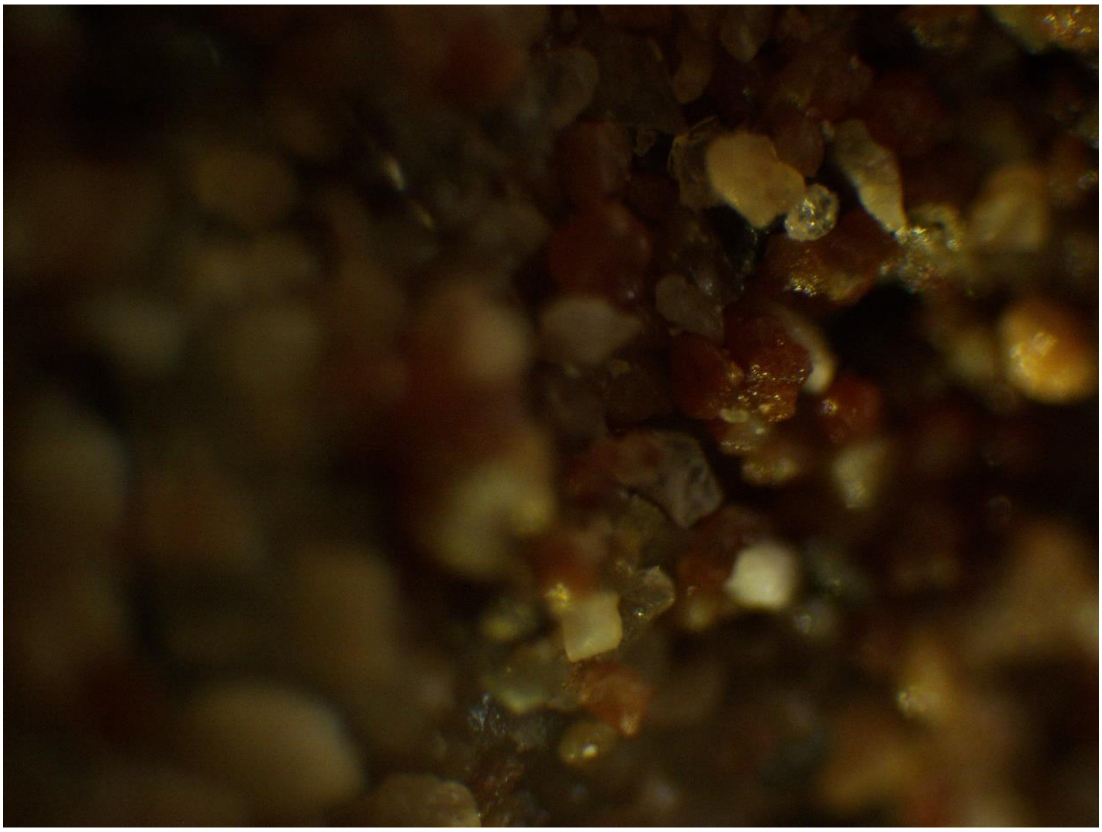


Figure 21: Sand with 5% plastic strip content

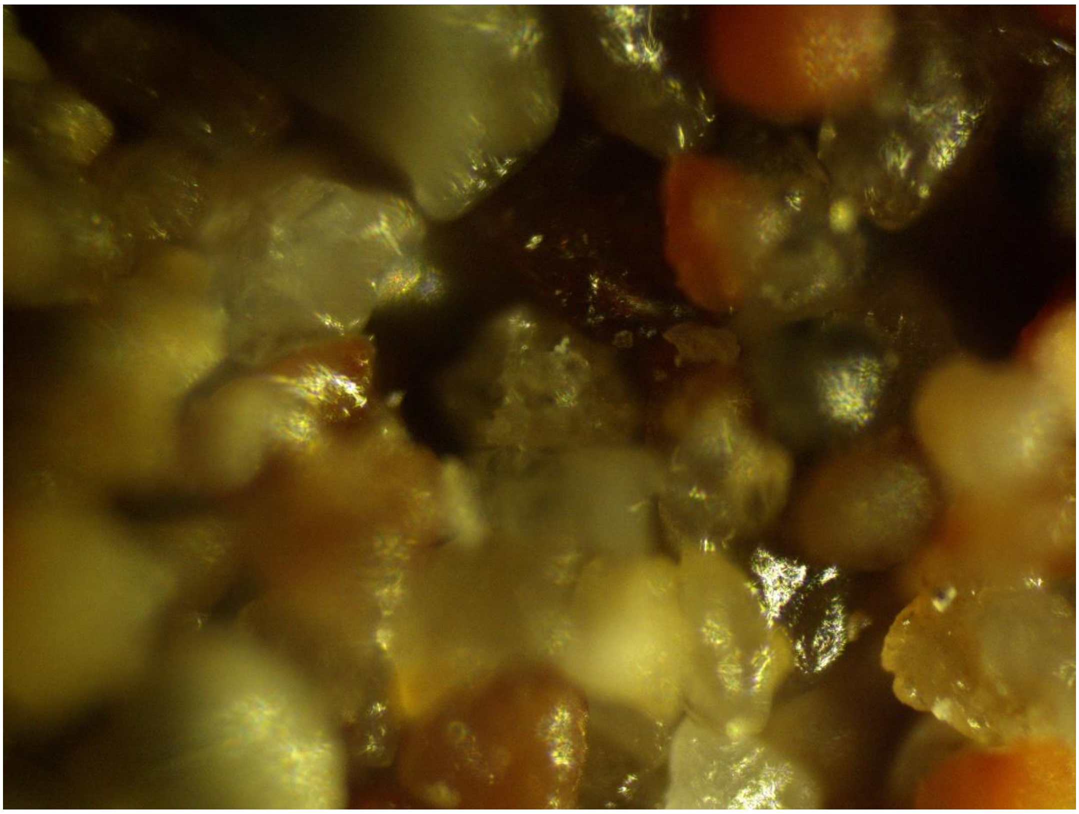


Figure 22: Sand with 5% plastic strip content

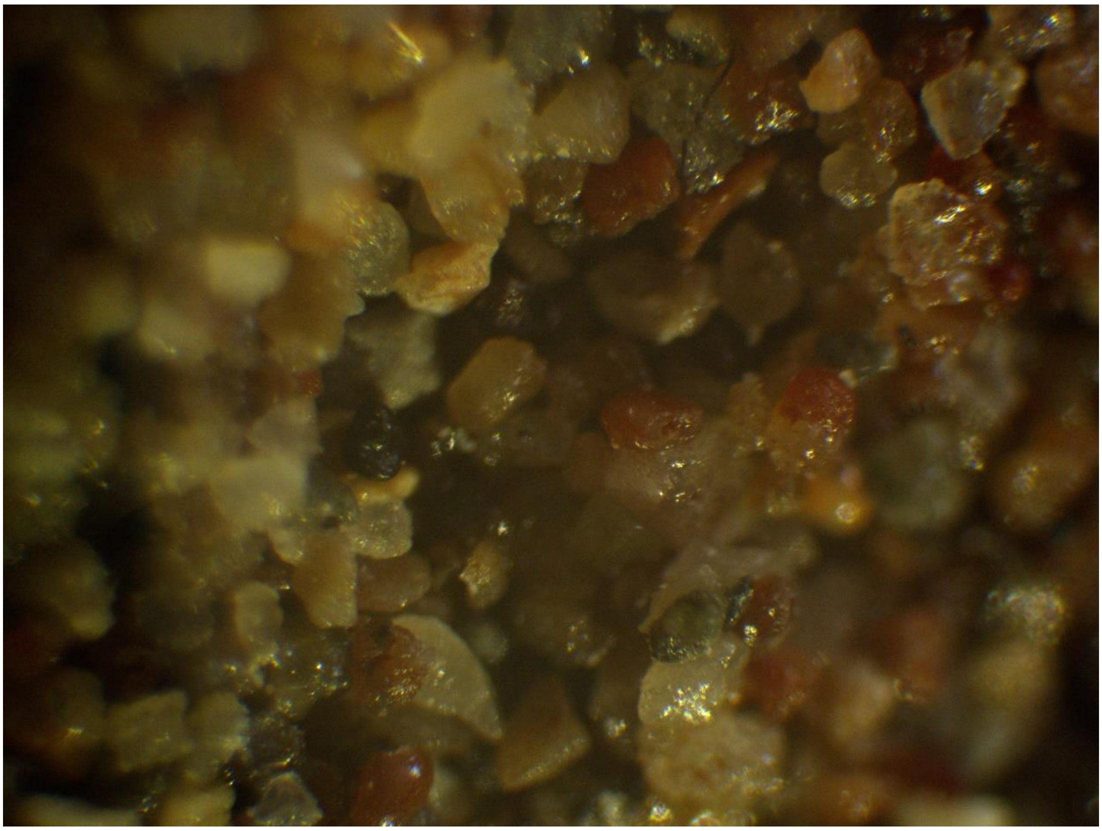


Figure 23: Sand with 7.5% plastic strip content

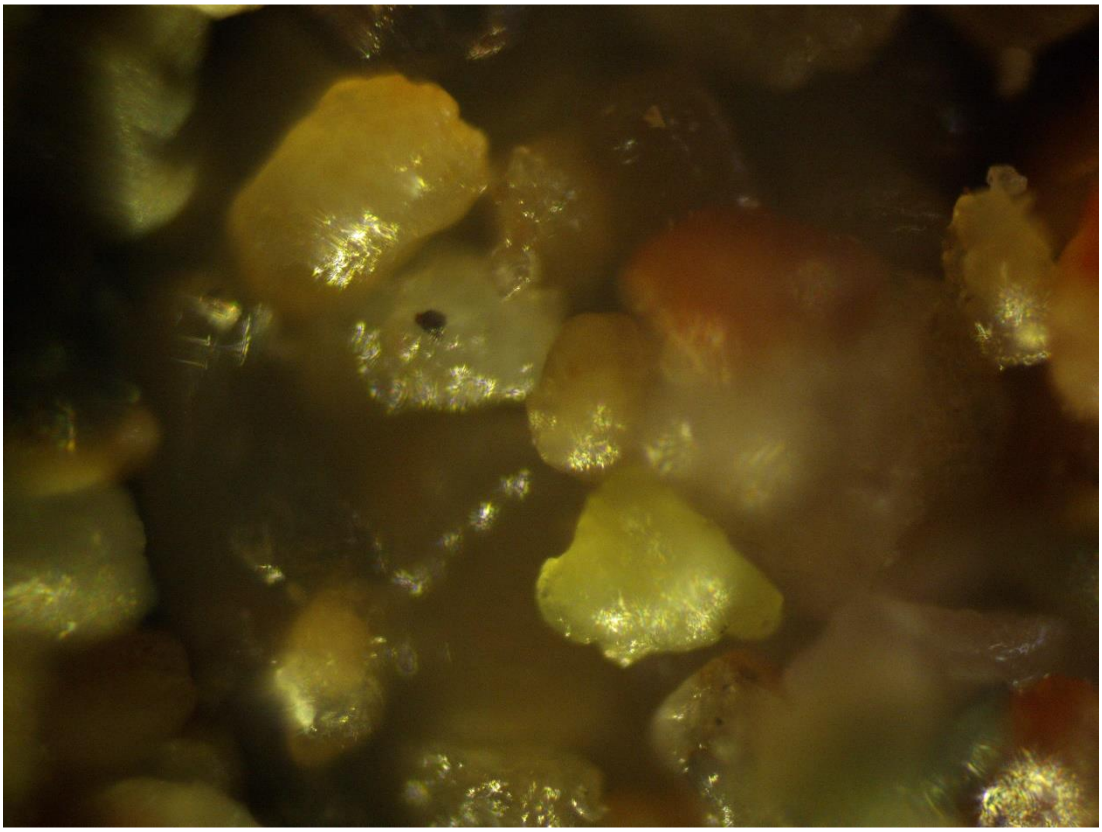


Figure 24: Sand with 7.5% plastic strip content

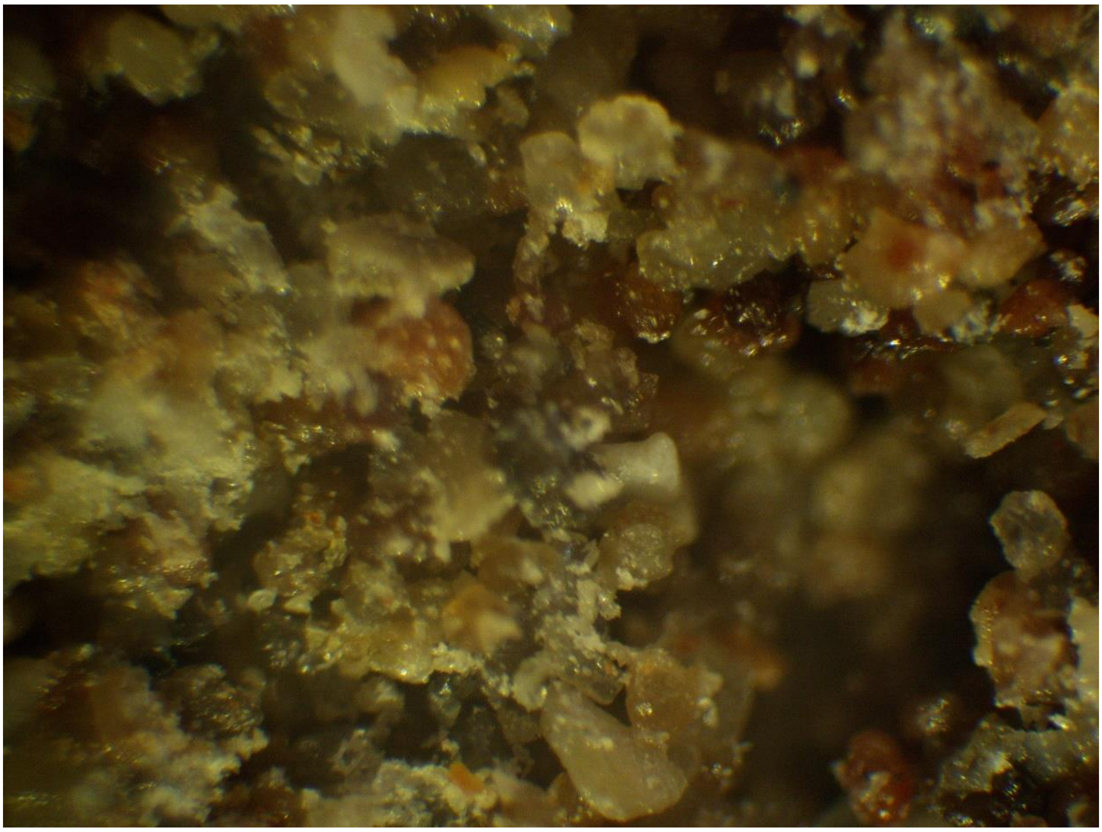


Figure 25: Sand with 10% plastic strip content

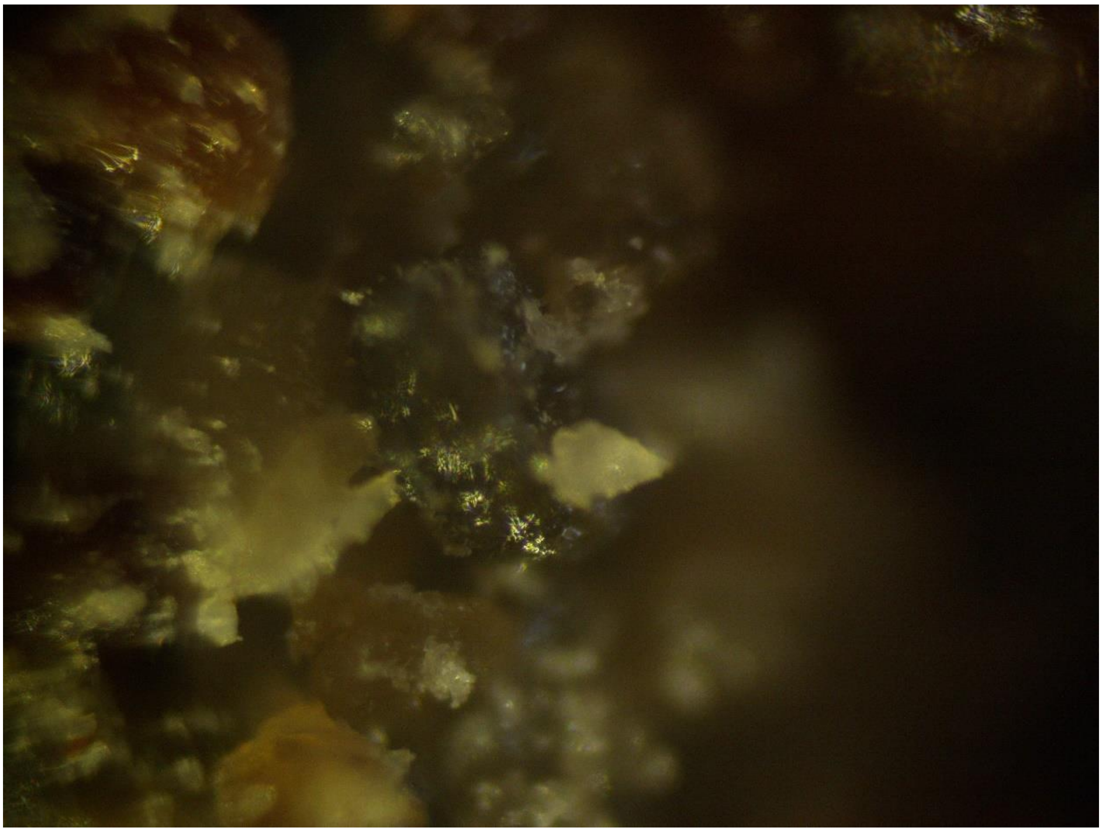


Figure 26: Sand with 10% plastic strip content

As can be seen from Figures 17 and 18, the fine sand retrieved from Famagusta Bay constitutes animal shells as well as calcium particles, which can cause small fluctuations in shear strength tests as they crack under lower strength than sand particles. However, this fluctuation is considered to be same for all samples.

