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Research Article

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Abstract

Large quantities of shredded high-density polyethylene (HDPE) plastic bits are generated in Kuwait as a by-product of the manufacturing of plastic pipes. Recycling and beneficial use of this waste material is important considering the shortage of disposal sites and for environmental protection. Toward this goad an extensive laboratory testing program was carried out to examine the use of HDPE plastic bits as an additive to the remolded clayey sand (locally known as gatch soil). This soil is naturally cemented but upon excavation it transformed into clayey sands with fines content of 20 to 40%. Testing included basic properties, Modified Proctor Compaction, permeability, direct shear, consolidation, and CBR tests. HDPE plastic bits was used as an additive in the amount of 0, 10%, and 20% by weight. All tests were carried out on samples prepared at maximum density and optimum moisture content. Moreover, model tests were carried out on a 70 mm circular metal plate resting on clayey sand with 0, and 10% HDPE plastic additive and compacted to 95% relative compaction. The purpose being to examine the effect of HDPE plastic additive on the ultimate bearing capacity and settlement of shallow foundations. Test results indicated that the use of HDPE plastic bits as an additive resulted in a light weight more compressible material with higher strength parameters and minor reduction in permeability. The bearing capacity decreased substantially with the addition of HDPE bits and the settlement increased at the applied working loads.

Keywords: Clayey sands, laboratory tests, geotechnical properties, model tests, high density polyethylene plastic bits (HDPE), recycled materials.

Introduction

Large quantities of high-density polyethylene bits (HDPE) shredded from damaged, scrap, or faulty double-wall corrugated pipes are produced locally in the state of Kuwait. It is produced by the international Kuwait company for developing industries. This material has favorable properties and can be recycled. It is corrosion resistant and environmentally friendly. It has superior chemical and abrasion characteristics and is resistant to many organic substances, unaffected by fungi and soil-borne bacteria (Orman 1944). One possibility is to use this material as an additive in small amounts to the local soils of Kuwait to form an engineering construction material. As a result, it will conserve resources and protect the environment (Hejazi et al. 2012)

Many studies were carried out recently to examine the use of waste HDPE bits as additive to soil or soil cement to strengthen the subgrade for road construction (Sobhan and Mashnad 2002, 2003) and maintain its long-term durability (Bueno et al.1997). The influence of HDPE bits on the shear strength characteristics of black cotton soils was examined by Meera and Hashifa (2015) and Patidar and Mahiyar (2014). They found that the angle of friction ϕ increased with increasing the HDPE content. The effect of HDPE fibers mixed with sandy and clayey soil in the amount of 2, 4, 6, and 8 percent by weight was investigated by Nsaif (2013). The results of the compaction and

direct shear tests revealed that the maximum dry density decreased and the angle ϕ increased with no change in the cohesion component C. Fauzi et al. (2016) observed similar finding from tests on a clayey soil but noted that the cohesion C decreased with increasing HDBE content. Abdelsalam et al. (2019) carried out laboratory tests on two Kuwaiti soils using HDPE as additive in the amount of 5%, 10%, 15%. The results indicated increased strength, compressibility, permeability and a reduction of the maximum dry density with the use of HDPE fibers.

This research examines the use of HDPE as additive to the local remolded cemented sand (gatch) soil. This soil is cemented and appears at a depth varying from 0 to 7 m in Kuwait. However, upon excavation it transforms into clayey sand with fines content of 20-40% (Ismael 1999, Ismael et al. 1986). It is used as backfill in engineering projects. An extensive laboratory testing program was carried out on this soil with HDPE additive in the amount of 0, 10%, 20% by weight. Testing included basic properties compaction, permeability, direct shear, consolidation, and CBR tests, on samples compacted to maximum dry density and optimum moisture content. Based on test results several practical applications were assessed including earthfill, embankment construction, road subgrade, and use of the bits as a drainage layer.

Model tests were also carried out on a 70 mm circular metal plate loaded in a sand box on the remolded gatch soil compacted to 95% relative compaction, and on the same soil mixed with 10% HDPE bits. The tests were carried out to failure to examine the influence of HDPE plastic additive on the ultimate bearing capacity and settlement of shallow foundations.

The Testing Program

The amount of HDPE plastic additive employed in the testing program was 0%, 10%, and 20% by weight. The following tests were performed:

1. Mechanical analysis to determine the grain size distribution curves
2. Liquid limit and plastic limit tests on the samples for proper classification
3. Modified Proctor Compaction tests on samples 101.6 mm diameter and 116.4 mm height
4. Falling head permeability test on samples prepared at maximum density and optimum moisture content. The samples were 100 mm diameter and 130 mm height
5. Direct shear tests on samples prepared at maximum density and optimum moisture content. The samples were 63 mm diameter and 20 mm thick. The tests were repeated on samples compacted to 95% of the maximum density (i.e. relative compaction equals 95%)
6. Consolidation test on samples compacted at maximum density and optimum moisture content. The samples were 75 mm diameter and 20 mm thick
7. CBR tests on soaked samples compacted to 95% of the maximum dry density in a 152.4 mm diameter mold
8. Model test employing a 70 mm circular steel plate loaded in a sand box measuring 0.3 m × 0.3 m × 0.28 m deep

All tests were carried out in accordance with ASTM standards.

Sample Preparation

Samples for permeability tests, direct shear and consolidation tests were prepared in four layers by tamping to reach the required density. For the model tests, the soil was placed and compacted in layers to reach 95% of the maximum dry density and optimum moisture content to match many field specifications. Tests were carried out on clean gatch soil with no additive, and on gatch soil mixed 10% HDPE additive. The load was applied at constant rate of strain, and load readings were taken at 1 mm deformation intervals until the ultimate bearing capacity failure was reached.

Test Results

Basic Characteristics

Figure 1 shows the grain size distribution curves for the gatch soil and for the HDPE plastic bits employed in the testing program. Table 1 is a summary of the sieve analysis. As shown the HDPE plastic bits have no fines, vary in size in a narrow range mostly from 2 mm to 4.75 mm, and can be classified as SP or poorly graded sand according to the Unified Soil Classification System. The gatch soil has a fines content (<0.075 mm) of 21.3%, liquid limit and plastic limit of 36.3, and 23.4 respectively, and a plasticity index of 12.9. it is classified as SC or clayey sand. The fines content consists mainly of carbonates and sulphates resulting from the crushing of the cementation bonds. Table 2 summarizes the raw material properties of the shredded plastic bits including density, tensile and elongation properties, flexural modulus, modulus of elasticity, melt flow index, carbon black content, shore hardness D, softening point, coefficient of thermal expansion, vicat softening point, and oxidation induction time (OIT). These properties were determined by Abdelsalam (2015).

