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Comparative Analysis of Shear Strength of Ravi, Chenab, and Lawrencepur Sands: The Effect of Moisture Content and Degree of Saturation

Sadia Kalsoom[a], Salman Ali Suhail[a,*], Arslan Qayyum Khan[b], Muhammad Qasim[a]

[a]*Department of Civil Engineering, The University of Lahore, Lahore, Pakistan*

[b]*Department of Civil and Environmental Engineering, Florida International University, Miami, FL 33174, United States*

[*] Corresponding Author: Salman Ali Suhail, Email: salman.suhail@ce.uol.edu.pk

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Shear Strength

ABSTRACT

The recent unpredictable and unprecedented rainfall events under climatic scenarios emphasized the effect of varied moisture content and fluctuating saturation levels on the mechanical properties of indigenous construction materials. This study investigates the influence of moisture content and degree of saturation on the angle of internal friction of three locally available sandy soils: Ravi, Chenab, and Lawrencepur sand. The aforementioned sands are extensively utilized in the construction industry as they are readily available, which also results in reduced cost. However, it is vital to explore the mechanical behavior of these sands, predominantly the effect of moisture condition on shear strength characteristics, prior to being employed for construction works. In the current study, extensive laboratory testing is conducted to study the impact of moisture content and saturation on the frictional angle of the soil. The results showed the highest friction angle at Optimum Moisture Content (OMC) for all three sands and a noteworthy reduction otherwise. Furthermore, a decreasing trend of the frictional angle is observed with an increase in the soil saturation. The study concludes that Lawrencepur sand, with a highest value of frictional angle of 25 degrees, dry density of 17.9 kN/m^{3,} and a lower void ratio of 0.68, is the most suitable sand for construction purposes.

1. Introduction

In the construction sector, the adoption of localized materials has always been encouraged due to their availability and cost efficiency. The utilization of local materials is particularly valuable for developing countries. However, a thorough understanding of the mechanical and engineering characteristics of materials is are prerequisite before being used for construction works.

Numerous factors, including particle size distribution, pores and voids, etc., may impact the mechanical behaviour of the soil. Moisture content is also considered a key parameter that has a significant effect on the strength characteristics of the soil. Sandy soil, considered to be a drained material, has a propensity for high saturation in the presence of very little moisture. Additionally, the groundwater table (GWT) also plays a huge role in the soil moisture dynamics. A shallow groundwater table leads to higher soil saturation levels. It is a well-known fact that the shear strength of the sandy soil is primarily governed by the frictional angle. Resultantly, understanding of the impact of the moisture and saturation on the angle of internal friction becomes vital for precision in the design and construction works.

The assessment of the geotechnical properties of sandy soil has been a domain of interest of research in recent years. The research work concluded that liquefaction resistance has an indirect relationship with soil saturation [1]. Another study showed that, in sandy soil, structural geometry and its corresponding

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particle size have a substantial effect on the shear strength. Nominal variation in the voids and porosity results in significant alteration in shear strength characteristics [2]. A research study investigated the relationship between frictional angle and geotechnical properties of the soil, and a correlation between soil index properties and frictional angle was proposed for sandy soil [3]. The mechanical behaviour of various sandy soils with varying saturation was investigated. The study concluded that gap-graded sand showed high shear strength characteristics as compared to the other two types [4]. The mechanical properties of mixed soil were investigated in various studies where the effect on the frictional angle and cohesion was evaluated by mixing soil with various stabilising materials [5-7]. An experimental study was performed to investigate the behaviour of clayey sand used for the subgrade layer. The result showed that moisture content had a significant effect on the strength characteristics and deformation of clayey sand [8]. In another study, it was highlighted that moisture was the dominant factor that influenced the strength of the soil [9]. Studies revealed that cohesion and shear strength of unsaturated gypseous soil were increased up to the saturation level of 60%. Beyond this level of saturation, the parameters were reduced [10]. Another study identified a slump in axial stress during shearing in partially saturated fine-grained soil due to higher matric suction [11]. An interesting observation was reported in cohesive soil where an increase in moisture resulted in a decrease in the angle of internal friction, along with an increase in cohesion values [12].