From the Figures 19 and 20, the difference of sand particle concentration in a single area in comparison with pure fine sand photos is completely evident which are caused by plastic particles that have coated the sand particles partially and enough to create a weak bonding between sand particles that make them stick together, On the other hand, as the photos get closer to higher plastic content percentages, as can be seen in Figures 21 to 26, the melted plastics that have coated sand particles are clearly visible as opaque color and white spots.

3.5 Test Groups

All laboratory tests were performed based on America standards for testing and materials, (ASTM, 2022).

The testing strategy considered performing basic physical and mechanical tests to help observe changes in engineering behaviour of the studied sand. The general testing programme is provided in Figure 27.

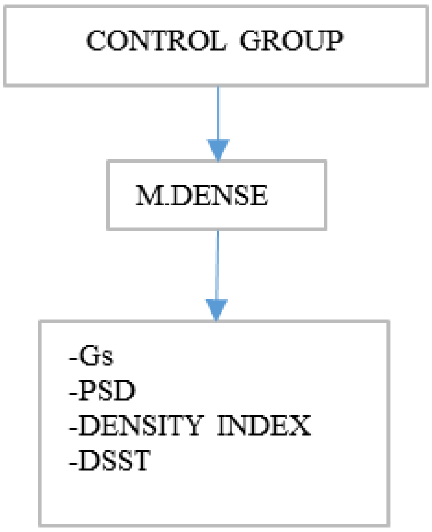


Figure 27: Control group tests for sand

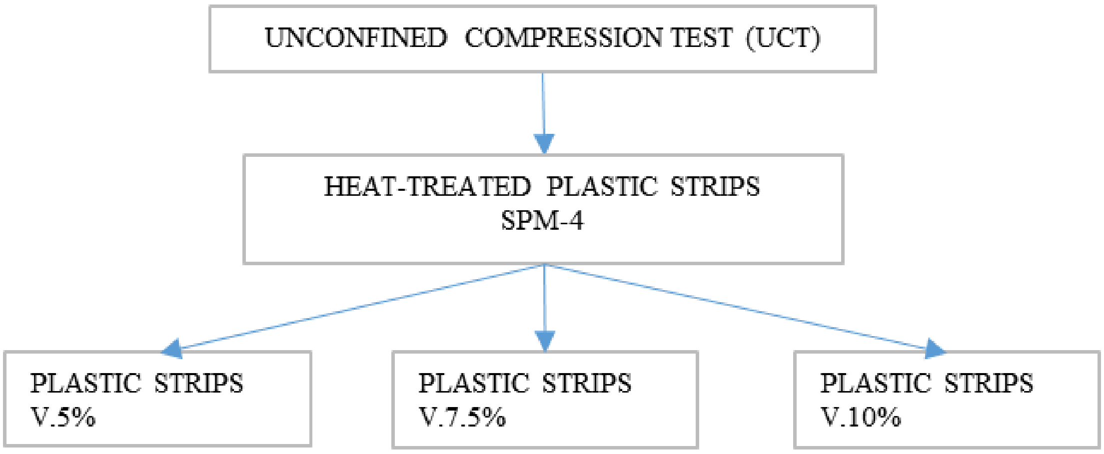
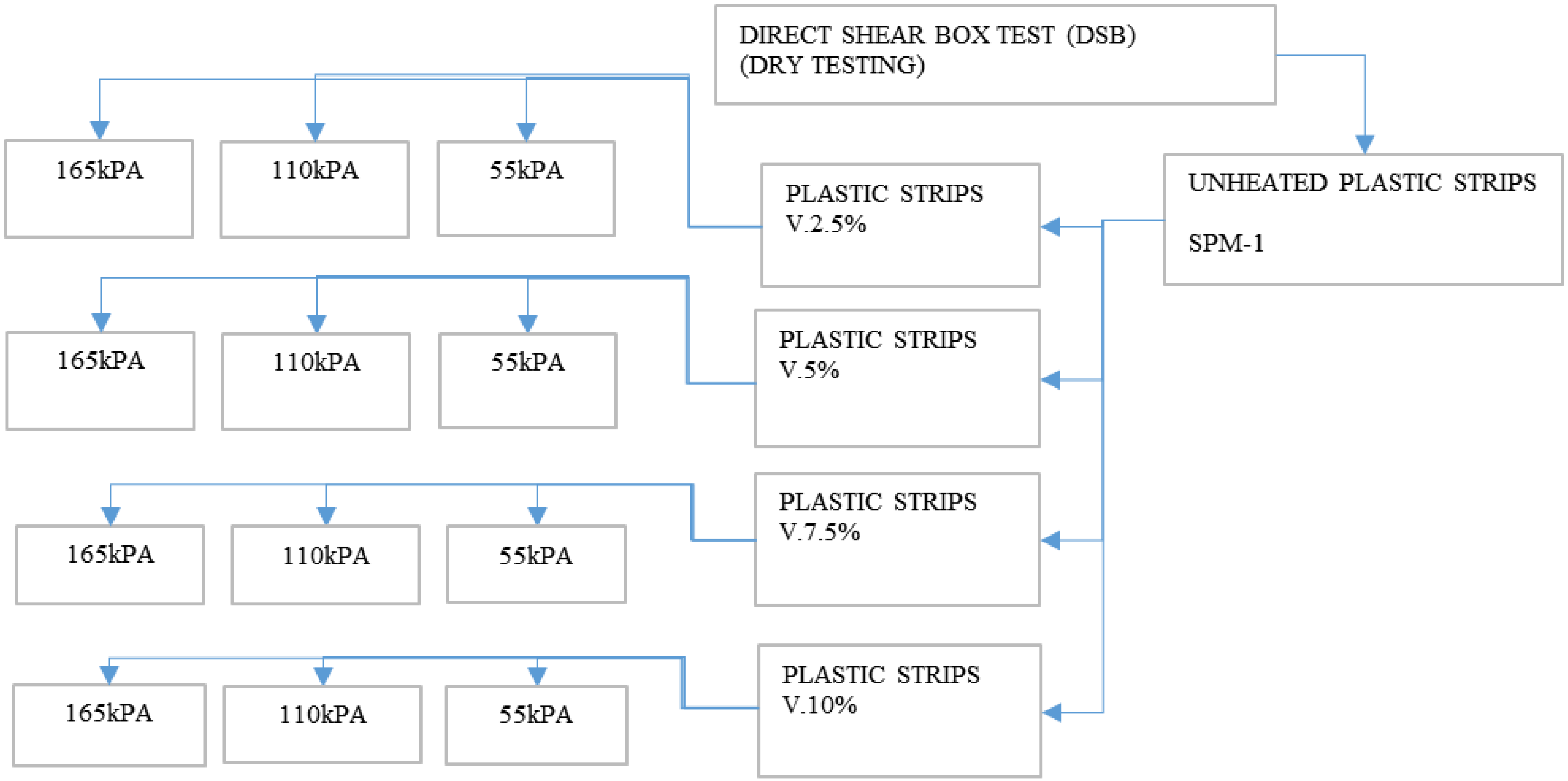
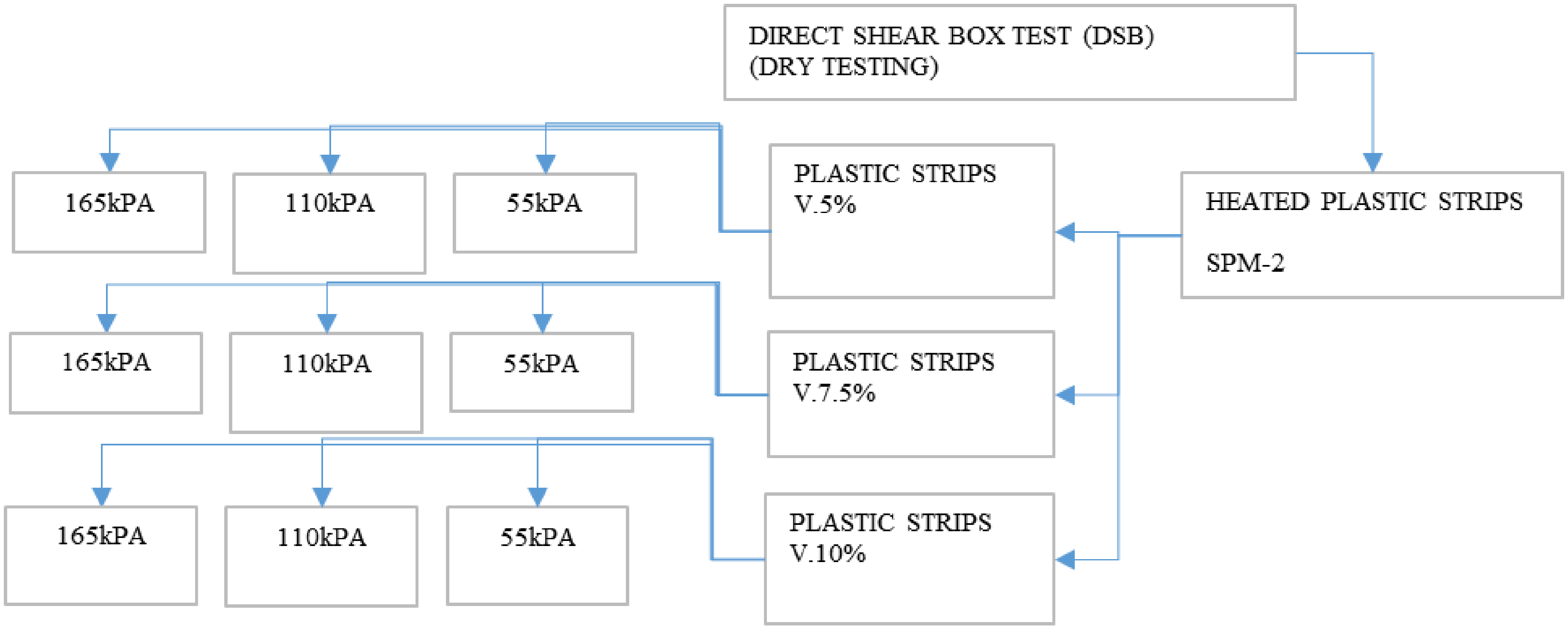


Figure 28: Unconfined compression test on cylindrical samples

Due to plastics ability to create bonding in between sand particles, it helps sand to achieve unconfined compressive strength. In other words, plastic strips as they melt, are capable of forming solid blocks with soil and turn them into a useful material for construction. Thus, in this study, in order to observe effect of bonding of the plastic and sand mixture, an unconfined compression test programme as well as direct shear box test were performed. These test programmes are provided in Figure 28 and Figure 29 respectively.


DIRECT SHEAR BOX TEST (DSB)
(DRY TESTING)
UNHEATED PLASTIC STRIPS
SPM-1
PLASTIC STRIPS
V.2.5%
PLASTIC STRIPS
V.5%
PLASTIC STRIPS
V.7.5%
PLASTIC STRIPS
V.10%
165kPA
110kPA
55kPA
165kPA
110kPA
55kPA
165kPA
110kPA
55kPA
165kPA
110kPA
55kPA


DIRECT SHEAR BOX TEST (DSB)
(DRY TESTING)
HEATED PLASTIC STRIPS
SPM-2
PLASTIC STRIPS
V.5%
PLASTIC STRIPS
V.7.5%
PLASTIC STRIPS
V.10%
165kPA
110kPA
55kPA
165kPA
110kPA
55kPA
165kPA
110kPA
55kPA

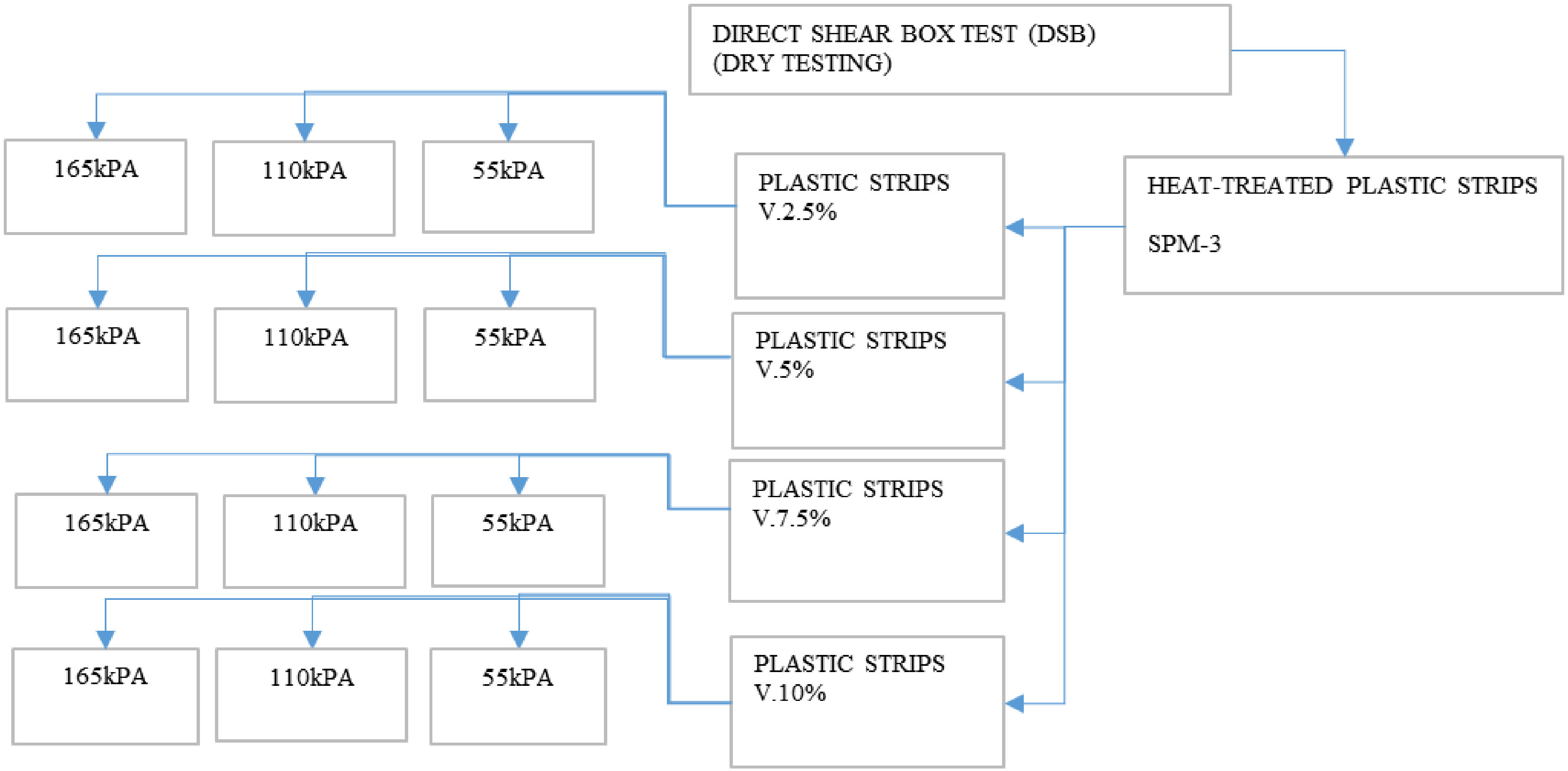


Figure 29: Direct shear box test programme

Direct shear box test could be performed on unheated samples as well as heated ones. Therefore, study on shear strength has been done on both melted and unmelted types and the results were compared. However, unconfined compression test, could only be performed for the melted samples.

3.6 Test Conditions

Tests are conducted at dry conditions and at room temperature (22 ± 1 C°).

Loading speed for unconfined compression test was 0.5 mm/min. The loading speed for direct shear box test was 0.5 mm/min.

Chapter 4

ANALYSIS AND DISCUSSION

4.1 Particle Size Distribution

In this study, to determine the physical properties of the mixtures containing plastic strips, experiments such as particle size analysis, relative density and specific gravity have been performed. Figure 30 shows the particle size distribution of the soil used in this study, which is identified as fine uniform sand based on unified soil classification system (USCS) (ASTM, 2009).