Compaction Tests

Figure 2 and Table 3 shows the Modified Proctor Compaction test results. As shown, with the addition of HDPE bits the maximum dry density decreased, and the optimum moisture content remained nearly the same. With 10% and 20% HDPE bits the maximum dry density decreased by 12% and 22% respectively. This is significant and indicate that a much lighter material is produced when HDPE bits are employed as an additive to the local clayey sand "gatch" soil. Fauzi et al. (2016) indicated similar findings with the use of HDPE plastic bits.

Permeability Tests

Falling head permeability tests were performed on the samples which were compacted to the maximum dry density and optimum moisture content. Because of the high density and the large fines content, and plasticity, the measured coefficient of permeability was $7*10^{-9}$ cm/sec. With

10% and 20% HDPE additive the coefficient K was $6.6*10^{-9}$ cm/sec and $5.1*10^{-9}$ cm/sec respectively. The results are also shown in Table 3 which is a summary of all test results and the measured parameters.

Based on the above results it is noticed that the use of HDPE plastic additives has slightly reduced the coefficient of permeability in connection with the local gatch soil. This is since the clayey sand gatch has high density, large plastic fines content which exceeded 20%, and very low permeability. Mixing this soil with up to 20% HDPE will not have any substantial effect on the measured value of the coefficient of permeability since the grain size distribution will almost be the same as the original gatch soil.

Direct Shear Tests

The shear strength parameters were obtained from direct shear tests conducted on samples compacted to 100% and 95% relative compaction "RC". The HDPE plastic bits employed were 0, 10%, and 20% for the samples compacted to RC=100% and 0, and 10% for samples compacted to RC= 95%. The shear strength parameters are given in Table 3. As shown the cohesion slightly decreased with HDPE plastic additive for the samples compacted to 100% and 95% relative compaction.

The angle of friction ϕ increased from 41º to 44º and 46º with 10% and 20% HDPE plastic additive respectively for samples compacted to RC= 100% and slightly decreased from 39.5º to 38º with 10% additive for samples compacted to RC= 95%. This indicates the rough nature of the plastic material yielding larger ϕ at the high density corresponding to RC= 100% and slightly lower values at lower density (RC= 95%) and low HDPE plastic content.

A close examination of Table 3 reveals that the shear strength parameters are lower for samples compacted to RC= 95% as compared to samples compacted to RC= 100%. This is expected in view of the lower density and higher void ratio at RC= 95% compared to RC= 100%. The decrease beings 1.5º to 6º in ϕ and 15 kPa in C.

Tables 4 shows a summary of the shear displacement at maximum shear stress for samples compacted to a relative compaction of 100% and 95% respectively. Figures 3 and 4 show the shear stress vs. shear displacement curves for samples with 0 and 20% HDPE plastic at RC= 100%, and for samples with 0, and 10% HDPE plastic at RC= 95% respectively. Examination of Table 4 indicates that the shear displacement at failure generally increased with HDPE plastic additive for samples compacted to 100% and 95% relative compaction. Examination of Figures 3 and 4 indicates a softer response with increased compressibility and lower soil modulus E with HDPE plastic additive. Also, no clear peak shear stress was observed for some samples. Since Gatch soil is incompressible material, peak shear stress will be observed due to the interlock between

particles. During shear tests, HDPE in the voids between the particles and at the particle contacts will be compressed, and no peak will stress be observed.

Consolidation Tests

Consolidation tests were performed on samples compacted to 100% relative compaction with HDPE plastic additive of 0, 10%, and 20%. The void ratio vs. effective pressure plots are shown in Figure 5. A summary of the parameters including the compression index Cc, the swell index Cs, and the average coefficient of consolidation C_v is given in Table 3. The values of these parameters although small in magnitude increased substantially with HDPE plastic additive indicating increased compressibility.

An examination of Table 3 reveals that Cc increased from 0.0229 for clean gatch to 0.0297 and 0.0388 with 10% and 20%. HDPE plastic additive respectively. This represents 30% and 69% increase. Cs also increased from 0.0096 to 0.012 and 0.0125 with 10% and 20% HDPE. This amount to 25% and 30% increase respectively. Although all values are small, they indicate an increase in compressibility. Table 3 includes the coefficient of consolidation C_v for samples with 0, 10%, and 20% HDPE plastic additive and the average values. These average values decreased minimally by 1% and 2% with the additive of 10% and 20% HDPE plastic. As such, the time required for a given degree of consolidation will be nearly the same with of or without HDPE plastic additive.

The free swell upon initial saturation and the swell pressure corresponding to zero swell were determined from the consolidation test results. They are plotted vs. the HDPE plastic content in Figure 6, 7 and the numerical values are given in Table 3. The free swell and the swell pressure decreased by 45% and 56% respectively with 20% HDPE plastic additive. This is interesting and indicates the possible use of this waste material to improve the volume change characteristics of the gatch soil which may occasionally swell upon saturation due to the presence of calcium sulphate (gypsum) and other minerals. It should be emphasized that all samples here were prepared at RC=100% and optimum moisture content prior to saturation.

CBR Tests

CBR tests were performed on soaked samples compacted to 95% relative compaction with HDPE plastic content of 0%, 10%, 20%. The CBR values decreased with increasing HDPE plastic content as shown in Table 3.

As shown the CBR values modestly decreased from 21 for clean gatch soil to 18 and 16 with 10% and 20% HDPE plastic additive respectively. This indicates some reduction of strength and bearing capacity which agrees with the results of the direct shear and the model tests.

Model Footing Tests

Model tests were performed to determine the effect of HDPE plastic additive on the bearing capacity and settlement of shallow foundations. A sand box measuring 0.3m*0.3m*0.28m deep was employed, and a 70 mm diameter steel plate was placed on the surface at the center and loaded until failure occurred. The soil was placed in layers compacted to reach 95% relative compaction. The amount of HDPE plastic bits additive was 0% and 10% by weight. Loading was applied at constant rate of strain with reading taken at each 1mm of vertical deformation. Figures 8 shows the test set up for the gatch soil mixed with 10% HDPE plastic bits. Figure 9 is an after-failure view of the punching shear failure which occurred in the test on clean gatch soil. The pressure vs. settlement curve is shown in Figure 10. The ultimate failure load was taken at the point at which continuous deformation was occurring at no change in load.

A summary of the measured parameters and the calculated bearing capacity values is given in Table 5. As shown the ultimate bearing capacity decreased from 4382 kN/m² to 2706 kN/m² with 10% HDPE plastic additive or to 62% of the value of the clean remolded gatch. The settlement in the elastic range corresponding to an applied pressure of 800 kN/m² increased from 1 mm to 2 mm or double the value of the clean gatch. Employing the soil unit weight, and the shear strength parameters, the ultimate bearing capacity was calculated using both the Terzaghi Equation and the general bearing capacity Equation (Das 2016). The results are given in Table 5.