From all the aforementioned studies, it can be well concluded that moisture and saturation of the soil have a significant impact on the shear strength characteristics of the soil. The shear characteristics of the soil have a direct relationship with soil dynamic characteristics, including the soil shear modulus. Therefore, the moisture and saturation level of the soil may have an indirect impact seismic response of the various geo infrastructures [13-16].

Pakistan lies in semi-arid regions where recorded annual precipitation ranges between 250mm to 500mm. Generally, the rainy season in Pakistan starts in May and ends in August. During this season, the groundwater table also rises, and hence the soil becomes saturated or partially saturated, resulting in higher moisture content and saturation. Sand is an important construction material that is used widely in the construction industry. Globally, the general practice of material selection is based on its access, availability, and understanding of its index and mechanical properties. In Pakistan, the three most common types of localised sand used in construction are: (i) Ravi sand, (ii) Chenab sand, and (iii) Lawrencepur sand. However, very limited studies are available in the literature that explain the mechanical behaviour of the aforementioned sands. It is well understood, the strength characteristics of the sandy soil are a function of the frictional angle. Hence, it is important to evaluate the effect of moisture content and degree of saturation on the frictional angle of the aforementioned localised sands.

This study investigates how soil moisture and saturation affect the angle of internal friction in three locally available sandy soils. The soils were collected from appropriate locations and transported to a laboratory for testing. The laboratory testing program covered both index and strength tests for each soil type. Direct shear tests were carried out using different moisture contents and degrees of saturation, as well as varying loading conditions, to determine the angle of internal friction for each scenario. The soil sample collection and its transportation to the designated laboratory were carried out as prescribed in ASTM standards.

2. Methodology

The current study intricate soil collection from the sites, sample preparation, and performance of experimental testing in the designated laboratory. The methodology employed in the present study in shown in Fig. 1.

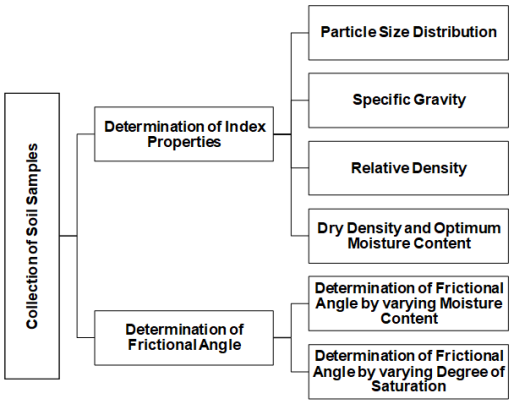

Fig. 1. Methodology Flowchart.

2.1 Soil Collection and Sampling

Soil samples of all three sands, i.e., (i) Ravi Sand; (ii) Chenab Sand; and (iii) Lawrencepur Sand, were extracted from different locations in Pakistan, as illustrated in Fig. 2. Ravi Sand was extracted from Badami Bagh, whereas Chenab Sand and Lawrencepur Sand were obtained from Akbar Kinara and Kamra, respectively. Bulk soil was collected,

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which was later transported to the designated laboratory after preservation following the standard procedures prescribed in ASTM standards.

Fig. 2. Location of Soil Collection Sites.

2.2 Experimental Program

A thorough experimental program was compiled to evaluate the index and strength characteristics of all three locally available sandy soils. The index testing of the soil involved the performance of sieve analysis, specific gravity, relative density, and modified proctor tests. Once the index properties were evaluated, Direct Shear Tests (DST) were conducted on all three types of sands by varying moisture content and saturation. All the aforementioned tests were performed following relevant ASTM standards [17-23]. Twenty-seven (27) DSTs were conducted considering variation in soil moisture and saturation to examine the effect of moisture content on the shear strength characteristics. The samples were formed at three (03) moisture content values, i.e., (i) at Optimum Moisture Content (OMC); (ii) 5% below the OMC; and (iii) 5% above the OMC. All the samples were prepared in the mould of the proctor test by adding water to the soil by weight. The weight of water to the affirmed soil moisture content, 5% below and above the OMC, was calculated using standard weight volume relationships. Once the weight of the water was determined, the water was added to the soil and mixed properly before preparing a sample in a mould for the proctor test. This procedure of sample preparation aligns with an already published study [24]. DSTs were performed on the aforementioned samples by considering three (03) loading variations of 10 lbs, 20 lbs, and 30 lbs. The effects of the saturation on the frictional angle of the three types of sands were investigated by considering three (03) percentages of saturation, i.e., 20%, 40%, and 60%. DSTs were then performed by considering the same load variation of 10 lbs, 20 lbs, and 30 lbs.