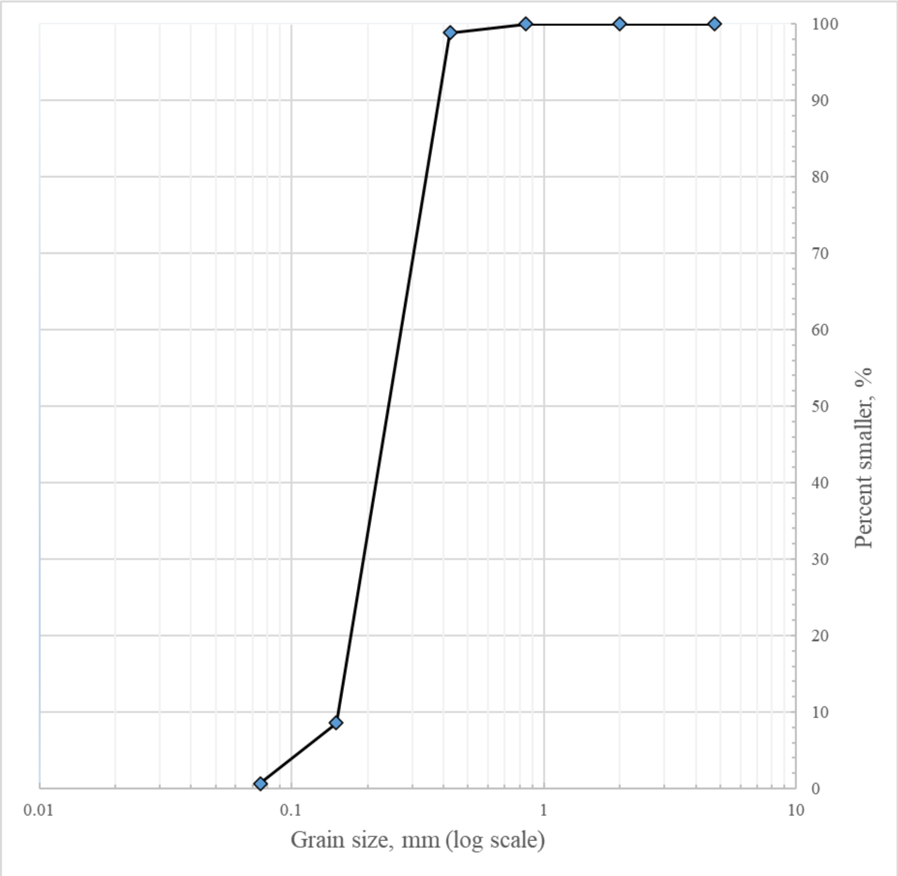


Figure 30: Particle size distribution of soil

4.2 Specific Gravity (G_s)

The experiment to determine the specific gravity of sand was performed based on ASTM standard no. D854-14 and it was repeated four times. In this test, 250ml pycnometer volumetric flask and in each experiment 60±5 sand was utilized. The average specific gravity of sand was obtained on 2.706.

4.3 Minimum and Maximum Dry Density and Unit Weight of the Soil

The test was performed based on ASTM standards D4253 and D4254. In this test dry soil was added to a cylindrical mould using a funnel with approximately zero dropping height. The top part of the cylinder was trimmed using a spatula and the weight was measured to determine the minimum dry density and maximum void ratio. Afterwards, the cylinder was placed on top of a vibrator with a surcharge of12 kg applied on top, the vibrator was set to 60 Hz, and the specimen was vibrated for 10 minutes. Measured minimum and maximum density and void ratio are provided in table 2.

Table 2: Minimum and maximum density and void ratio.

Soil type	Minimum density (g/cm^3)	Maximum density (g/cm^3)	e_{max}	e_{min}
Fine sand	1.367	1.616	0.979	0.675

For the sample preparation method 1 shown in Table 3, 12 samples were considered with strip contents of 2.5, 5, 7.5 and 10 percent. The amount of initial compression in each test procedure caused by the initial application of normal strength was observed and the change in relative density, void ratio and bulk density of the sample after being exposed to different normal stresses was measured. Since, logically, it is expected for higher applied normal stresses to have a denser mixture, it can be observed that by increasing the applied normal stress, the amount of density after initial compression slightly increases. However, the plastic strips content seemed to affect the trend as the percentage of strips was increased. Data regarding the effect of plastic strip content also seemed to be sensitive to the method of preparation. Further elaboration of this information per group is provided in the following section for direct shear box test results.

4.4 Unconfined Compression Test

The test group for unconfined compression test was named as SPM-4. As natural sand does not have any unconfined compressive strength, the test has been performed to plastics added group only, results of which indicate the overwhelming effect of melted plastic on test results provided in Figure 31.

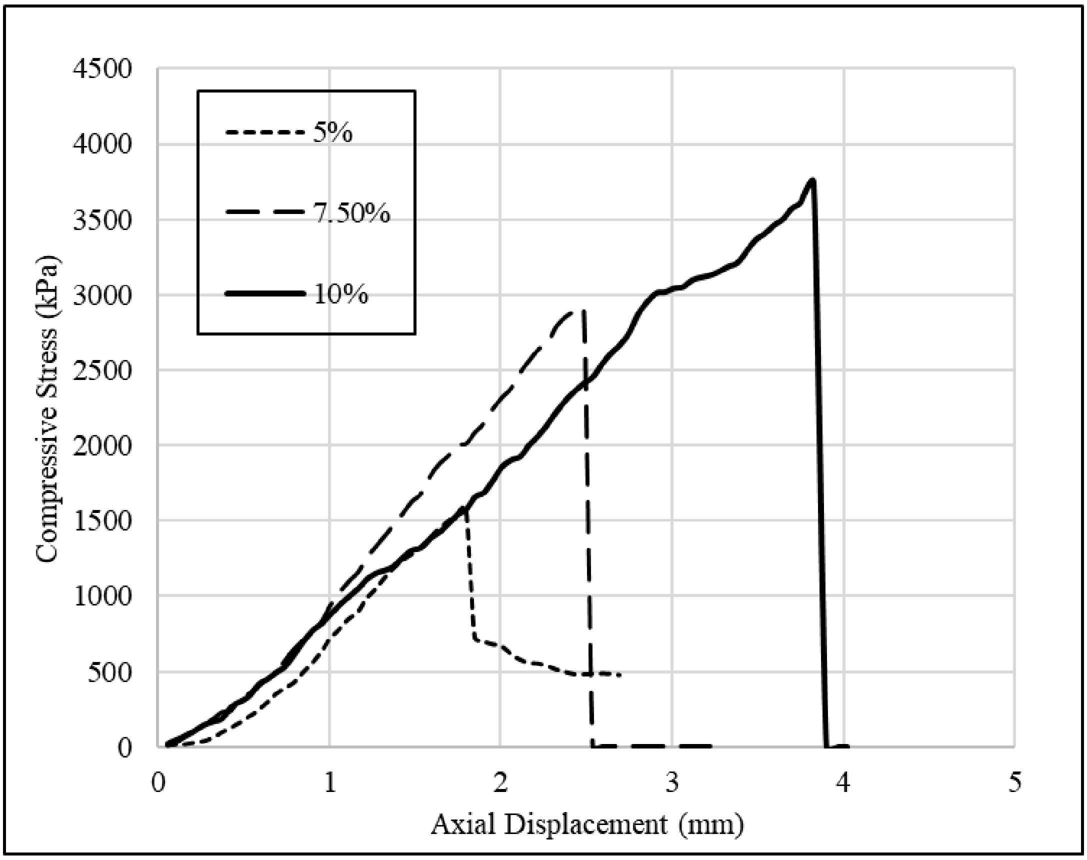


Figure 31: Unconfined Compression Test (UCT) for SPM-4 samples

As it is obtained from Figure 31, with an increase in the plastic content percentage, the compressive strength as well as axial displacement at failure increases. Indicating plastic contents not only improve unconfined compressive strength of the soil, but also, they increase the stabilized soil’s ductility. However, upon reaching the compressive stress at failure, specimens spontaneously exploded and were no longer capable of carrying any stress, indicating an overall brittle behaviour.

As a result, in SPM-4, the unconfined compressive strength of the soil in comparison within the groups tested stress increased as much as 3 times with an increase up to 3.2 MPa for dense condition. Thus, making melted-samples, although superior very difficult, proved to be superior to the findings of the previous studies (Bai et al., 2019).

4.5 Direct Shear Box Test

This test has been performed on 4 different sample groups including pure fine sand, SPM-1, SPM-2, and SPM-3 to thoroughly show the details of the behaviour of the sand and its difference in shear strength where sand was exposed to melted plastic rather than solid plastic strips.

4.5.1 Pure Fine Sand

The direct shear box test for soil was performed in order to observe the difference in engineering properties between natural sand and specimens prepared using sample preparation methods (SPM-1, SPM-2, SPM-3, and SPM-4) provided in this study. The results of DSBT for natural sand can be seen in Figure 32 to 34.

Although, the sand in site is in a loose condition, the study was performed in dense condition since the effective normal stress applied will eventually compresses the samples and make them denser. While being dense by effective normal stress has a different behaviour from initially preparing the specimens in a dense condition, the focus of this study was to compare the difference between natural sand, SPM-1, SPM-2, SPM-3, and SPM-4 and since melted plastic methods will keep the form intact and do not allow a change in structure, they will not follow the same behaviour of natural sand while experiencing the initial compression.

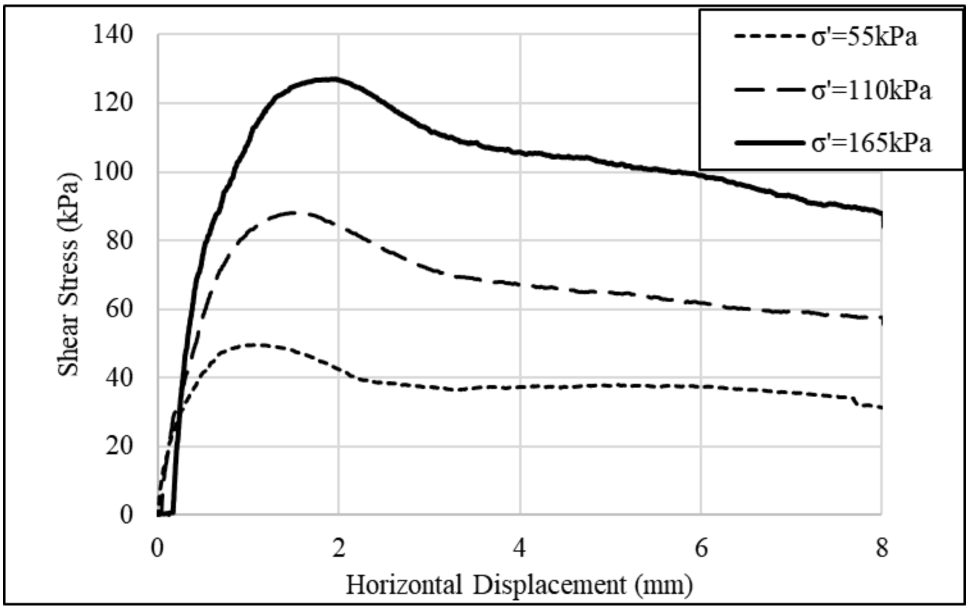


Figure 32: Direct shear box result for the pure fine sand

According to the direct shear test of pure fine sand, the effective cohesion value (c’) and internal friction angle (φ’), have been obtained and presented to compare the changes with other methodologies mentioned in this study. According to test results, the shear strength presented for fine sand was obtained; c’ as 9 KPa and φ’ as 35.6°.

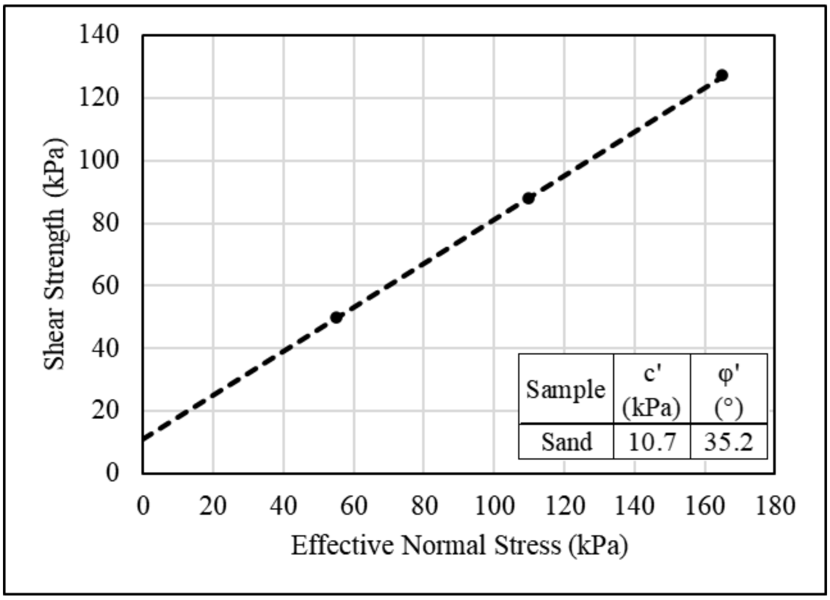


Figure 33: Failure envelop of pure fine sand

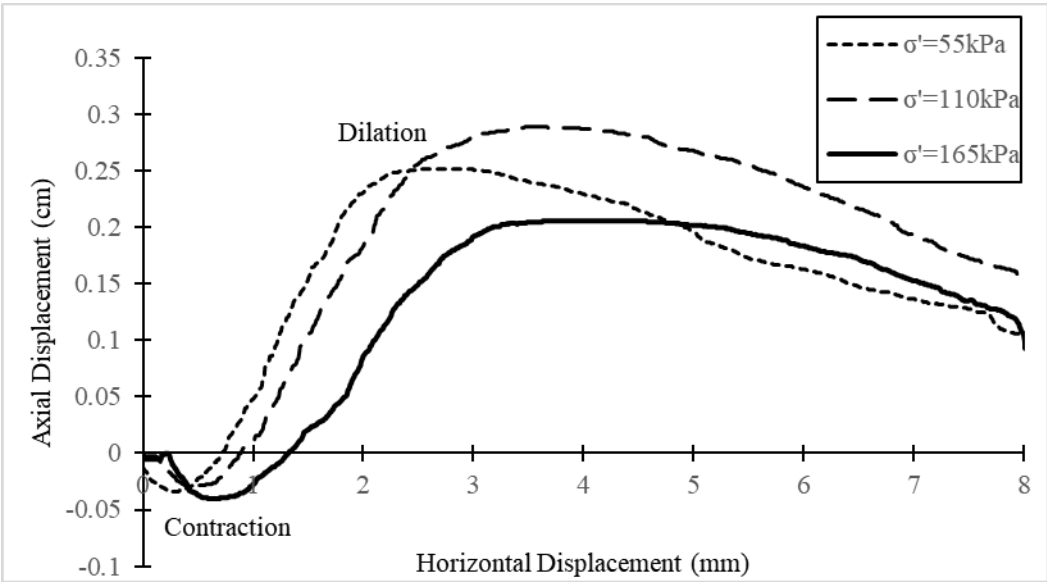


Figure 34: Vertical-Horizontal displacement relationship for natural sand

The sand was tested in a dense condition and all stages of normal stresses, it experienced an initial contraction while shearing under constant normal loading and it resembled a similar behaviour of dilation in all normal stresses as it moved on to higher horizontal displacement due to shearing. Figure 34.

4.5.2 SPM-1

In this sample group, similar to the provided studies, the soil was mixed with solid plastic waste bottles cut into 12 mm × 4 mm strips and tested to compare the result with the pure sand group.

Sample details of SPM-1 was measured both prior to testing and after the application of effective normal stress, subsequently, density and void ratio was measured in both conditions and are presented in table 3.

Table 3: Sample details of SPM-1

Sample strip content (%)	Effective normal stress (kPa)	Initial density (g/cm^3)	Density after settlement (g/cm^3)	Initial Void ratio ($e_{\circ}$)	Void ratio after settlement (e)	Initial relative density (%)	relative density after settlement (%)
2.5	55	1.527	1.574	0.772	0.719	68.2	85.5
2.5	110	1.531	1.583	0.767	0.710	69.7	88.5
2.5	165	1.516	1.566	0.785	0.728	63.7	82.5
5	55	1.532	1.580	0.766	0.712	69.9	87.7
5	110	1.531	1.579	0.768	0.713	69.4	87.3
5	165	1.526	1.579	0.773	0.713	67.7	87.3
7.5	55	1.518	1.567	0.782	0.727	64.7	82.9
7.5	110	1.513	1.566	0.788	0.728	62.7	82.4
7.5	165	1.520	1.583	0.780	0.709	65.4	88.6
10	55	1.457	1.514	0.858	0.787	40.0	63.0
10	110	1.441	1.495	0.878	0.810	33.4	55.6
10	165	1.430	1.503	0.891	0.800	28.8	58.8

According to Table 3, the application of effective normal stress caused the specimens to have initial compression, resulting in higher density and subsequently, lower void ratio .