As observed the calculated values of the ultimate bearing capacity is larger than the measured values by 7.5% to 19% for the clean remolded gatch soil, and by 20% to 31% when 10% HDPE additive is employed. Noting the uncertainties and assumptions in the bearing capacity Equation, the calculated values are considered close to the measured values.

Figure 9 shows the failure mode which occurred when 0, and 10% HDPE plastic additive are employed. No heave in the soil surface occurred in both cases and big cracks can be seen on the surface extending in all direction from the plate. It is noticed the punching shear failure occurred with 0 and 10% plastic additive respectively.

Discussion and Practical Application

The objectives of this research were to examine the potential use of HDPE plastic additive to the local clayey sand “gatch” in civil engineering and construction applications. Table 3 and Figure 2 indicate that using HDPE plastic as additive to the local gatch soil produced a lightweight material with maximum dry densities 11% and 22% lower with HDPE plastic additive of 10% and 20% respectively. This soil can be used in embankment construction. With its light weight it will reduce the pressure on base deposits of soft clays and loose sands. It may also be used as backfill around foundations, pipelines and retaining walls. The lateral pressure will decrease being equal to ½

$\gamma H^2 K_H$ where K_H is the coefficient of lateral earth pressure, H is the height of the wall, and γ is the soil unit weight. This is since γ will be smaller.

Examination of the summary Table 3 indicates that the permeability slightly decreased with the HDPE plastic additive. This is since the gatch soil is very impermeable at RC=100% with k value of $7*10^{-9}$ cm/sec. Adding 10% or 20% HDPE plastic will not influence the measured values. As such it cannot be used as a drainage layer in highway and landfill construction. This is true in case of mixing HDPE with soil, however constructing layers from HDPE between the soil layers can serve as a drainage layer. The shear strength parameter C slightly decreased with HDPE plastic at RC=100% and 95%. The angle of friction ϕ, however, increased with HDPE plastic additive at RC=100% and slightly decreased for RC=95%. This may be due to the rough surface of the additive yielding large friction at very high density. The clayey sand gatch soil became more compressible with 10% and 20% HDPE additive as Cc increased by 30% and 69% respectively. The free swell and the swell pressure decreased substantially with HDPE plastic additive. This indicate that the volume change characteristics of the gatch soil can be improved using this plastic additive. It is noted that remolded gatch soil may swell after compaction upon saturation due to the presence of gypsum and other minerals (Ismael et. al. 1991).

Considering the CBR tests and the model footing tests it is clear that both CBR values and the ultimate bearing capacity decreased with the HDPE plastic additive. However, the reduction is modest being 14% and 24% in the CBR values with 10% and 20% additive respectively and 38% in the ultimate bearing capacity. These values allow the use of HDPE plastic additive in the asphalt mixes or as base for road construction. Compacted gatch soil mixed with HDPE additive can be used to support foundations for light structures and recreational facilities.

The above applications can utilize large amounts of HDPE plastic additive. It is also possible to recycle this material and transform it into new pipes. However, it will all depend on the amount of material, and the cost of recycling compared to disposal as a waste material for use in engineering and earthwork construction.

Conclusions and Recommendations

A laboratory testing program and model footing tests were performed to examine the possible use of high-density polyethylene (HDPE) plastic bits as additive to the local remolded clayey sand "gatch" soil in Kuwait. Based on tests results the following conclusions were reached:

1. The remolded gatch employed in the testing program is classified as SC or clayey sand according to the Unified Soil Classification System. The fines fraction in this soil (< 0.075 mm) is 21%.

2. Mixing the compacted gatch (RC=100%) with 10% and 20% HDPE plastic bits resulted in a lightweight material with a reduction of the maximum dry density of 11% and 22% respectively.
3. For samples compacted to RC=100% the permeability slightly decreased with the addition of 10% and 20% HDPE plastic bits.
4. The direct shear tests results showed that the angle of friction ϕ increased by 3 to 5 degrees for samples compacted to 100% relative compaction with 10% and 20% HDPE additive respectively. It decreased, however, by 1.5 degrees for samples compacted to 95% relative compaction with 10% HDPE additive. The cohesion C decreased in the presence of HDPE additive.
5. The compressibility increased with HDPE plastic additive as indicated by the values of Cc and Cs. Cc increased by 30% and 69% and Cs increased by 25% and 30% with HDPE plastic additive of 10% and 20% respectively.
6. For samples compacted to a relative compaction of 95% the CBR values decreased from 21 for clean gatch soil to 18 and 16 with 10% and 20% HDPE plastic additive respectively.
7. The model test results indicated that the ultimate bearing capacity of a circular plate loaded on gatch soil compacted to RC=95% decreased by 38% from 4375 kPa to 2700 kPa when 10% HDPE plastic was employed as additive. The vertical settlement at an applied pressure of 800 kPa, increased from 1 mm to 2 mm.
8. The HDPE plastic bits can be used in many practical applications including embankment construction, backfill around foundations and walls, base for road construction and as additive in small quantities to bitumen mixes in road asphalt. It will also improve the volume change characteristics of the local gatch soil by preventing excessive swelling upon saturation.
9. It is recommended to carry out loading tests at a test site. The tests should be porformed on compacted gatch soil with and without HDPE plastic additive. Plate load tests should be carried out first followed by full scale footing tests.

Declaration

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Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable

Data availability statement: All data generated or analysed during this study are included in this published article.

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Table 1. Mechanical analysis of the clean soil and HDPE plastic

Sieve size (mm)	% Passing	
	Gatch soil	HDPE plastic
9.5	100	100
4.75	100	89.3
2.36	98.8	8.5
1.18	97.1	1.2
0.6	94.3	0.2
0.3	87.2	0.1
0.15	59.7	0
0.075	21.9	0

Table 2. Raw material properties of the HDPE plastic bits

Test Name	Results
Density @ 23°C	947.32 kg/m^3
Tensile strength at yield	23.85 MPa
Ultimate elongation at break	730.0%
Flexural modulus	879.97 MPa
Melt flow Index @ 190^{0}C 5 kgf	0.389 g/10 min
Modulus of elasticity @ 25^{0}C	810 MPa
Modulus of elasticity @ 40^{0}C	680 MPa
Carbon black content	2.09%
Shore hardness D	63.80
Co-efficient of linear thermal expansion	0.18%
Vicat softening point	128.5°C
Oxidation induction time @ 200°C	50 min

Table 3. Summary of all test results

Parameters	RC= 100%		
	0% HDPE plastic	10% HDPE plastic	20% HDPE plastic
ρ_d (kg/m³)	1905	1685	1494
w% (opt)	12.5	12.5	11.5
ϕ	41.07	44	46
C (kP_a)	55.65	41	47.3
Cc	0.0229	0.0297	0.0388
Cs	0.0096	0.012	0.0125
C_v (mm²/min)	653	647	639
Free Swell %	0.684	0.458	0.374
Swell Pressure (kPa)	43.6	27	19
k (cm/s)	$7*10^{-9}$	$6.6*10^{-9}$	$5.1*10^{-9}$

Parameters	Rc= 95%	
	0% HDPE plastic	10% HDPE plastic
	Clean Sand	Inner Plastic
ρ_d (kg/m³)	1800	1600
w%	12.8	12.5
ϕ	39.5	38
C (kP_a)	41.86	32
Ultimate (Bearing capacity kN/m²)	4375	2700

Parameter	RC= 95%		
	0% HDPE plastic	10% HDPE plastic	20% HDPE plastic
CBR	21	18	16

Table 4. Shear displacement at maximum shear stress for compacted samples (RC=100% and RC 95%).