3. Results and Discussion

The results of the study at hand are categorised into three (03) sections. In the first section, the results of index testing are reported, and a comparative assessment of the obtained properties is performed. In the second section, the effect of moisture content on the frictional angle and stress-strain curves is discussed. Finally, the effect of the saturation on the angle of internal friction and stress-strain curves is then presented.

3.1 Soil Index Properties

The index testing of the soil included sieve analysis, specific gravity tests, relative density, and modified proctor tests. The gradation curve of all three types of sandy soil is presented in Fig. 3. The soil classification was performed using the Unified Soil Classification System (USCS) and AASHTO soil classification systems, utilising the results obtained from index testing, as presented in Table 1. The results showed that both Ravi sand and Chenab sand were poorly graded soil, whereas Lawrencepur sand was classified as well-graded soil. The coefficients of uniformity of Ravi, Chenab, and Lawrencepur sand were 1.7, 3.9, and 6.3, respectively. The coefficients of curvature of 1.3, 0.8, and 0.7 was recorded for Ravi, Chenab, and Lawrencepur sand, respectively. All three soils are classified as A-3 soil as per the AASHTO soil classification.

The results of index testing are presented in Table 2. Index properties obtained in the present study showed that the unit weight of Ravi sand ranged from 11.38kN/m3 to 14.85kN/m3. The unit weight of Chenab sand ranged from 12.90kN/m3 to 15.48kN/m3, and the unit weight of Lawrencepur sand ranged from 15.38kN/m3 to 18.46kN/m3. The results further revealed that the void ratio of Ravi sand ranged from 0.74 to 1.20, whereas the void ratio ranged from 0.67 to 1.01 for Chenab Sand and 0.41 to 0.68 for Lawrencepur sand. The relative densities of Ravi, Chenab, and Lawrencepur sand were 50%, 59%, and 79%, respectively.

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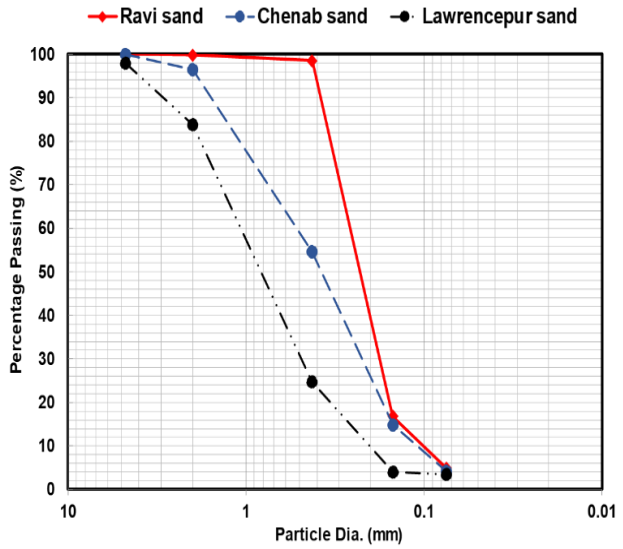


Fig. 3. Gradation Curve of Three Types of Soil.

The specific gravity of Ravi, Chenab, and Lawrencepur sand was found to be 2.67, 2.71, and 2.80, respectively. Modified proctor test results showed MDD of Ravi, Chenab, and Lawrencepur sand was 16.2 kN/m3, 16.8 kN/m3, and 17.9 kN/m3, respectively, whereas the corresponding OMCs were 12.5%, 11.2%, and 10.5%, respectively. The relationship between MDD and OMC obtained from the modified proctor test is presented in Fig. 4.