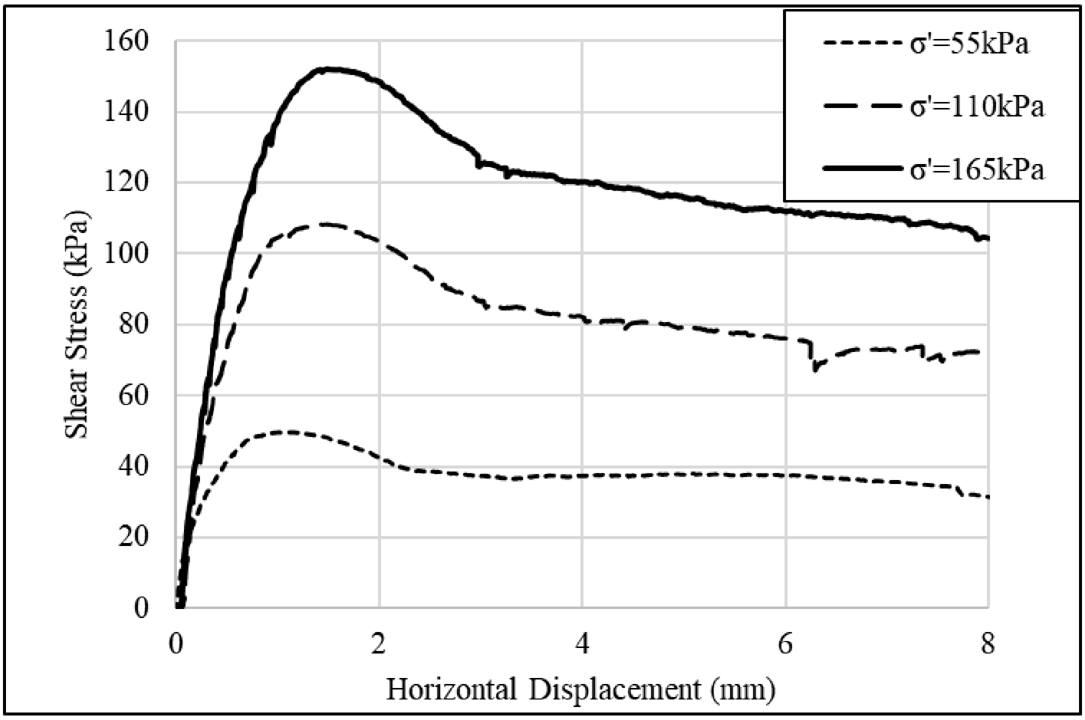


Figure 35: Direct shear box test result of 2.5% plastic content, SPM-1

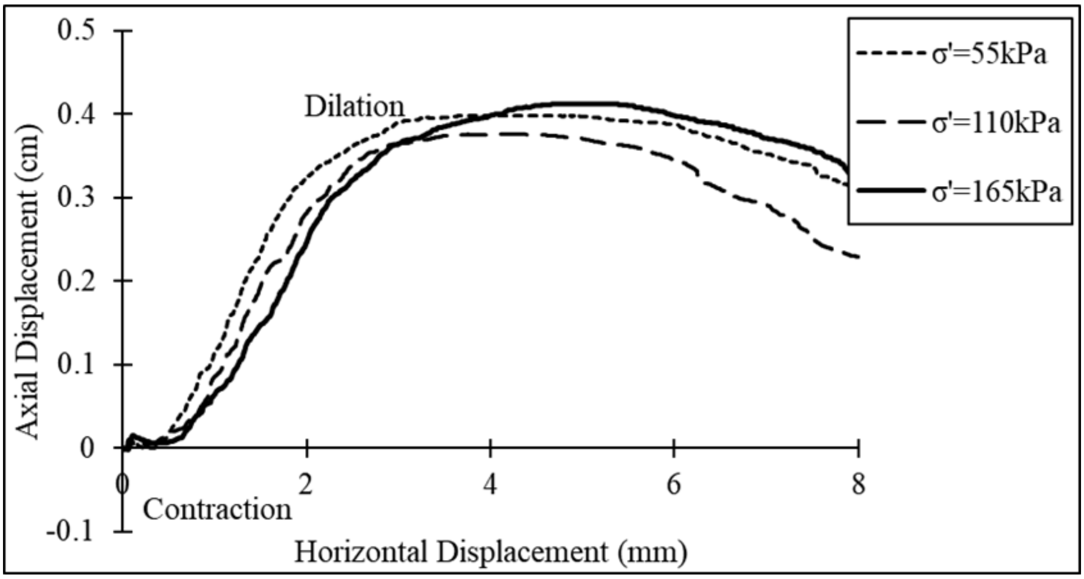


Figure 36: Vertical-Horizontal displacement relationship of 2.5% plastic content, SPM-1

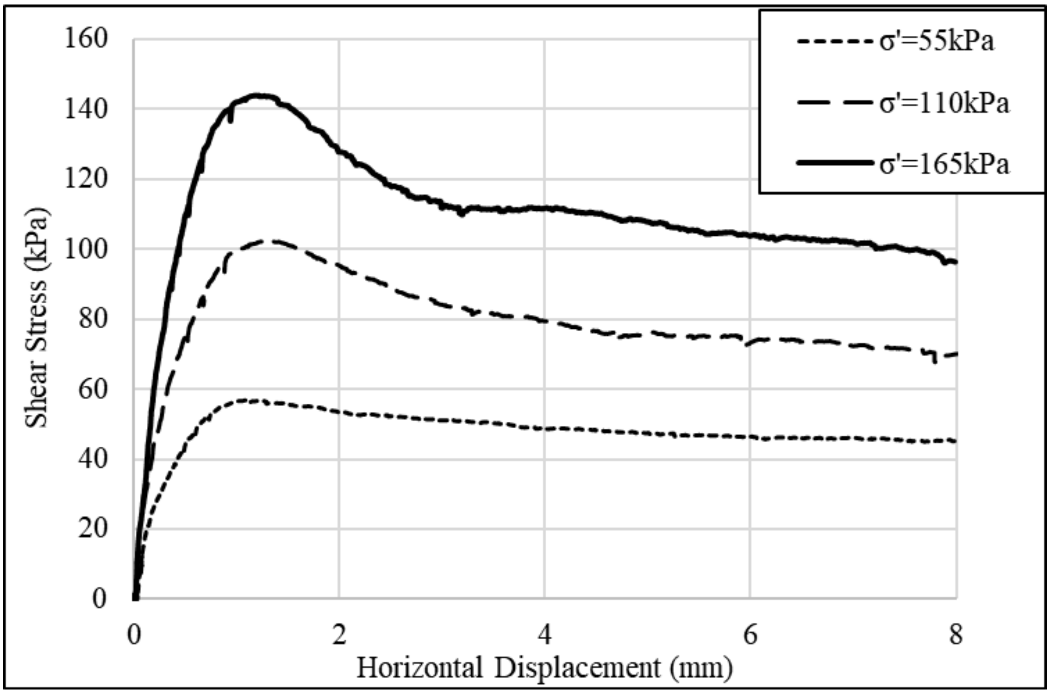


Figure 37: Direct shear box test result of 5% plastic content, SPM-1

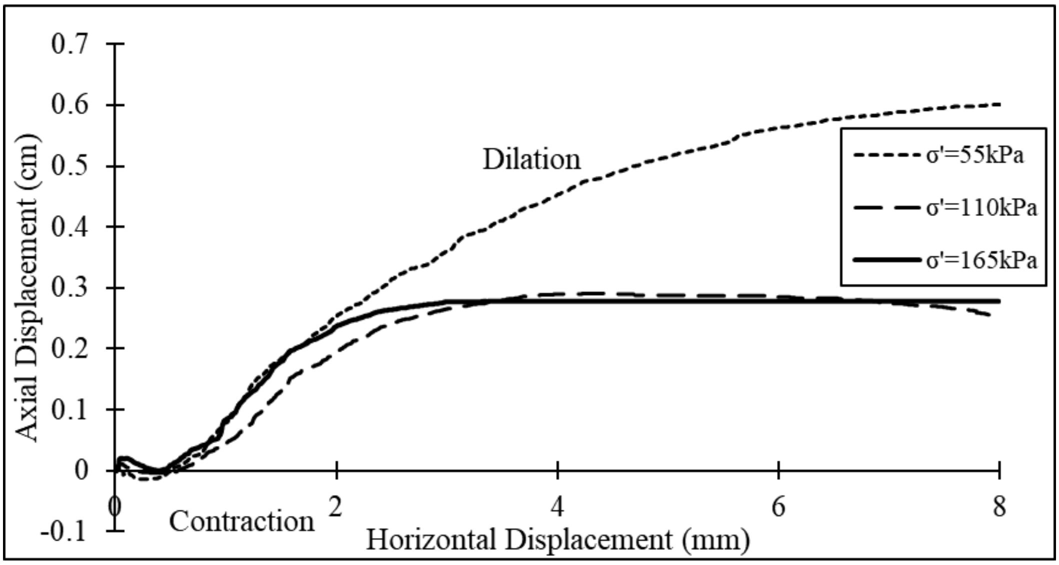


Figure 38: Vertical-Horizontal displacement relationship of 5% plastic content, SPM-1

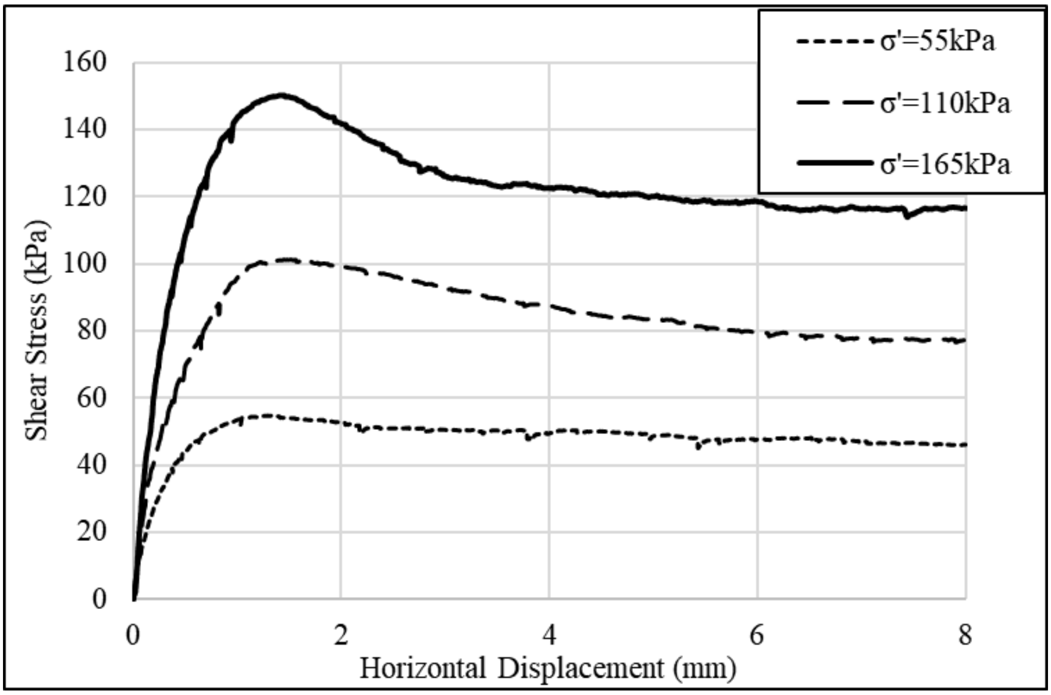


Figure 39: Direct shear box test result of 7.5% plastic content, SPM-1

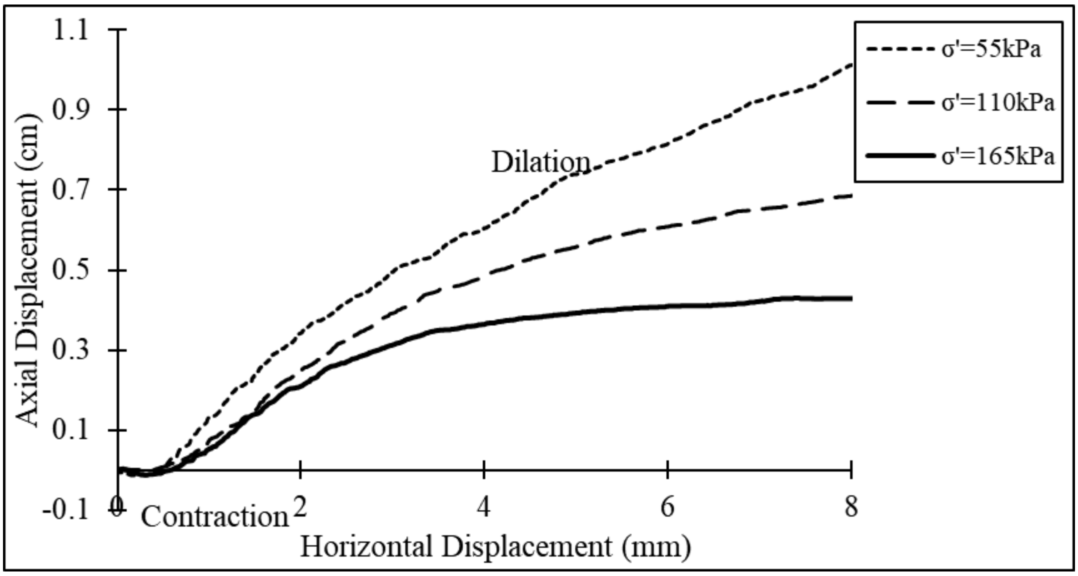


Figure 40: Vertical-Horizontal displacement relationship of 7.5% plastic content, SPM-1