% HDPE plastic	RC= 100%					
	σ_n = 31.5kPa		σ_n = 63kPa		σ_n = 125.9kPa	
	τ_{max}(kPa)	Δ(mm)	τ_{max}(kPa)	Δ(mm)	τ_{max}(kPa)	Δ(mm)
0	83.8	0.577	109.9	0.426	165.2	0.741
10	70	0.974	104.5	0.788	160.9	1.180
20	81	1.192	111.8	1.372	176.1	1.074

% HDPE plastic	RC= 95%					
	σ_n = 31.5kPa		σ_n = 63kPa		σ_n = 125.9kPa	
	τ_{max}(kPa)	Δ(mm)	τ_{max}(kPa)	Δ(mm)	τ_{max}(kPa)	Δ(mm)
0	69	0.792	93.7	0.613	145.6	0.962
10	55.8	0.749	83.1	0.642	103.8	3.522

Table 5. Summary of the Model Test Results

Parameter		Clayey sand gatch RC 95%	
		0% HDPE plastic	10% HDPE plastic
C (kN/m^2)		41.86	32
ϕ^o		39.5	38
γ (kN/m^2)		17.66	15.7
q_{ult} -measured (kN/m^2)		4382	2706
q_{ult} -calculated (kN/m^2)	Terzaghi	4713	3250
	General	5205	3555
Settlement at q= 800 kN/m^2		1	2