Table 1

USCS and AASHTO Classification of Three Types of Sand

Parameter	Ravi Sand	Chenab Sand	Lawrencepur Sand
D_{10} (mm)	0.1	0.13	0.19
D_{30} (mm)	0.15	0.23	0.4
D_{50} (mm)	0.17	0.39	0.75
D_{60} (mm)	0.18	0.51	1.2
C_u	1.7	3.9	6.3
C_c	1.3	0.8	0.7
USCS	SP	SP	SW
AASHTO	A-3(0)	A-3(0)	A-3(0)

Table 2

Index Properties of Three Types of Sand

Parameter	Ravi Sand	Chenab Sand	Lawrencepur Sand
$\gamma_{b(max)}$ (kN/m^3)	14.85	15.48	18.46
$\gamma_{b(min)}$ (kN/m^3)	11.38	12.9	15.38
e_{max}	1.2	1.01	0.68
e_{min}	0.74	0.67	0.41
D_r (%)	50	59	79
G_s	2.67	2.71	2.80
MDD (kN/m^3)	16.2	16.8	17.9
OMC (%)	12.5	11.2	10.5

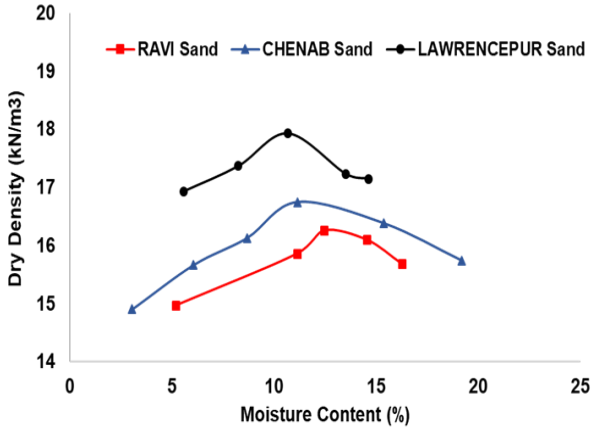
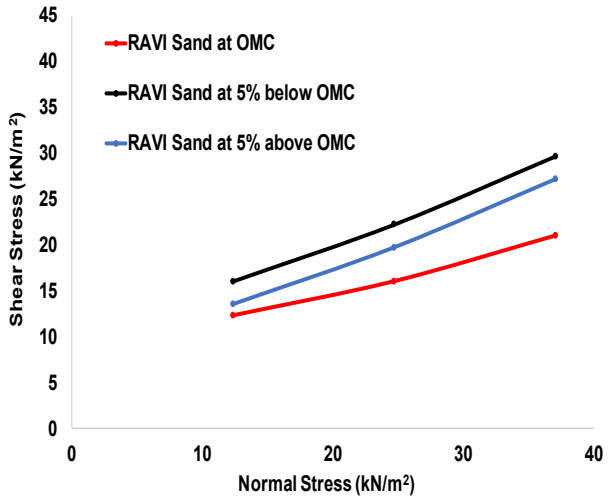


Fig. 4. Results of Modified Proctor Test

The results of relative density tests showed that Ravi sand may be considered as loose in its natural state due to a higher void ratio, whereas Lawrencepur sand was coarser and denser as compared to the other two types of sand. This is the fundamental reason that Lawrencepur sand exhibits higher MDD as compared to Ravi and Chenab sand. Index testing results lead to a noteworthy conclusion that Lawrencepur sand required less water to reach maximum dry density as compared to Ravi sand and Chenab sand.

3.2 Effect on Frictional Angle by Varying Moisture Content

The frictional angle was obtained by performing a series of DSTs. To probe the impact of moisture content on the angle of internal friction, tests were performed at three moisture content values, i.e., (i) at OMC, (ii) at 5% above the OMC, and (iii) at 5% below the OMC of sands. The frictional angle was evaluated using the relationship between the normal and shear stress for all three locally available sands, as presented in Fig. 5.