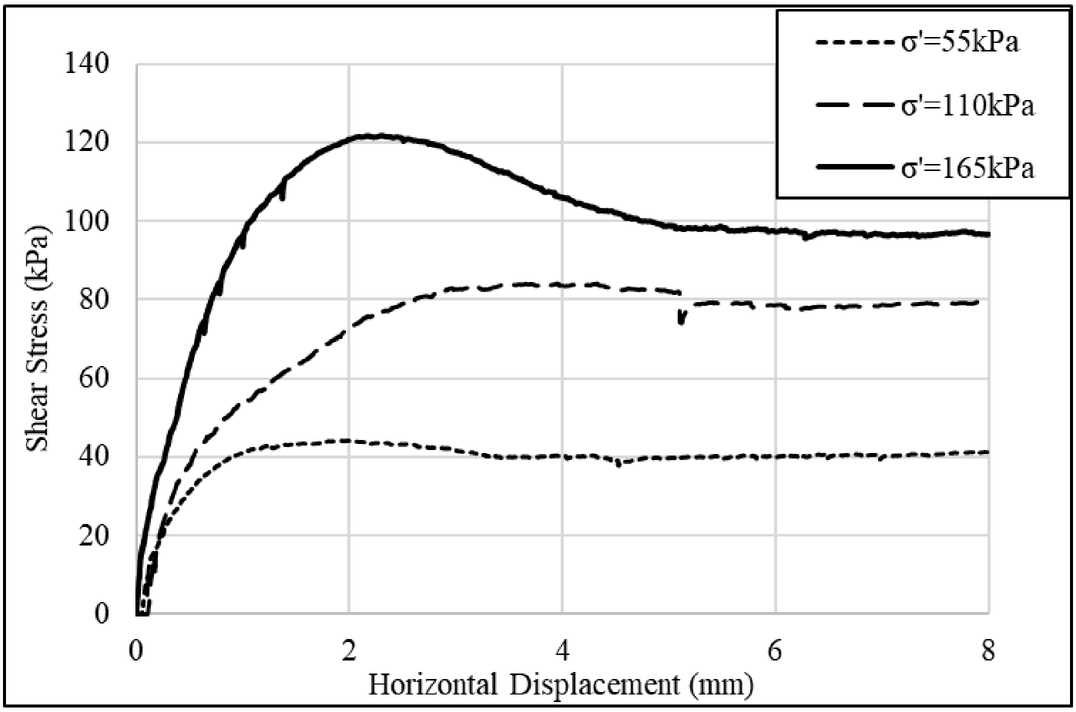


Figure 41: Direct shear box test result of 10% plastic content, SPM-1

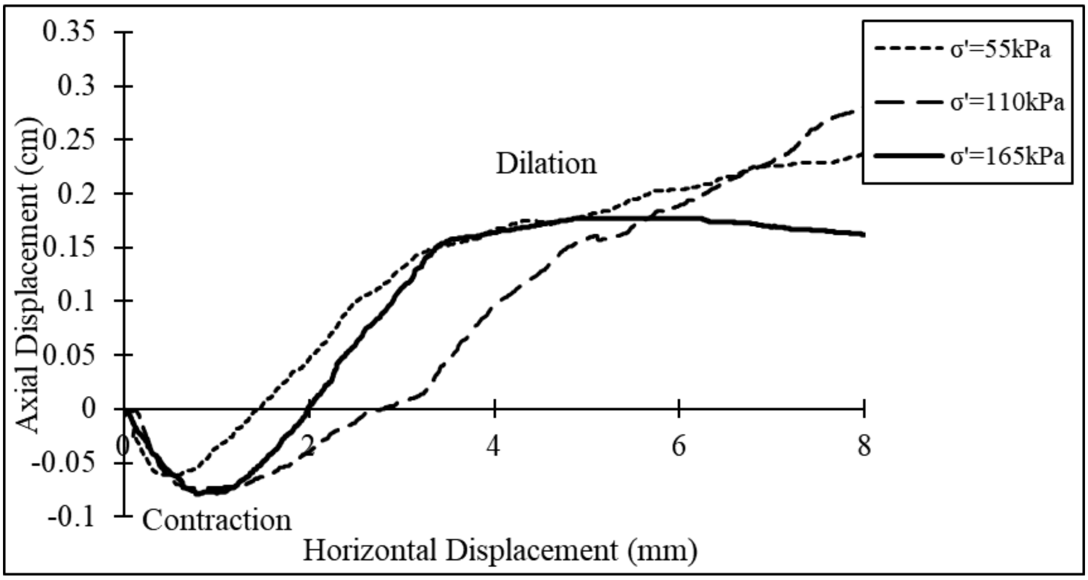
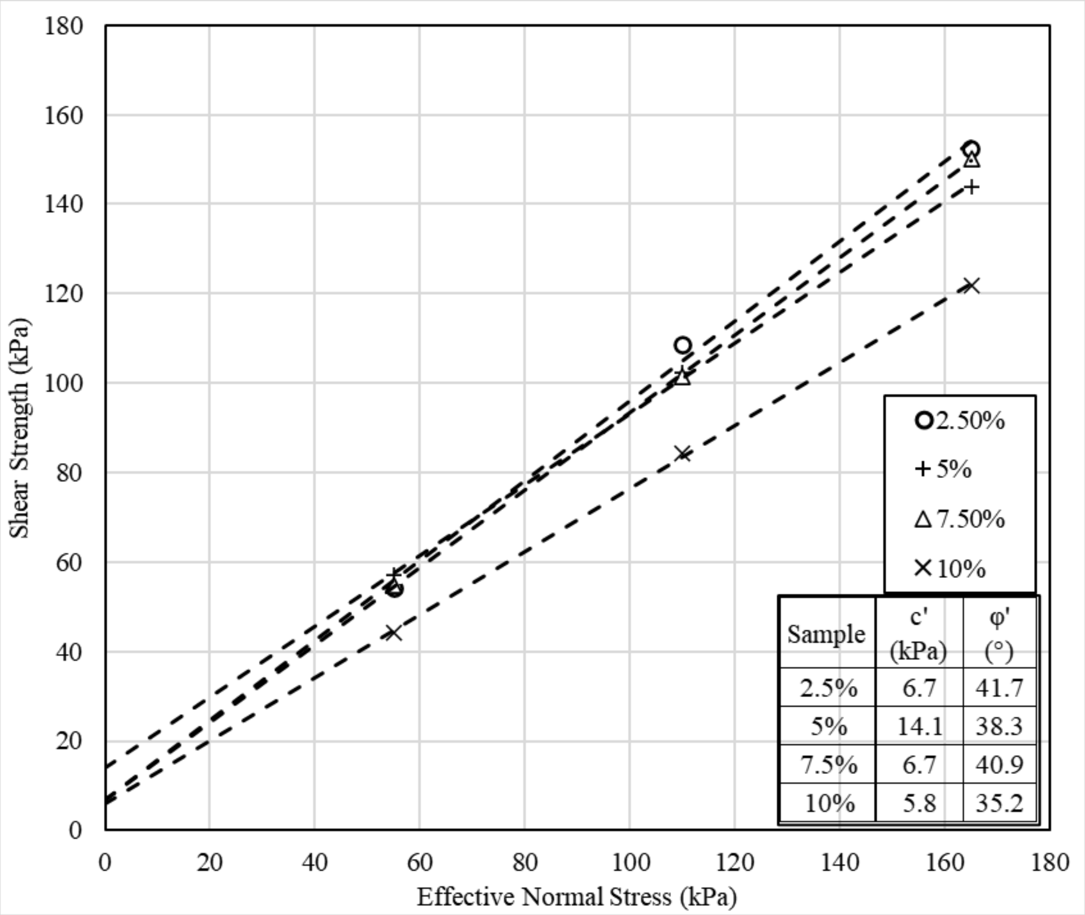


Figure 42: Vertical-Horizontal displacement relationship of 10% plastic content, SPM-1

According to Figure 38, 40, and 42, as the effective normal stress increases, the dilation decreases. This is due to replacement of sand with plastic strips. However, in Figure 36 for 2.5% plastic strip content, this phenomenon did not occur as a consequence of high resemblance of 2.5% to the natural sand, because the change of sand particles with plastic strips was not significant.



Sample	c' (kPa)	φ' (°)
2.5%	6.7	41.7
5%	14.1	38.3
7.5%	6.7	40.9
10%	5.8	35.2

Figure 43: Failure envelops for SPM-1 (normally mixed. Without heating)

In previous studies conducted on plastic strips, the content percentage was always kept at a minimum and the highest percentage they used was up to 1% plastic strip content. (Dutta et al., 2015; Farah, 2015; Gray & Ohashi, 1983). However, in the present study, higher percentage inclusions were used. The results show that with an increase in the strip content, the shear stress at failure (τ_{max}) decreases dramatically. However, this dramatic decrease occurs at 10% strip content and up to 7.5% it remains approximately constant. The effective cohesion seems to increase with increasing plastic strip content as the internal friction angle reduces slightly.

Figure 35 indicates that adding 2.5% strip content increases the shear strength of soil by approximately 20%. And this value almost remains constant up to 7.5% strip content in the soil. However, as the strip content reaches 10%, there is a sudden drop in the shear strength at the failure envelope, indicating that 10% strip content will not affect the shear strength positively and in fact, it almost goes back to the original pure fine sand shear strength and is almost identical to the original sand in terms of shear.

When it comes to C and φ values, they remain constant until the 10% strip content when the C value suddenly drops significantly. Meaning that although 10% of strip content specimens have identical shear at failure with sand, they have lower cohesion compared to them. Thus, has negative effects on soil.

According to Figures 36, 38, 40, and 43, the 2.5% plastic volume samples, showed similar behaviour to pure fine sand and the maximum dilation was also relatively close. However, as the plastic volume increases in the sand, we observe a different behaviour in different normal stresses. As normal stress increases, it will negatively affect the higher plastic volume's (higher than 2.5%) dilation. Resulting in lower vertical displacement as normal stress gets higher than 55 kPa. On the other hand, this decrease does not mean that maximum dilation gets lower than the initial pure sand. Therefore, as the plastic strips' content percentage grows, according to normal stresses, as the normal stress progresses, the dilation rate decreases and this is understandable because of the amount of vertical pressure applied on the specimen.

4.5.3 SPM-2

This sample group contains specimens that are made in a designed sample box and later on, the samples were cut into shear box dimensions (6cm × 6cm) for testing.

SPM-2 was performed to compare the heat-treated samples with not-heated ones, as well as to compare disturbed and not disturbed condition in case of manufacturing prior to utilizing.

Table 4: Sample details of SPM-2

Sample strip content (%)	Normal stress (s)	Initial density ($\rho_{\circ}$)	Density after settlement (ρ)	Initial Void ratio ($e_{\circ}$)	Void ratio after settlement (e)	Initial relative density (%)	relative density after settlement (%)
5	55	1.371	1.399	0.974	0.934	1.8	15.0
5	110	1.321	1.549	1.049	0.747	-22.7	76.2
5	165	1.219	1.271	1.220	1.129	-78.9	-49.0
7.5	55	1.491	1.598	0.814	0.693	54.2	94.0
7.5	110	1.547	1.592	0.750	0.700	75.4	91.7
7.5	165	1.540	1.605	0.757	0.685	73.0	96.4
10	55	1.504	1.538	0.799	0.759	59.1	72.4
10	110	1.380	1.436	0.961	0.884	6.2	31.4
10	165	1.421	1.455	0.903	0.860	24.9	39.3

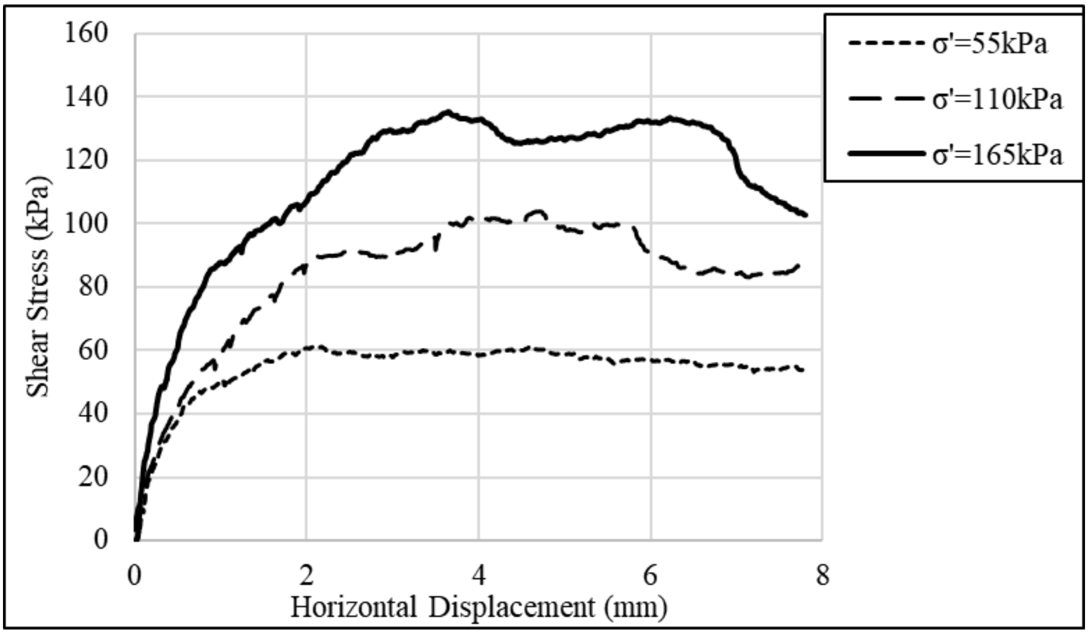


Figure 44: Direct shear box test result of 5% plastic content, SPM-2

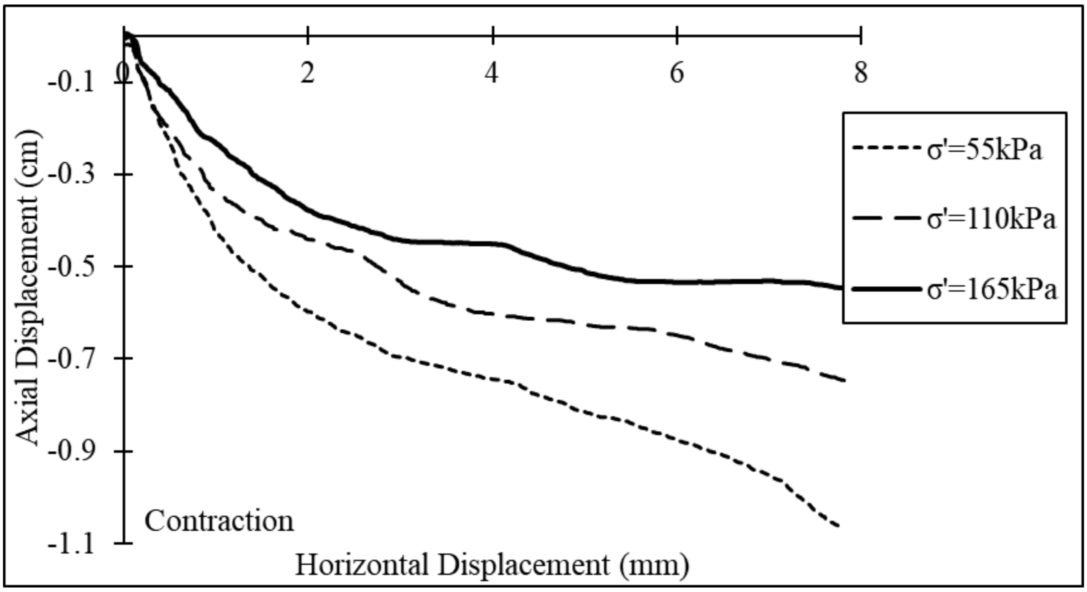


Figure 45: Vertical-Horizontal displacement relationship of 5% plastic content, SPM-2

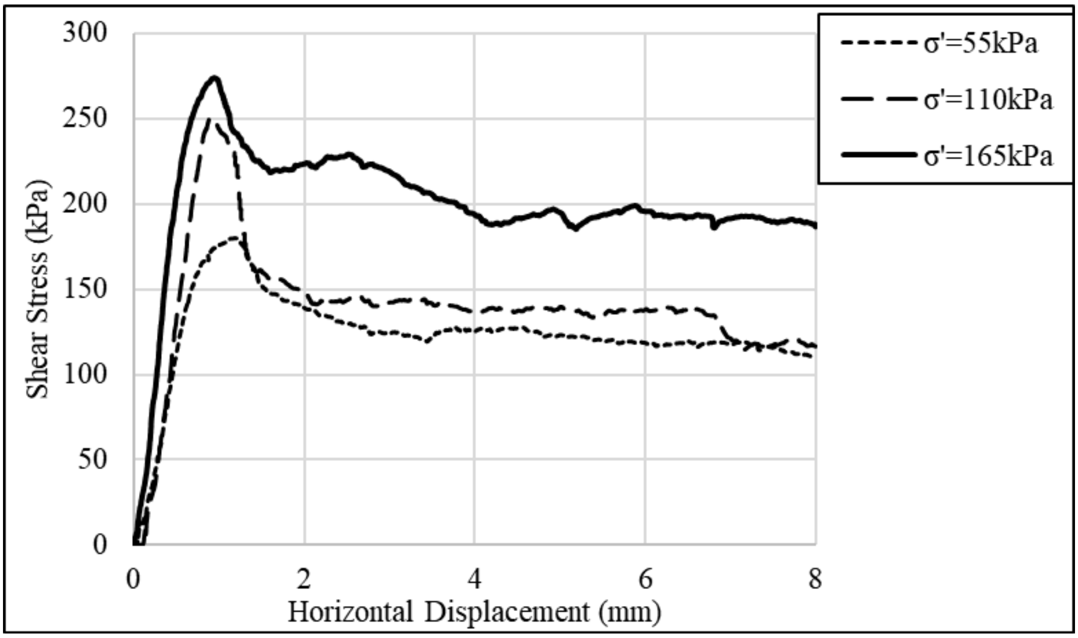


Figure 46: Direct shear box test result of 7.5% plastic content, SPM-2

According to Figure 46, as the plastic content percentage grows, the difference in the shear strength between corresponding effective normal stresses (σ’) decreased in higher ones (110 and 165kPa) than what was expected. This phenomenon is due to the effect of σ’ on sand particles coated by melted plastic, causing the bonding created by plastic to break, thus, resulting in lower bonding strength and lower shear strength. However, this fact can be prevented by increasing the density of the samples and lowering the void ratio.