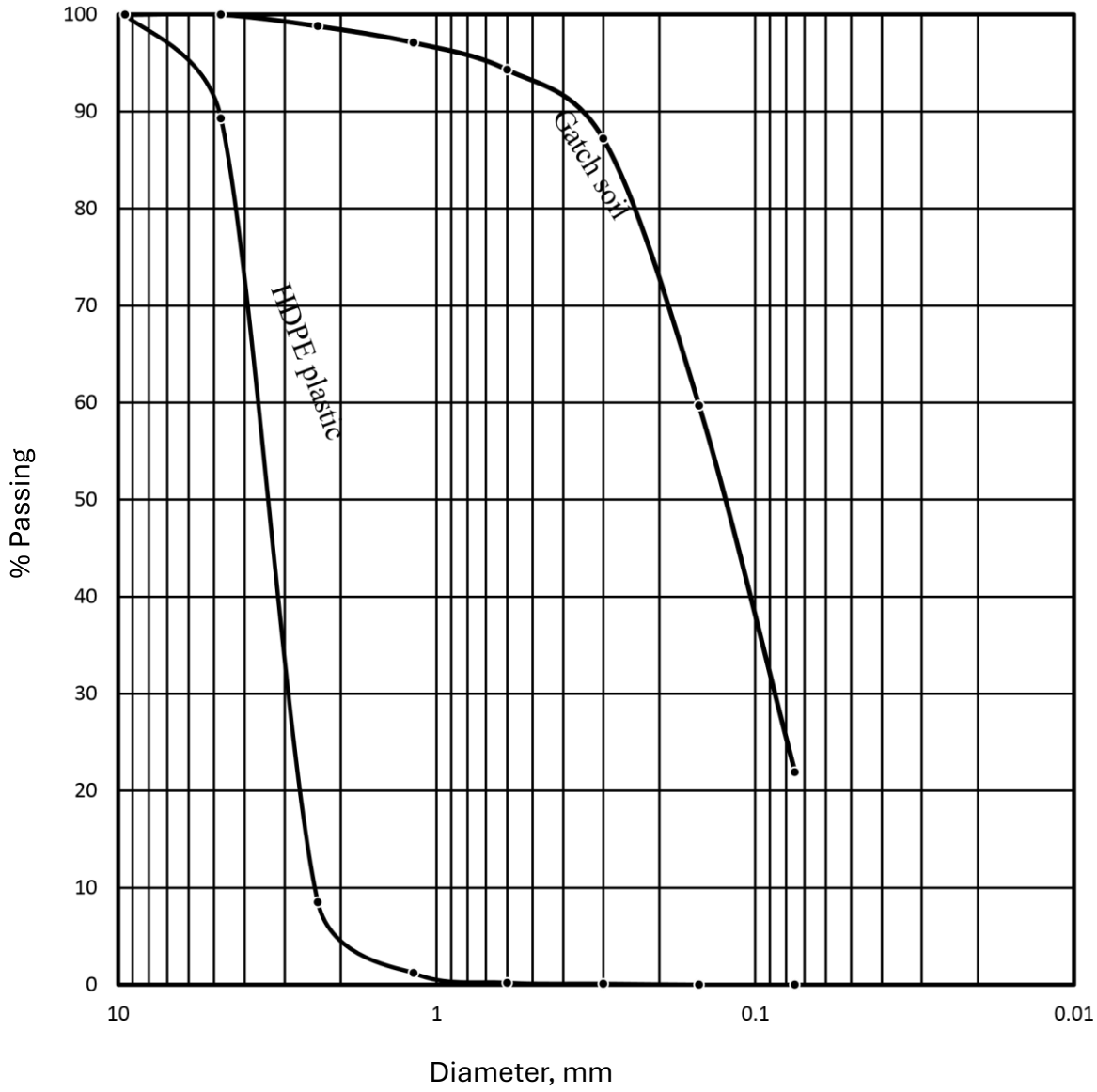


Figure 1. Grain size distribution curves

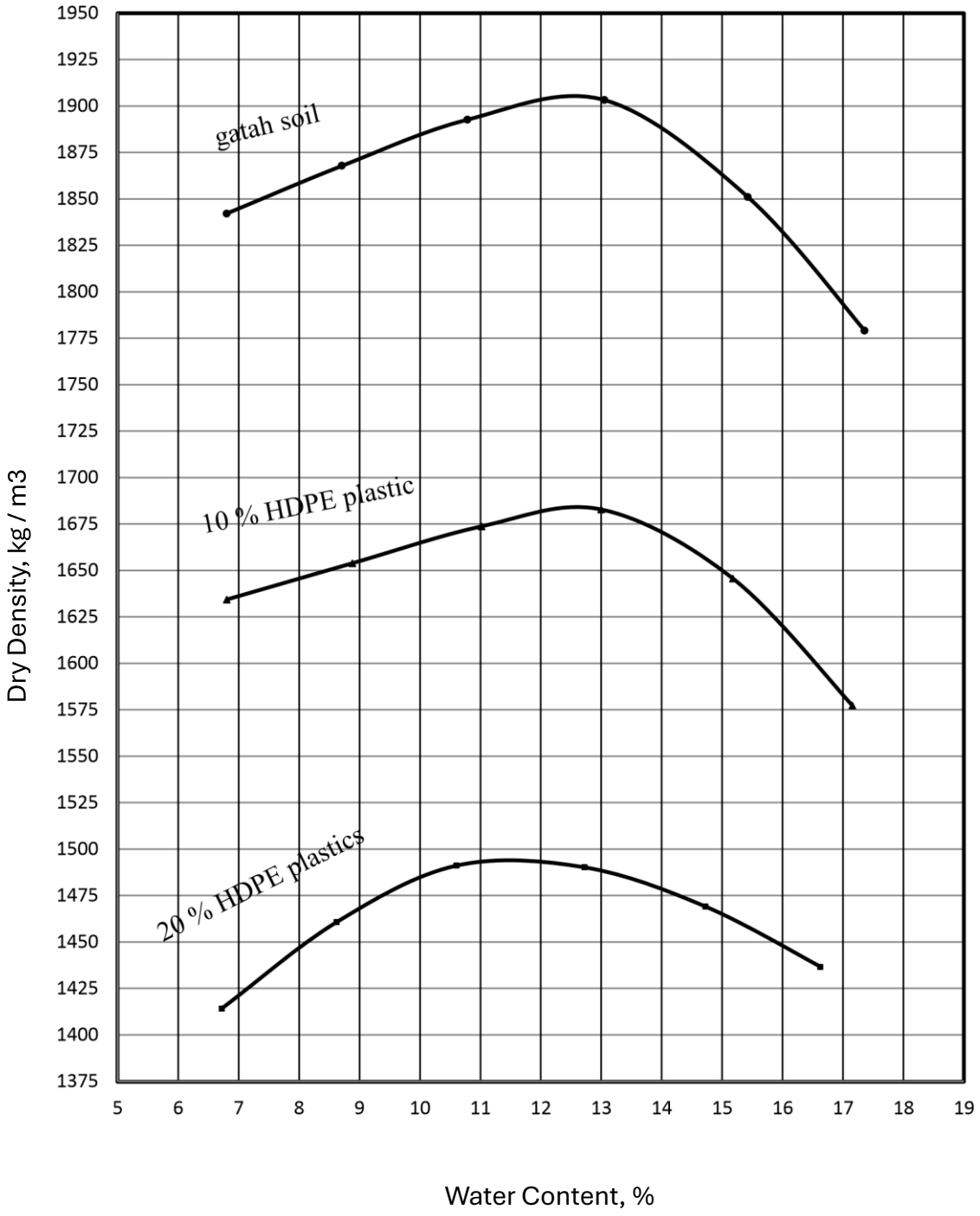


Figure 2. Compaction test results

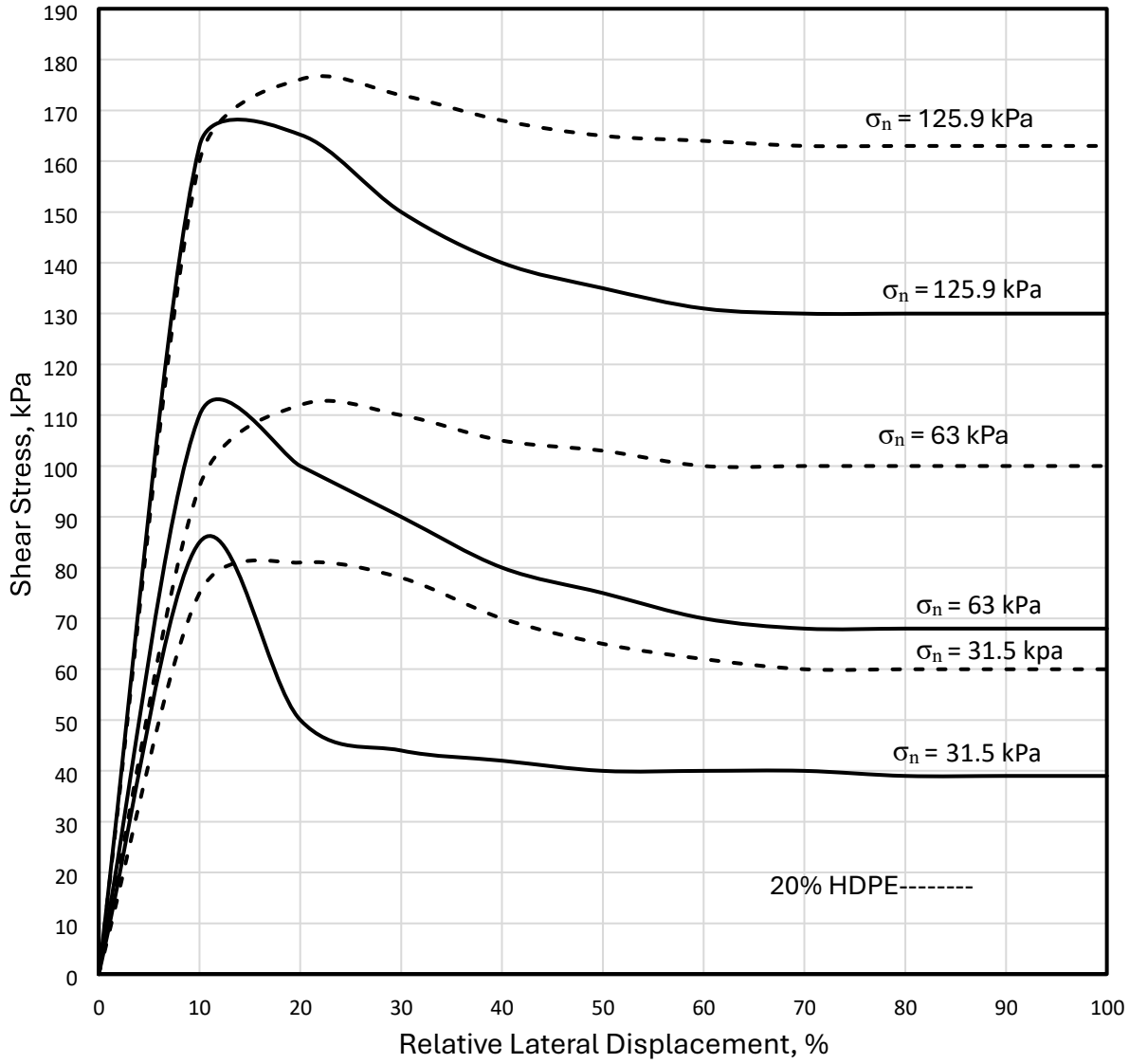


Figure 3. Variation of shear stress with relative lateral displacement for clean gatch soil and for sand with 20% inner plastic content at 100% relative compaction.

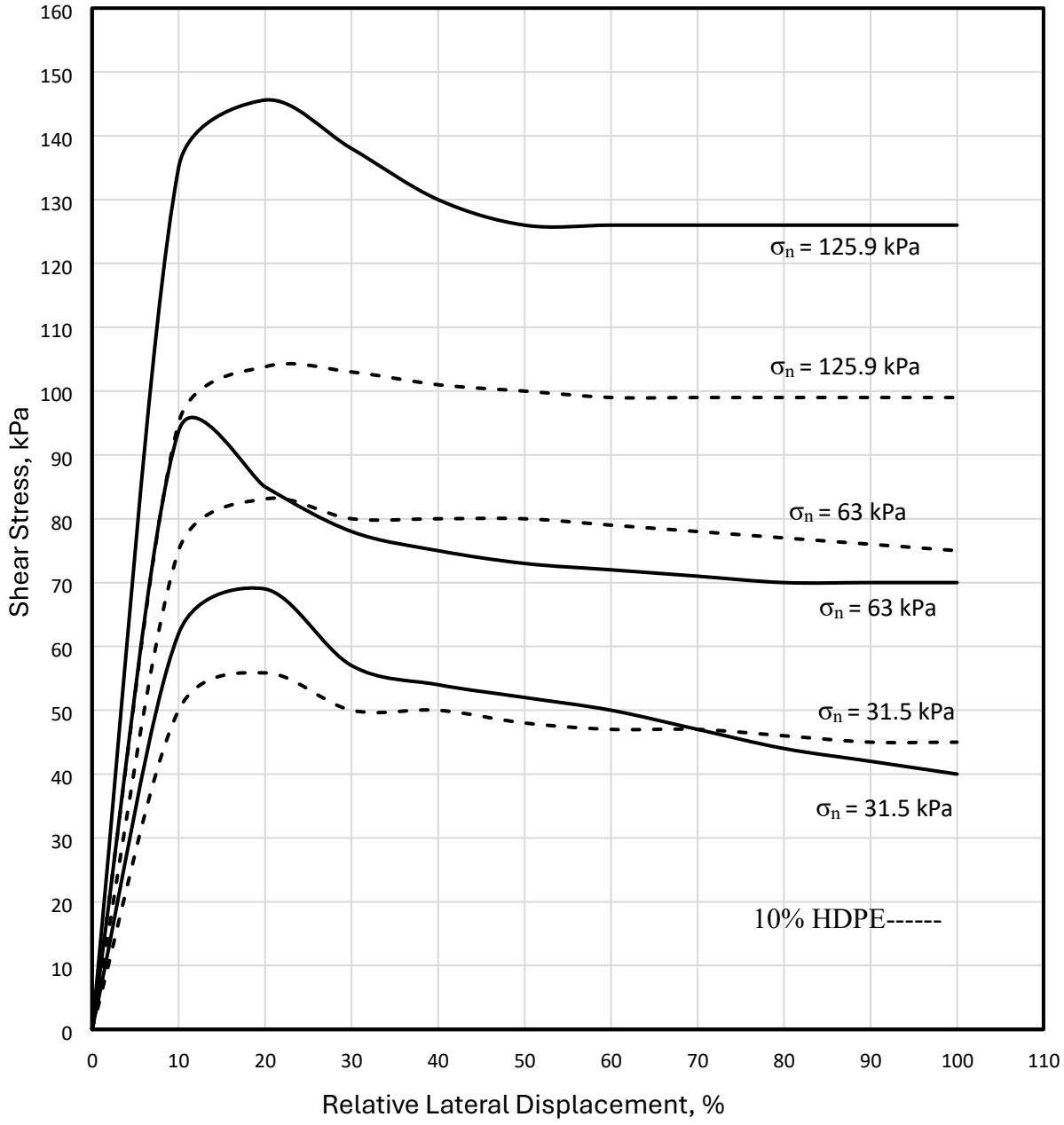


Figure 4. Variation of shear stress with relative lateral displacement for clean gatch soil and for gatch with 10% HDPE plastic content at 95% relative compaction.