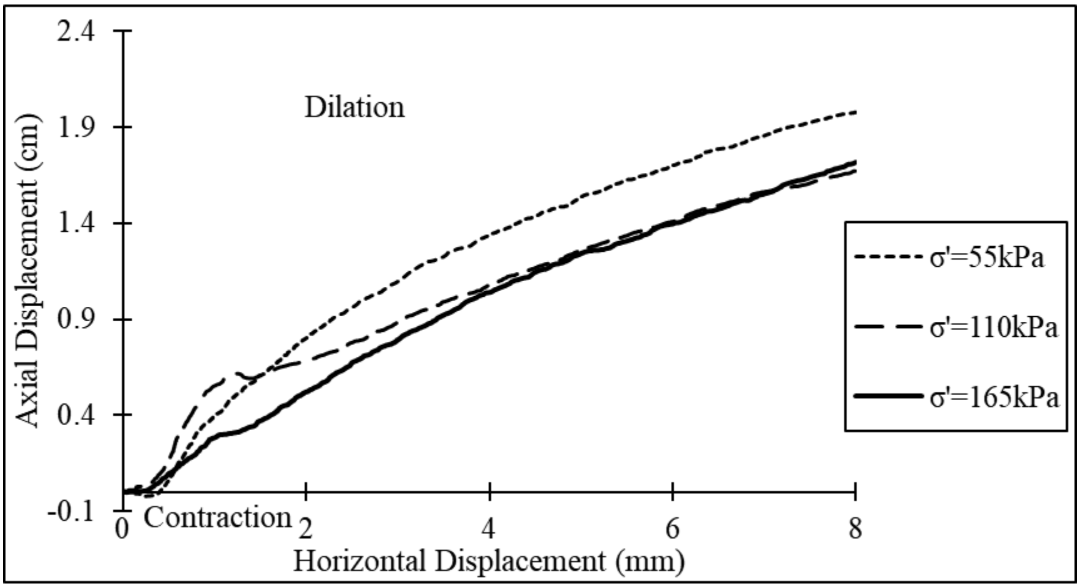


Figure 47: Vertical-Horizontal displacement relationship of 7.5% plastic content, SPM-2

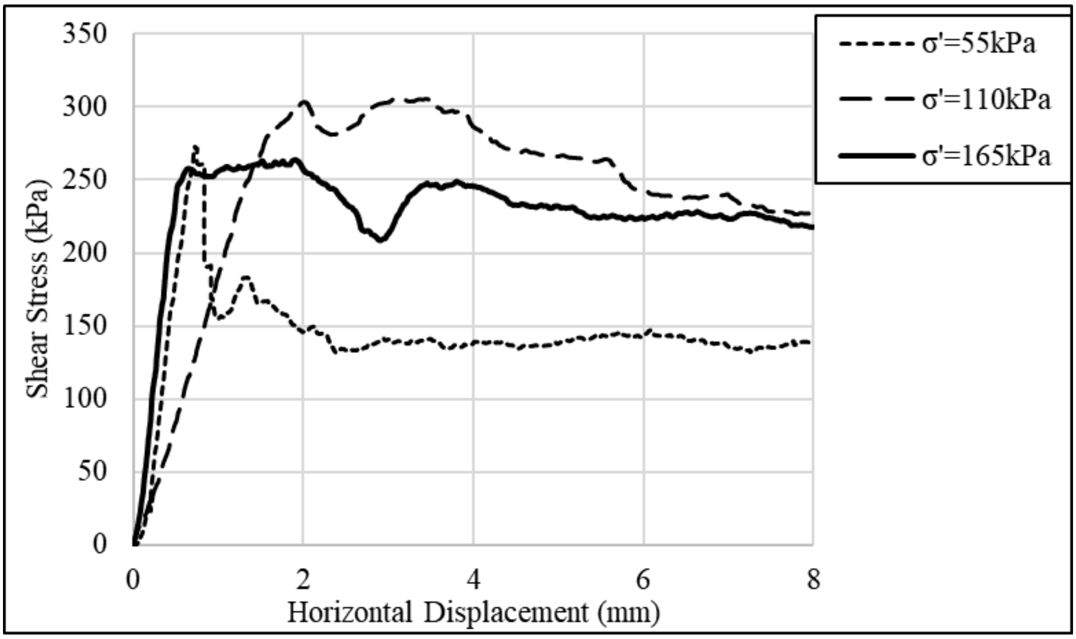


Figure 48: Direct shear box test result of 10% plastic content, SPM-2

According to Figure 48, The shear strength for 110kPa effective normal stress, reached to higher amount than the shear strength for 165kPa effective normal stress. This behabiour is due to the 165kPa σ' breaking the bonding created by melted plastic between sand particles more than 110kPa σ'. Although, this effect has also occurred in lower plastic content percentages, in 10% plastic content it is more visible as the lower effective normal stress's shear strength surpassed the higher one which is expected to be opposite in a natural sand's shear strength.

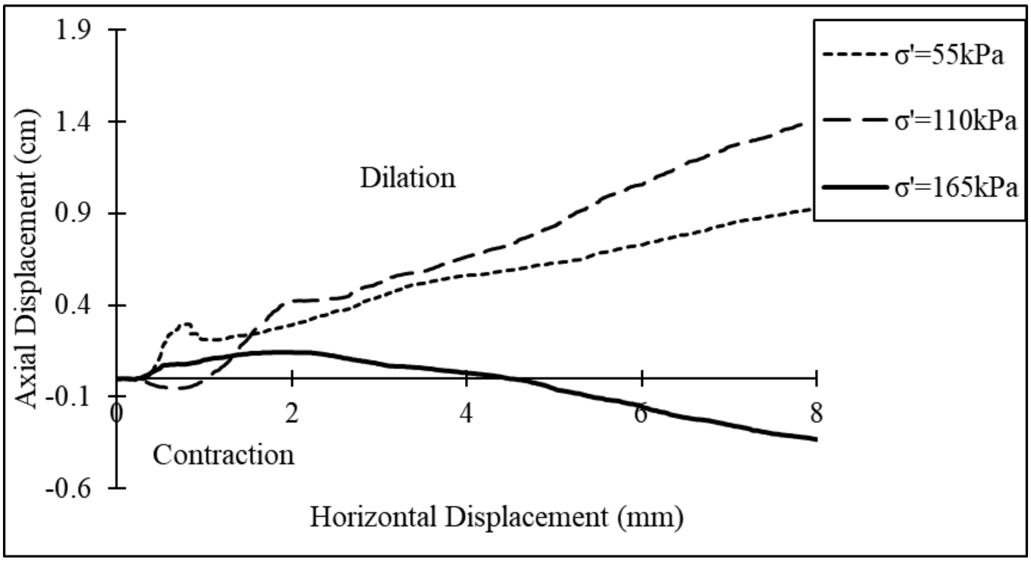
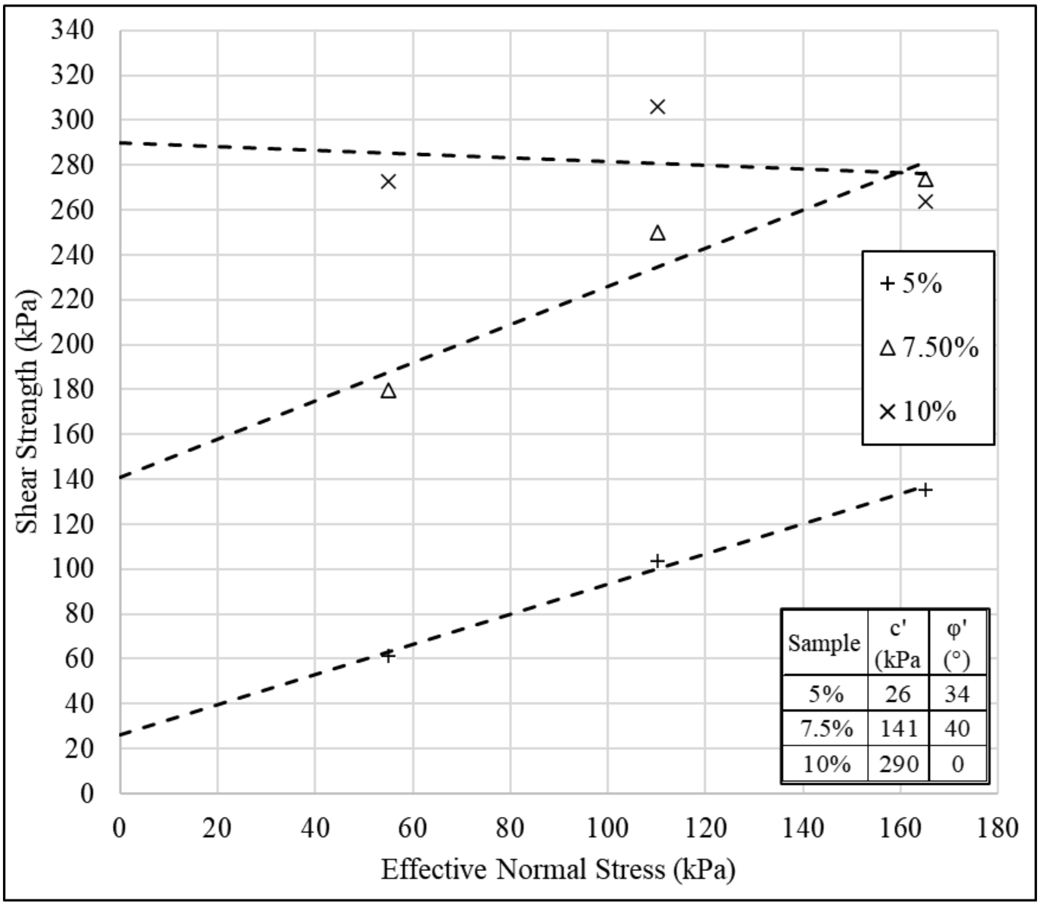


Figure 49: Vertical-Horizontal displacement relationship of 10% plastic content, SPM-2



Sample	c' (kPa	φ' (°)
5%	26	34
7.5%	141	40
10%	290	0

Figure 50: Failure envelop for SPM-2

SPM-2 was created to compare the result of heated samples with one another in a controlled case and a non-controlled one. SPM-2 representing the non-controlled samples can be seen in Figures 44 to 50.

SPM-2 samples although they are not the strongest methodology of plastic-sand mixtures, they indicate a significant difference between the heated samples and non-heated samples. Showing that the heating methodology of using plastic wastes in the sand will always have a significant impact on soil's properties.

SPM-2 in its 5% plastic content shown in Figure 44, samples had a 23% increase in its shear strength. However, as the normal stress increased, the increment in shear strength also decreased. Indicating that as more normal stress is applied to specimens with the presence of shear stress, their aggregates' bonding that was strengthened by plastics were broken and aggregates are moving on one another to fill up the void spots in the specimen. However, this issue can be reduced to the minimum amount if we consider a denser specimen.

The failure envelope for SPM-2 shown in Figure 50, indicated that when samples of higher plastic percentages 7.5 and 10% were exposed to effective normal stress, as it was increased, they represented a lower shear strength from their previous normal stress. However, only in 10% samples, we can see a lower shear strength from the first and lowest effective normal stress samples in the ultimate normal stress. And as they are not identical with SPM-3 10% plastic content samples, it shows that SPM-2 as they were cooled down in a separated designed box than the shear box, they had a higher void content as well as lower density and looser bonding.

As can be seen from Figure 49 and the failure envelope related to SPM-2 in Figure 50, the shear strength of the plastic heat-treated soil reaches up to 3.2 times the original sand strength in 10% plastic content. However, as effective normal stress increases, the shear strength decreases due to the previously mentioned issue with stress moving the sand into the voids of the samples. Thus, causing the bond to break.

For the SPM-2, since the 2.5% plastic content sample was too fragile and was quickly falling apart, it was not tested and the test started from 5% plastic content.

4.5.4 SPM-3

Theoretically, due to its way of preparation, this SPM was expected to have the best result and as can be seen further, the highest improvements belong to this SPM. Plus, in comparison with improvements of SPM-1 and SPM-2, the SPM-3 has higher shear strength in 2.5, 5, 7.5 and 10 per cent plastic content by 1.22, 2.17, 5.28 and 9.7 times, respectively for SPM-1. And as for SPM-2, the SPM-3 has higher shear strength in 5, 7.5 and 10 per cent plastic content by 2, 1.6, and 2.28 times, respectively.

This proves that there is a significant increase in shear strength when melting and heating are involved in comparison with previous studies' sample preparation methods. Therefore, the presented method of this study is far more compelling and affordable than the suggestions of past studies.

Table 5: Sample details of SPM-3

Sample strip content (%)	Normal stress (s)	Initial density ($\rho_\circ$)	Density after settlement (ρ)	Initial Void ratio ($e_\circ$)	Void ratio after settlement (e)	Initial relative density (%)	relative density after settlement (%)
2.5	55	1.533	1.576	0.765	0.717	70.4	86.1
2.5	110	1.428	1.524	0.895	0.776	27.8	66.8
2.5	165	1.473	1.530	0.837	0.769	46.6	69.1
5	55	1.439	1.462	0.880	0.851	32.6	42.1
5	110	1.458	1.491	0.855	0.815	40.7	54.0
5	165	1.435	1.488	0.885	0.818	31.0	52.9
7.5	55	1.441	1.480	0.878	0.828	33.2	49.5
7.5	110	1.478	1.509	0.831	0.793	48.8	61.1
7.5	165	1.397	1.452	0.937	0.864	14.1	37.9
10	55	1.483	1.549	0.825	0.747	50.8	76.2
10	110	1.428	1.473	0.895	0.836	27.6	46.9
10	165	1.439	1.511	0.880	0.791	32.7	61.9

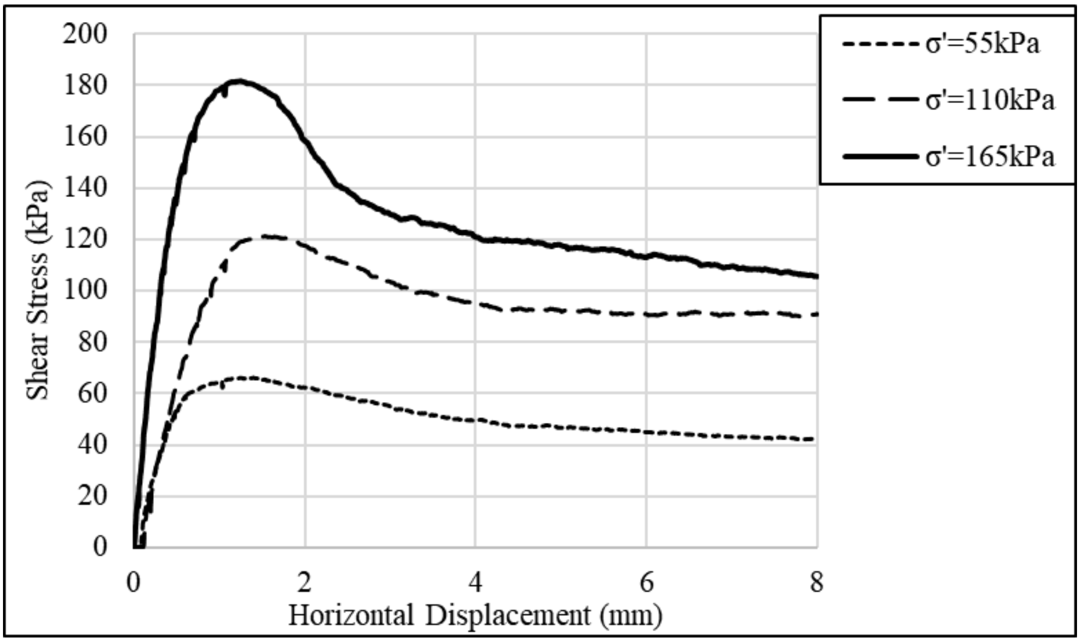


Figure 51: Direct shear box test result of 2.5% plastic content, SPM-3

As can be seen in Figure 51, 2.5% plastic content has similar behaviour to natural sand and the samples are not brittle do not follow a sudden fall in their shear strength as they reach the maximum. In addition, in Figure 51, by adding 2.5% plastics in a melted form for SPM-3, the bonding made by melted plastic, increases the shear strength by 1.4 times compared to natural sand.

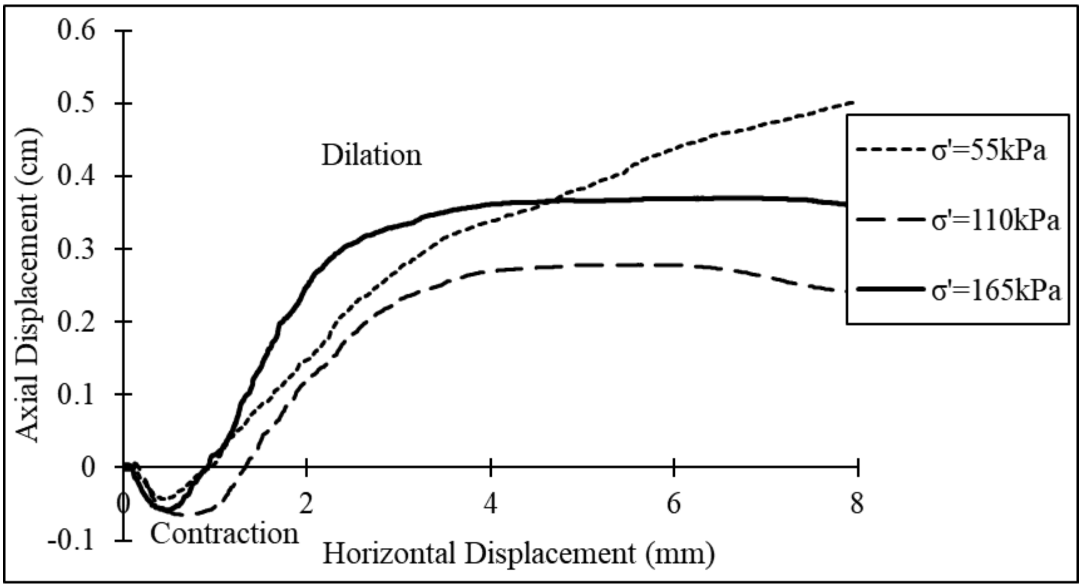


Figure 52: Vertical-Horizontal displacement relationship of 2.5% plastic content, SPM-3

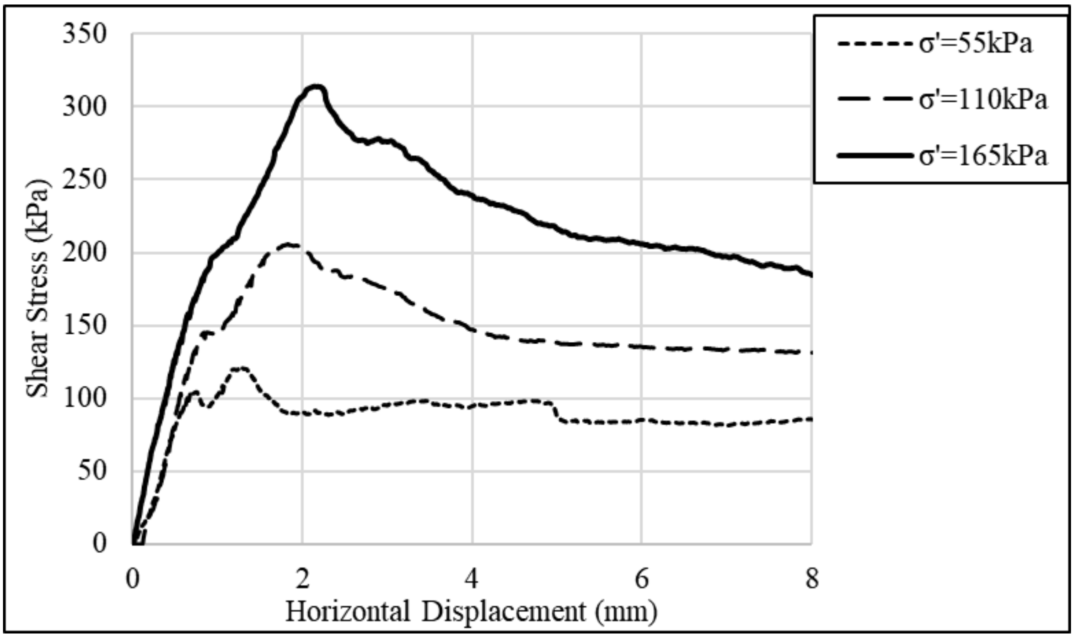


Figure 53: Direct shear box test result of 5% plastic content, SPM-3

According to Figure 53, samples reached brittleness stage in 5% plastic content. Resulting in sudden drop in shear strength. However, the shear strength reached to higher point than the 10% plastic content of SPM-2. This means that, the shear strength of SPM-2 is the equivalent of 5% plastic content's shear strength in SPM-3.