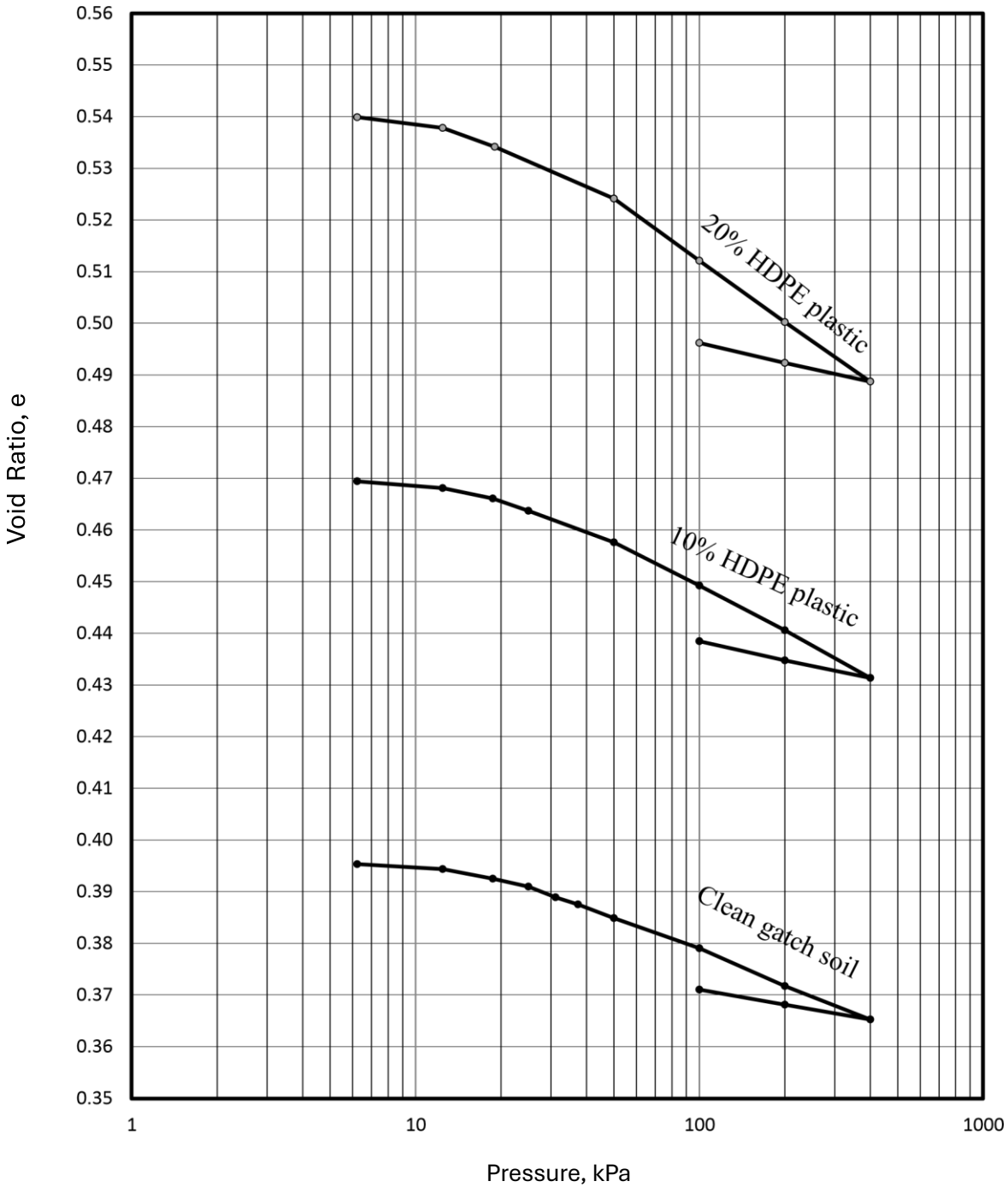


Figure 5. e-log σ plots from consolidation tests on samples of clean gatch soil, and sample with 10% and 20% HDPE plastic bits at 100% relative compaction.