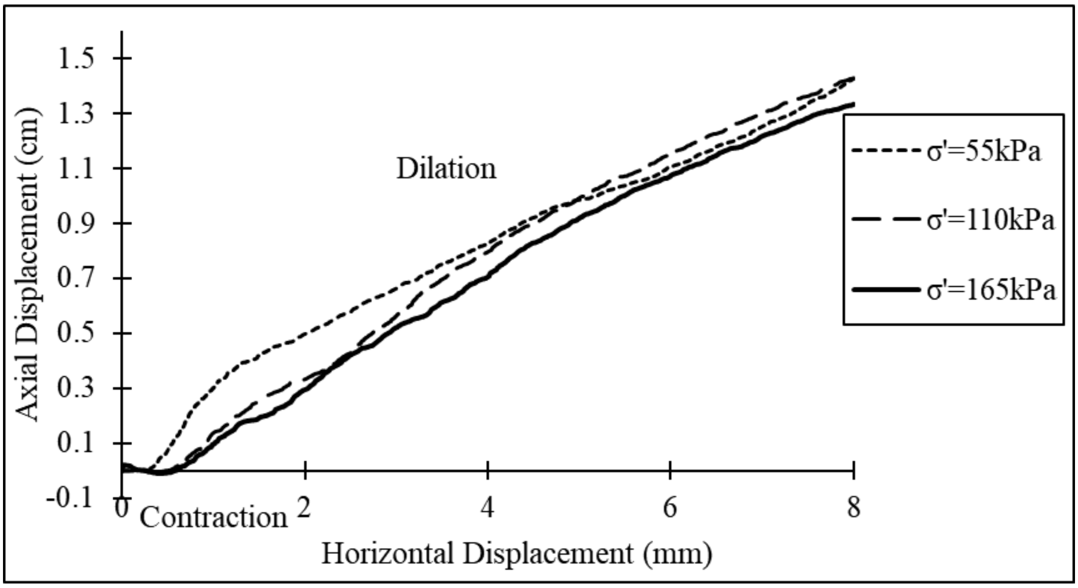


Figure 54: Vertical-Horizontal displacement relationship of 5% plastic content, SPM-3

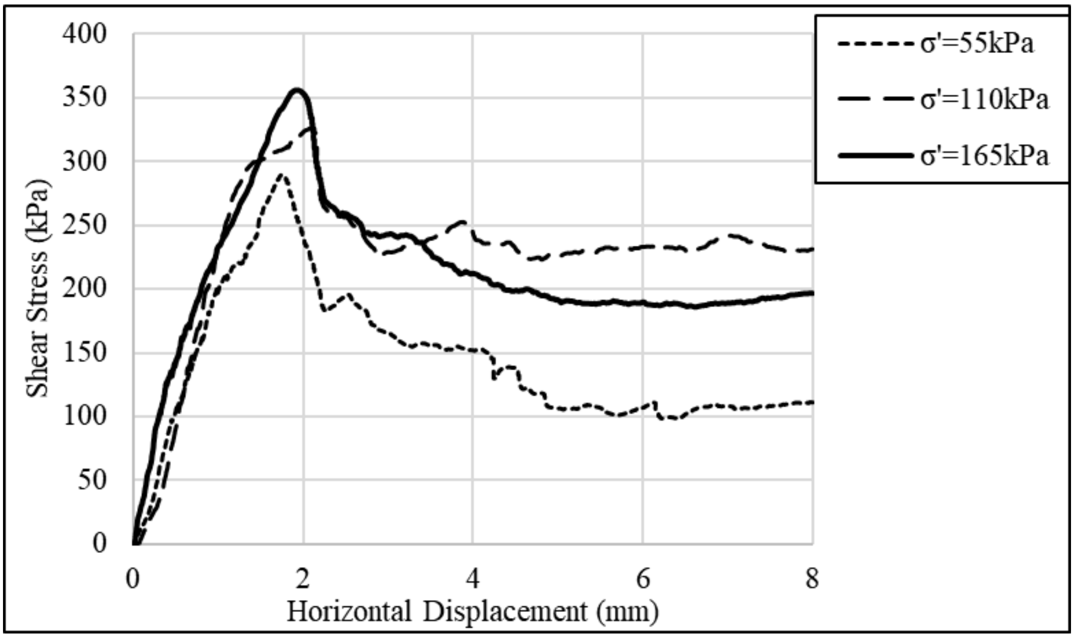


Figure 55: Direct shear box test result of 7.5% plastic content, SPM-3

According to Figure 55, the shear strength of 7.5% plastic content reached to more than 350kPa and they became more brittle than the 5% plastic content specimens. However, even with sudden drops in shear strength, the residual strengths of these samples were still higher than all of SPM-1 and SPM-2 sample as well as SPM-3's 2.5% and 5% plastic content samples. This means that, even with high brittleness as plastic content increased, the residual strengths were improved in all cases.

In addition, similar to SPM-2 samples, for 7.5%, the shear strength had a closer alteration for different effective normal stresses, due to the breakage of bonding made by melted plastic between sand particles. The effective normal stress broke the bonding and forced the particles into the voids, as a result, lower difference of shear strength, as well as lower dilation for higher effective normal stresses were obtained (see Figure 56 and 58).

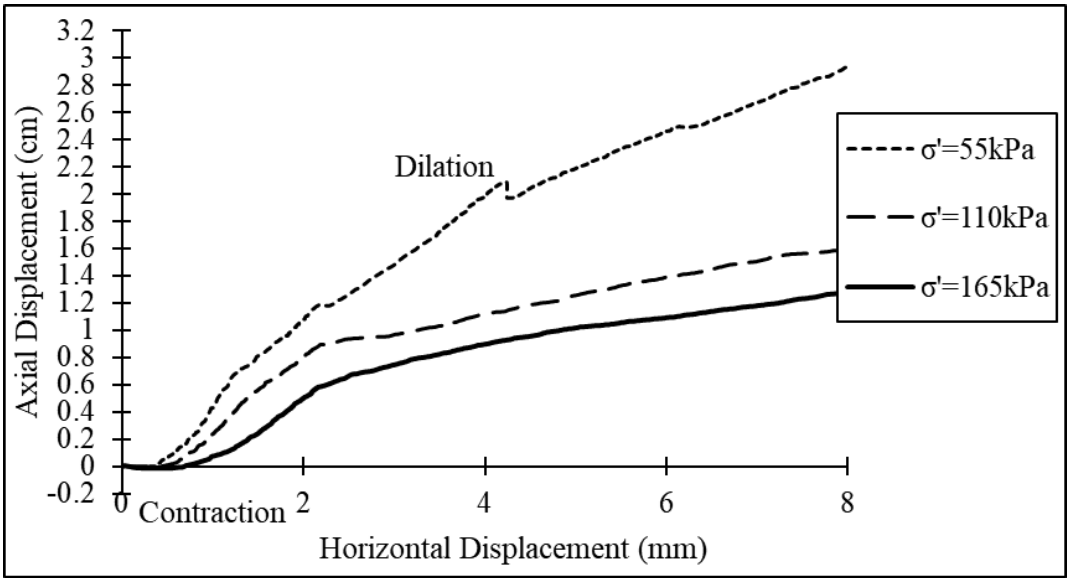


Figure 56: Vertical-Horizontal displacement relationship of 7.5% plastic content, SPM-3

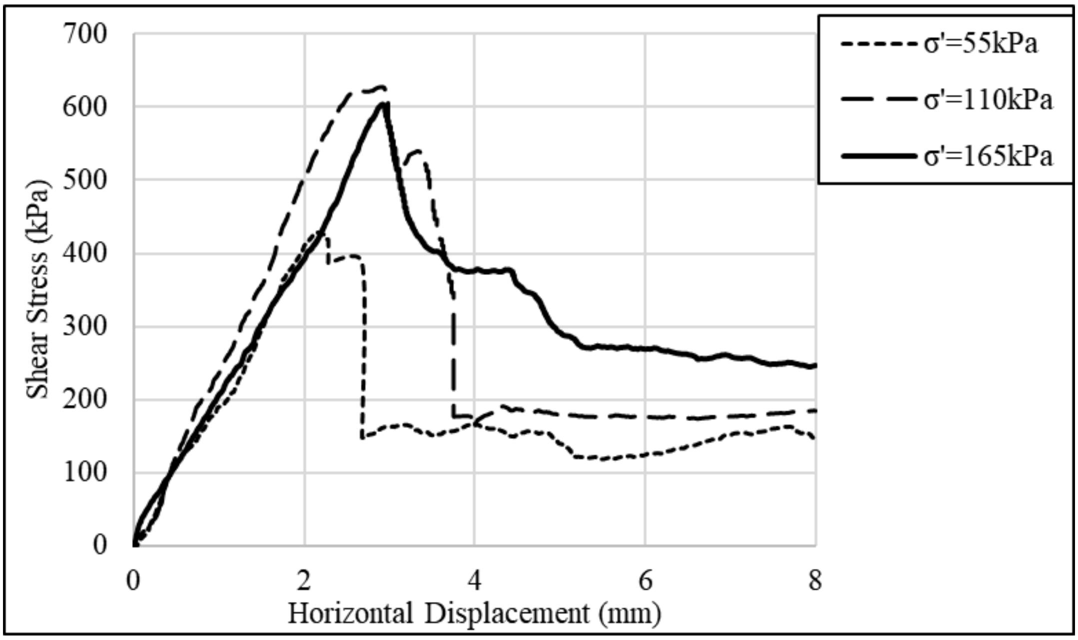


Figure 57: Direct shear box test result of 10% plastic content, SPM-3

According to Figure 57, the samples had more severe brittle behaviour. However, the residual strength obtained proves that even with the massive sudden drops in shear strength of samples, the residual strength were always similar between samples of any SPM-3 plastic content groups except for 2.5%, meaning that, after the drop in shear strength, all samples show more than 100kPa residual strength in any stage.

The shear strength similar to SPM-2 10% plastic content, was observed to be higher for 110kPa effective normal stress than 165kPa effective normal stress. However in terms of maximum shear strength improvement, 10% plastic content of SPM-3 had approximately 4.8 times improvement compared to natural sand.

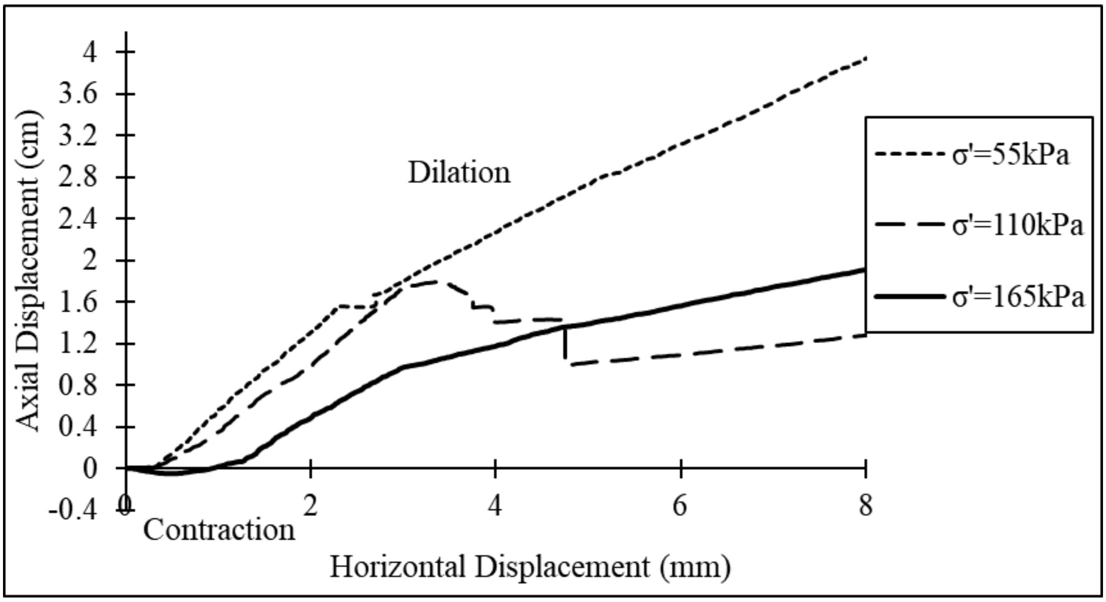


Figure 58: Vertical-Horizontal displacement relationship of 10% plastic content, SPM-3

The lower dilation of higher effective normal stresses (110kPa and 165kPa) were due to the breakage of bonding created by melted plastic between sand particles and making samples dense. This issue can be dealt with by increasing the density of samples (see Figure 56 and 58).

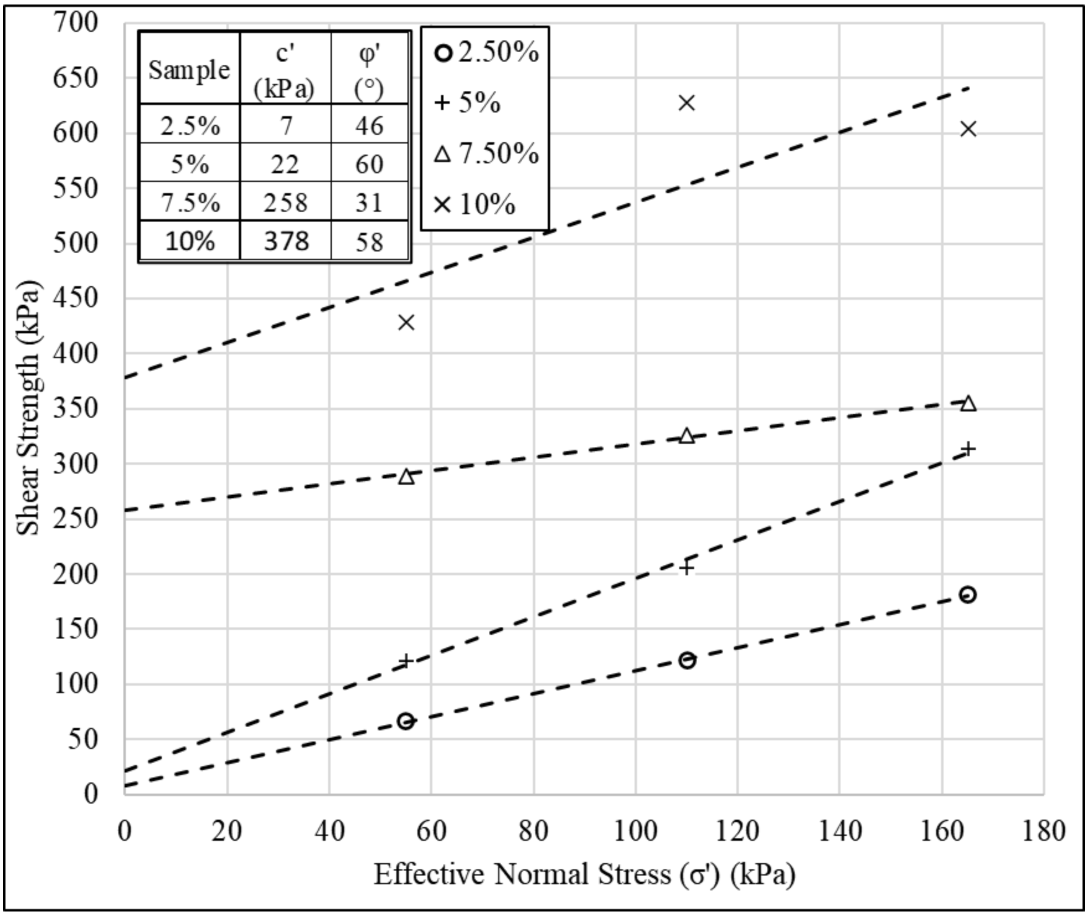


Figure 59: Failure envelop for SPM-3

The SPM-3 results are presented in Figure 51 up to Figure 59. The results have some resemblance to the SPM-2. Especially in 10%, plastic content samples as in both cases higher effective normal stress (σ′) hurt shear strength. The reason being is that as the samples are being pressured vertically, the samples tend to get denser. Thus, forcing the aggregates to break their bonding with melted and then hardened plastics to move to voids in samples. Causing them to break their initial bonding strength between aggregates achieved by plastics and as a result, have lower shear strength. However, in this case, it does not occur with other samples such as 7.5% plastic content specimens because they do not have as high shear strength as 10% specimens. Therefore, the break of bonding does not affect the 7.5% that much. Although they won't be much stronger than their previous normal stress samples, they will be higher in strength to some extent.