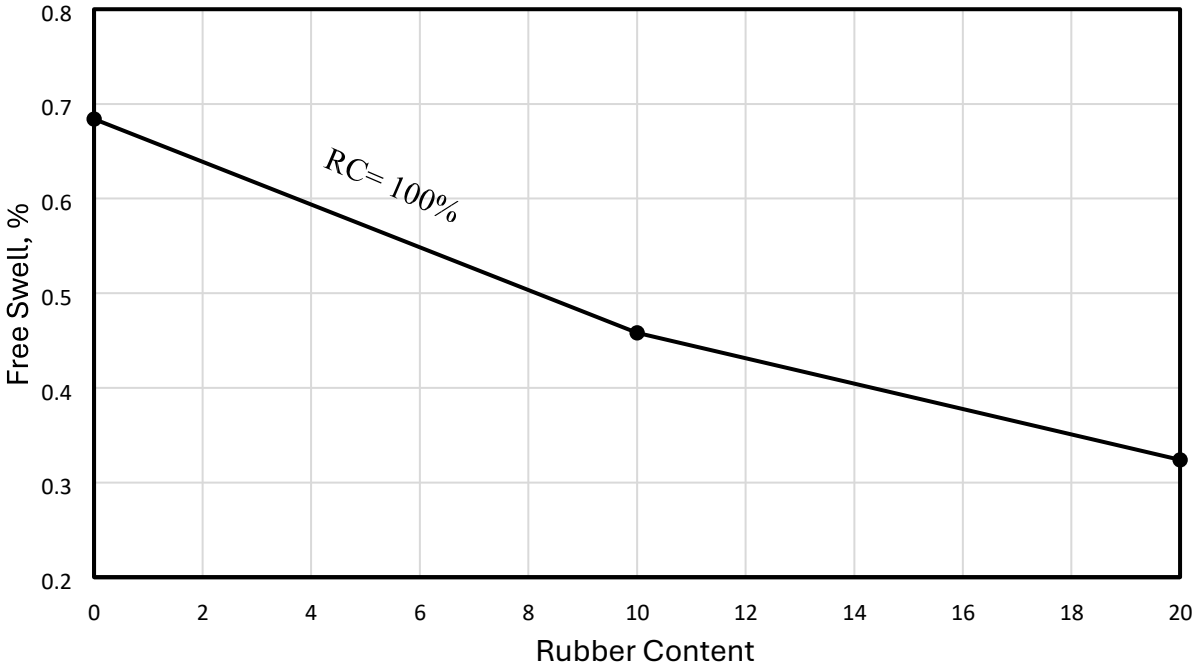


Figure 6. Variation of Free Swell with HDPE plastic

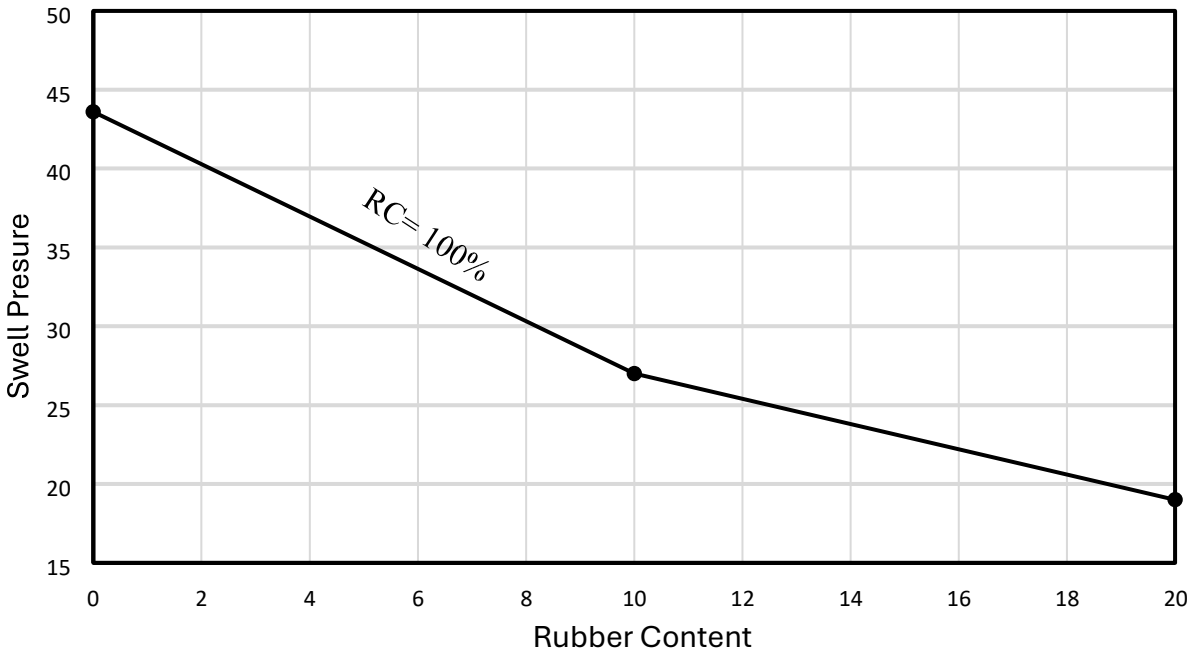


Figure 7. Variation of Swell Pressure with HDPE plastic



Figure 8. Model Load Test setup on gatch soil mixed with 10% HDPE plastic bits

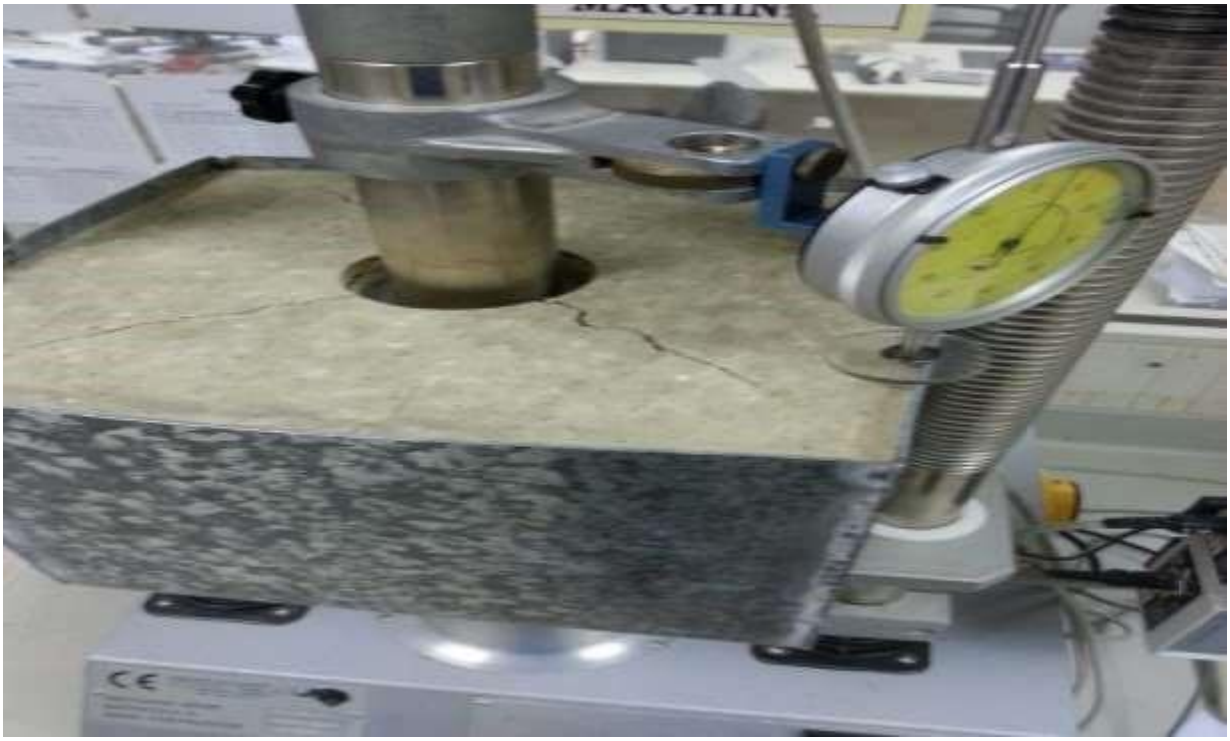


Figure 9. View of the punching shear failure of the gatch soil below the circular plate

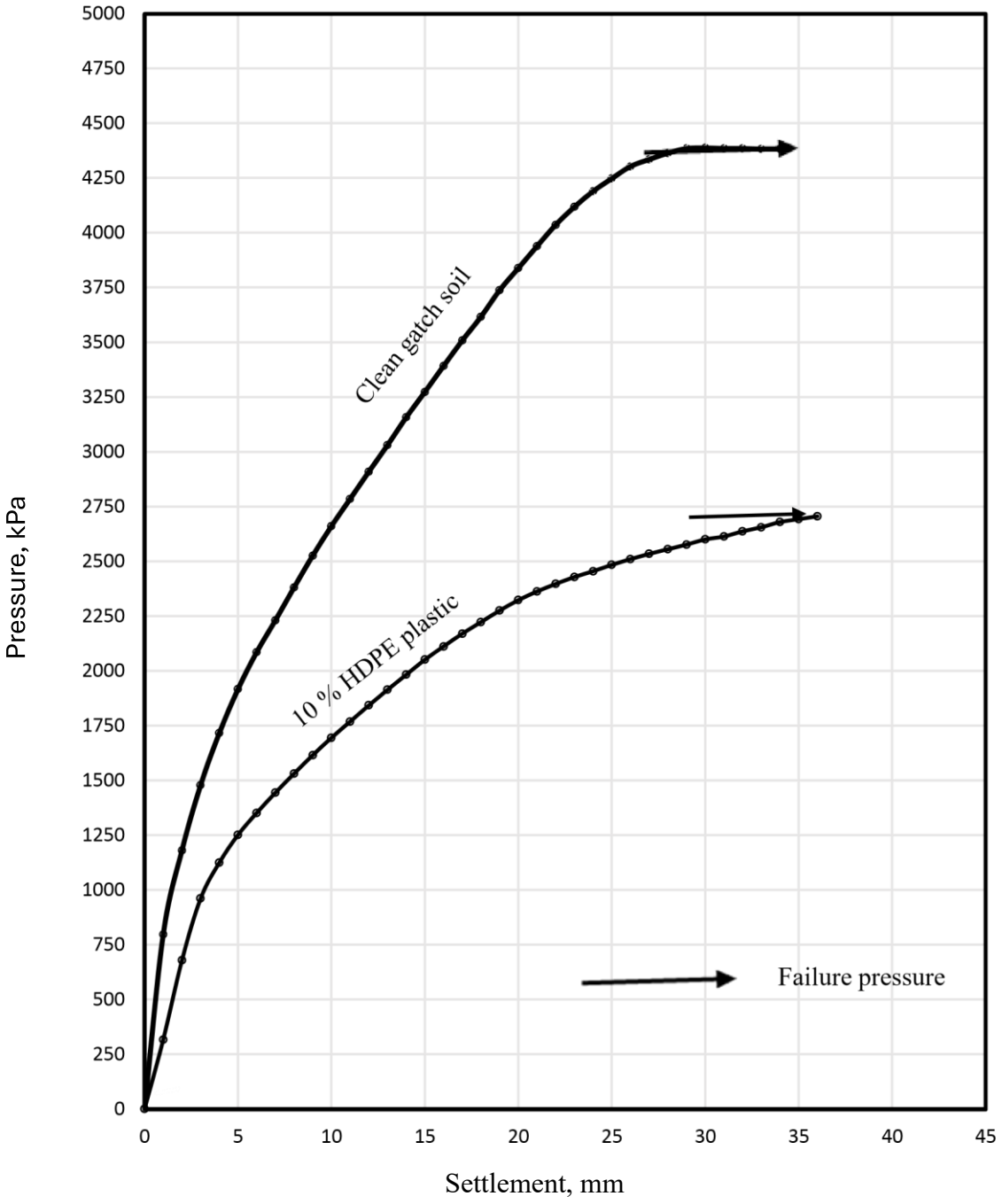


Figure 10 The pressure settlement curves from the model tests