As can be obtained from Figure 51, with 2.5% plastic content, the shear strength has been improved up to 33, 38, and 42% concerning the normal stresses applied at 55, 110 and 165 KPa respectively. In Figure 53, with 5% plastic content, it is evident that the shear strength increased up to 2.45, 2.34, and 2.46 times of the original pure sand concerning the normal stresses from the lowest to the highest one. In Figure 55, with 7.5% plastic content, also the shear strength increased up to 5.82, 3.71, and 2.79 times of the original pure sand concerning the normal stresses from low to high. In Figure 47, with 10% plastic content, it can be seen that shear strength increases up to 8.62, 7.13, and 4.74 times of the original sand concerning the normal stresses applied from the lowest to the highest. However, much like other specimens due to the same problem with moving aggregates to voids of the specimen and breaking the bond between aggregates created by plastics, as normal stress increases, the shear strength decreases in both 7.5% and 10% plastic content. But this decrease never gets lower than the highest shear strength increases of the lower plastic percentage except for only one point where it only surpasses it by 90% out of 600% available increment. Thus, means an increase in the plastic content percentage has always a positive point in terms of shear strength and adding more plastic in the melted form to the soil will always increase its shear strength and as the plastic percentage gets higher, this increase in the shear strength in comparison with the original soil increases and the higher the plastic content, the more rapid shear strength increase.

According to Figures 52, 54, 56, and 58, in the heat-treated samples, higher dilations were observed than in normally mixed samples. Meaning that although the resembling behaviour with different dilation according to normal stress getting plastic strip percentage getting higher is evident, the maximum dilation in heat-treated samples as the plastic volume percentage increases, it also increases up to 2 times as much.

SPM-3 was obtained as the superior methodology compared to SPM-1, SPM-2, and SPM-4 as they were prepared inside the shear box. Therefore, preparing the material in site and not-disturbed is expected to have better improvements on engineering properties of sand as well.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the results of the experimental work performed on the mechanical properties of natural and the combination of sand with plastic in melted and unmelted forms, the following conclusions can be retrieved:

- For the fine sand mixed with plastic strips in a non-melted form, no unconfined compression strength can be obtained. Thus, making it identical to natural soil.
- SPM-4: For the sand combined with plastic in a melted form, there can be unconfined compression strength developed in the soil structure and comparison, with other studies related to polymers, as much as 3 times improvement up to 1.4, 2.5, and 3.2 MPa can be observed in a dense form for the 5, 7.5, and 10% plastic content respectively.
- SPM-1 proves that there is a high resemblance between natural sand's behaviour when it comes to shear strength and plastic strips mixed sands. Thus, the addition of plastic strips with 4 mm × 12 mm, does not affect the soil properties dramatically. In fact, in 10% strip content, the shear strength decreases and becomes lower than the natural sand. And for the 2.5, 5, and 7.5 percentage, the shear strength only increases up to 1.2 times as the natural sand. Although addition of plastic strips in a solid form improves the residual strength of the soil and also improves the shear

strength by 20%, melted plastic improves these parameters by superior amount up to 8.6 times of the natural sand.

- SPM-1: As the plastic strips' content percentage grows, according to normal stresses, as the normal stress progresses, the dilation rate decreases and this is understandable because of the amount of vertical pressure applied on the specimen.
- SPM-2: 1.2 increase in shear strength of 5% plastic strip content can be observed. And overall, up to 5.5 times, the shear strength of the natural sand can be obtained in 10% plastic content. As not-heated samples reached up to 1.2 times the strength of natural sand, it indicates the significant difference between heat-treated and not-heated methodologies of sample preparation with over 4.5 times increment in the shear strength in heat-treated samples (SPM-2)
- As plastic content percentage is increased, higher stages of normal stress can hurt the bonding created by plastics in between sand particles more and cause it to fail in earlier stages than lower normal stresses such as 55 kPa and 110 kPa. This effect is most visual in 10% plastic content heat-treated samples.
- Not only melting plastic improved the shear and residual strength significantly, but also, the mass of samples has been reduced and a more porous specimens were created.
- SPM-3: The shear strength increment in 2.5% plastic content reaches up to 1.42 of the natural sand. Indicating 2 times the increment compared to not-heated samples for 2.5% strip content which reached 1.2 of the natural sand. However, the increase in plastic content, for the not-heated samples, affected the maximum shear strength in a negative way and decreased the amount. But with heat-treated samples of SPM-3, as the plastic content grows, so does the maximum shear strength.

Maximum shear strength ultimately reaches up to 8.62 times the natural sand's maximum shear strength. And this is more than 7 times than the not-heated samples in terms of shear strength indicating the heat-treated samples' superiority in terms of strength and improvements in the sand.

- Although, the cost of gathering plastic waste is affordable, the energy consumption for melting plastic must be noted. In addition, in order to produce these methodologies in a large scale, isolation to minimize energy consumption is needed.
- Although, minor emissions can be seen while melting, controlling the temperature at the melting point of plastic will reduce emissions and will be negligible.

This study proved that melting waste plastic, can improve sand's engineering properties, as well as removing wastes from the nature and changing their productivity.

5.2 Recommendation

- Shredding plastic particles into smaller pieces will cause plastics to be distributed in sand more thoroughly and resulting in better bonding thus, potentially removing stirring from the sample preparation steps.
- Thoroughly distributed heat with isolation can reduce the heating time and required energy.
- Since the bonding created by plastic was strong, there can be ideas for making porous samples that would allow water to pass through
- It is required to observe the change in permeability for these sample preparation methods in order to observe the difference.
- Since usage of these methods might bring up some concerns regarding the chemical problems it might cause, performing tests to see the effect of these samples while water passes through them is essential.

- It is necessary to provide a study with energy consumption calculations in order to specifically determine the cost of energy of producing such material.
- The high melting temperature of plastics, make them suitable for areas with higher temperatures on earth. Therefore, applying SPM-2 and SPM-3 could be more suitable than other materials.

REFERENCES

Abdulrahman, S. M., Fattah, M. Y., & Ihsan, E. A. (2021). Influence of plastic fiber on the geotechnical properties of gypseous soil. *International Journal of Engineering, Transactions B: Applications*, *34*(2), 367–374. https://doi.org/10.5829/IJE.2021.34.02B.08

Ackah, M. (2019). Soil elemental concentrations, geoaccumulation index, non-carcinogenic and carcinogenic risks in functional areas of an informal e-waste recycling area in Accra, Ghana. *Chemosphere*, *235*, 908–917. https://doi.org/10.1016/J.CHEMOSPHERE.2019.07.014

Ahmed, A. (2012). Simplified regression model to predict the strength of reinforced sand with waste polystyrene plastic type. *Geotechnical and Geological Engineering*, *30*(4), 963–973. https://doi.org/10.1007/s10706-012-9519-0

ASTM. (2009). *Standard test methods for particle-size distribution (gradation) of soils using sieve analysis D6913-04*. https://www.astm.org/d6913-04r09.html

ASTM. (2022). *ASTM compass - enterprise solutions - products and services*. https://www.astm.org/products-services/enterprise-solutions/astm-compass.html?utm_source=google&utm_medium=cpc&utm_campaign=astm+compass&gclid=Cj0KCQjw9ZGYBhCEARIsAEUXITWCwx1oVzA5pxqOzCnSnBwgUNRVJ6o0KQqkM9cdHiDNffKFbDA_f1IaArurEALw_wcB

Babu, G. L. S., & Chouksey, S. K. (2011). Stress-strain response of plastic waste mixed soil. *Waste Management*, *31*(3), 481–488. https://doi.org/10.1016/j.wasman.2010.09.018

Bai, Y., Liu, J., Song, Z., Chen, Z., Jiang, C., Lan, X., Shi, X., Bu, F., & Kanungo, D. P. (2019). Unconfined compressive properties of composite sand stabilized with organic polymers and natural fibers. *Polymers*, *11*(10). https://doi.org/10.3390/POLYM11101576

Bamford, & Jenkins. (1955). Density of amorphous polyethylene terephthalate. *Nature*, *176*, 78–79.

Benson, C. H., & Khire, M. V. (1994). Reinforcing sand with strips of reclaimed highdensity polyethylene. *Journal of Geotechnical Engineering*, *120*(5), 838–855. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:5(838)

Bhattarai, P., Kumar, B., Santosh, K., Manikanta, T. C., & Tejeswini, K. (2013). Engineering behavior of soil reinforced with lastic strips. *International Journal of Civil , Structural , Environmental and Infrastructure Engineering Research and Development*, *3*(2), 2249–6866.

Chebet, F., & Kalumba. (2014). Laboratory investigation on re-using polyethylene (plastic) bag waste material for soil reinforcement in geotechnical engineering. *Academia.Edu*. https://www.academia.edu/download/35965450/1114civej06.pdf

Choudhary, J.N.Jha, & K.S.Gill. (2010). Utilization of plastic wastes for improving the sub-grades in flexible pavements. *In Paving Materials and Pavement Analysis (*, *1*(I), 97–102.

Choudhary, Jha, J. N., & Gill, K. S. (2010). A study on cbr behavior of waste plastic strip reinforced soil. *Emirates Journal for Engineering Research*, *15*(1), 51–57.

Dash, S. K., Rajagopal, K., & Krishnaswamy, N. R. (2004). Performance of different geosynthetic reinforcement materials in sand foundations. *Geosynthetics International*, *11*(1), 35–42. https://doi.org/10.1680/gein.2004.11.1.35

Dutta, R. K., Dutta, K., & Jeevanandham, S. (2015). Prediction of deviator stress of sand reinforced with waste plastic strips using neural network. *International Journal of Geosynthetics and Ground Engineering*, *1*(2), 1–12. https://doi.org/10.1007/S40891-015-0013-7

Dutta, R. K., & Sarda, V. K. (2007). CBR behaviour of waste plastic strip-reinforced stone dust / fly. *Turkish J. Eng. Env. Sci*, *31*(Jan), 171–182.

Dutta, & Rao, G. V. (2004). Engineering properties of sand reinforced with strips from waste plastic. *Scientia Iranica*, *28*(3 B), 1212–1222. https://doi.org/10.24200/sci.2020.55886.4448

Eartheasy. (2020). *Plastics by the numbers | eartheasy guides & articles*. https://learn.eartheasy.com/articles/plastics-by-the-numbers/

EPA. (2021). *Plastics: material-specific data | US EPA*. https://www.epa.gov/factsand-figures-about-materials-waste-and-recycling/plastics-material-specific-data

Evans, M. C., & Ruf, C. S. (2022). Toward the detection and imaging of ocean microplastics with a spaceborne radar. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, *60*, 4202709. https://doi.org/10.1109/TGRS.2021.3081691

Fadhil, S. H., Al-Soud, M. S., & Kudadad, R. M. (2020). Enhancing the strength of clay-sand mixture by discrete waste plastic strips. *Journal of Applied Science and Engineering (Taiwan)*, *24*(3), 381–391. https://doi.org/10.6180/jase.202106_24(3).0013

Farah. (2015). Performance evaluation of problematic soils reinforced with plastic wastes. *Institute of Graduate Studies and Research in Partial Fulfilment of the Requirement*. http://i-rep.emu.edu.tr:8080/xmlui/handle/11129/3716

Fathi, H., Jamshidi Chenari, R., & Vafaeian, M. (2021). Large scale direct shear experiments to study monotonic and cyclic behavior of sand treated by polyethylene terephthalate strips. *International Journal of Civil Engineering*, *19*(5), 533–548. https://doi.org/10.1007/s40999-020-00580-x

Google. (2022). *X= 582835 and Y= 3891992*. Www.google.com

Gray, D. H., & Ohashi, H. (1983). Mechanics of fiber reinforcement in sand. *Journal of Geotechnical Engineering*, *109*(3), 335–353. https://doi.org/10.1061/(ASCE)0733-9410(1983)109:3(335)

Guo, S.-L., Chen, B.-L., & Durrani, S. A. (2020). Solid-state nuclear track detectors. In *Handbook of Radioactivity Analysis* (pp. 307–407). Elsevier. https://doi.org/10.1016/b978-0-12-814397-1.00003-0

Kalliyath, J. V., Joy, J. T., Paul, J. M., & Vadakkel, A. M. (2016). Soil stabilization using plastic waste. *International Journal of Research in Engineering and Technology*, *05*(05), 391–394. https://doi.org/10.15623/ijret.2016.0505074

Kumar, Das, V., Gupta, A., & Ameta, N. K. (2016). Stabilization of dune sand ixed with plastic (LDPE) waste strips for design of flexible pavement in construction of roads. *American Journal of Engineering Research (AJER)*, *5*, 315–320. www.ajer.org

Kumar, T., Panda, S., Hameed, S., & Maity, J. (2018). *IRJET-Behaviour of soil by mixing of plastic strips*.

Laskar, A., & Pal, S. K. (2013). Effects of waste plastic fibres on compaction and consolidation behavior of reinforced soil. *Electronic Journal of Geotechnical Engineering*, *18 H*, 1547–1558.

Muntohar, A. S., Widianti, A., Hartono, E., & Diana, W. (2013). Engineering properties of silty soil stabilized with lime and rice husk ash and reinforced with waste plastic fiber. *Journal of Materials in Civil Engineering*, *25*(9), 1260–1270. https://doi.org/10.1061/(asce)mt.1943-5533.0000659

Neopaney, Wangchuk, & Tenzin. (2012). Stabilization of soil by using plastic wastes.

International Journal of Emerging Trends in Engineering and Development, *2*(2).

Nibudey, R. N., Nagarnaik, P. B., Parbat, D. K., & Pande, A. M. (2013). Strengths prediction of plastic fiber reinforced concrete (M30). *International Journal of Engineering Research and Applications*, *3*(1), 1818–1825.

Okunola A, A., Kehinde I, O., Oluwaseun, A., & Olufiropo E, A. (2019). Public and environmental health effects of plastic wastes disposal: a review. *Journal of Toxicology and Risk Assessment*, *5*(2). https://doi.org/10.23937/2572-4061.1510021

Peddaiah, S., Burman, A., & Sreedeep, S. (2018). Experimental study on effect of waste plastic bottle strips in soil improvement. *Geotechnical and Geological Engineering*, *36*(5), 2907–2920. https://doi.org/10.1007/S10706-018-0512-0

Perkins. (2014). *Plastic waste taints the ocean floors*. Nature News. https://doi.org/10.1038/nature.2014.16581

Saeed, H., Nalbantoglu, Z., & Uygar, E. (2021). Liquefaction susceptibility of beach sand containing plastic fines. *Https://Doi.Org/10.1080/1064119X.2021.2007556*. https://doi.org/10.1080/1064119X.2021.2007556

Sayı, C. Ö., & Eren, Ö. (2021). Physical and durability properties of recycled polyethylene terephthalate (PET) fibre reinforced concrete. *Https://Doi.Org/10.1080/19648189.2021.1976681*. https://doi.org/10.1080/19648189.2021.1976681

Schmidt, C., Krauth, T., & Wagner, S. (2017). Export of plastic debris by rivers into the sea. *Environmental Science and Technology*, *51*(21), 12246–12253. https://doi.org/10.1021/ACS.EST.7B02368

Singh, M., Thind, P. S., & John, S. (2018). Health risk assessment of the workers exposed to the heavy metals in e-waste recycling sites of Chandigarh and Ludhiana, Punjab, India. *Chemosphere*, *203*, 426–433. https://doi.org/10.1016/J.CHEMOSPHERE.2018.03.138

Sobhan, K., & Mashnad, M. (2003). Mechanical stabilization of cemented soil-fly sh mixtures with ecycled plastic strips. *Journal of Environmental Engineering*, *129*(10), 943–947. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:10(943)

Thorneycroft, J., Orr, J., Savoikar, P., & Ball, R. J. (2018). Performance of structural concrete with recycled plastic waste as a partial replacement for sand. *Construction and Building Materials*, *161*, 63–69. https://doi.org/10.1016/J.CONBUILDMAT.2017.11.127

Uygar, E., & Doven, A. G. (2005). Monotonic and cyclic oedometer tests on sand at high stress levels. *Granular Matter 2005 8:1*, *8*(1), 19–26. https://doi.org/10.1007/S10035-005-0216-Z

Vismaya, A., Simon, M., Jayasree, P. K., & Peter, L. (2021). Strength characteristics of subgrade soil stabilized with plastic bag strips. *Lecture Notes in Civil Engineering*, *136 LNCE*, 485–493. https://doi.org/10.1007/978-981-33-6444-8_43