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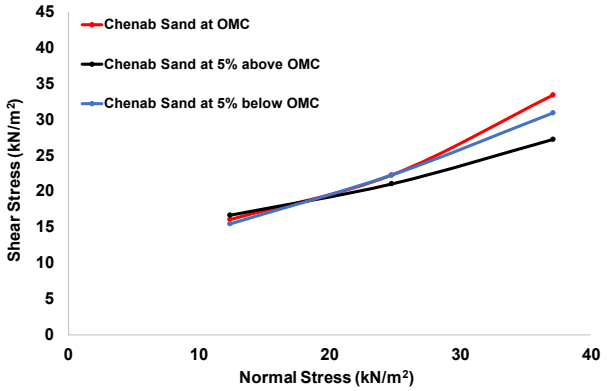

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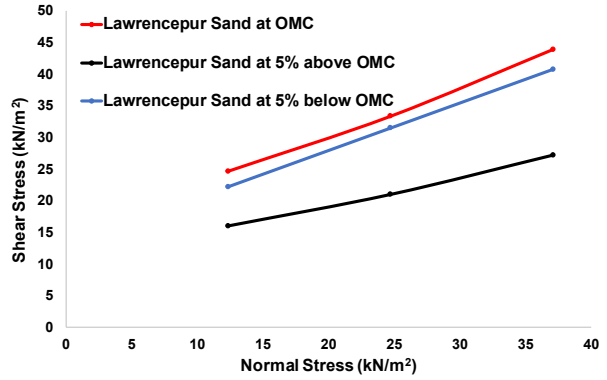

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Fig. 5. Relationship between Normal and Shear Stress by Varying Moisture Content (a) Ravi Sand, (b) Chenab Sand, (c) Lawrencepur Sand

The frictional angles of Ravi, Chenab, and Lawrencepur sand at OMC were 32 degrees, 34.9 degrees, and 37.7 degrees, respectively. Furthermore, the frictional angle of Ravi, Chenab, and Lawrencepur sand at 5% below the OMC was observed to be 29 degrees, 31 degrees, and 34 degrees, respectively, whereas the angle of internal friction of Ravi sand, Chenab sand, and Lawrencepur sand at 5% above the OMC were 20 degrees, 22.4 degrees, and 29.9 degrees, respectively. The alteration of the frictional angle with the soil's moisture content is summarised in Fig. 6.

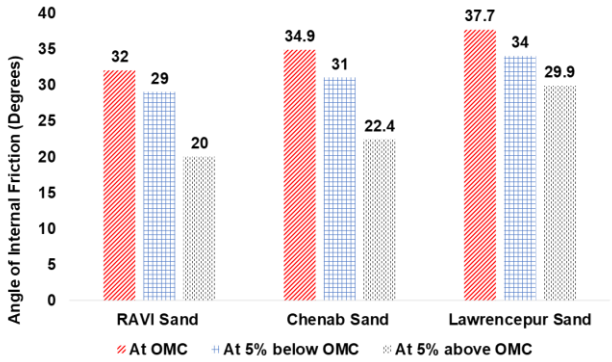

Fig. 6. Summary of Angle of Internal Friction of All Three Types of Soil by Varying Moisture Content

The obtained values of the frictional angles indicated a nominal reduction at 5 % below OMC when compared with the values of frictional angles at OMC for all three types of sands. Pronounced reduction in the values of frictional angles was noted at 5% above OMC, indicating detrimental impact of pore water pressure, which resulted in particle contraction and minimisation of particle interlocking.

Lawrencepur sand consistently exhibited the highest friction values across all moisture content values, which is mainly because of its intrinsic material characteristics. Well-defined morphology, uniform gradation, and higher particle friction are fundamental characteristics of Lawrencepur sand, which lead to a lower void ratio, thereby resulting in stronger particle interlocking. These mechanistic trends noted in the present study align with the findings of the already published research study [2].

3.3 Effect on Stress-Strain Response by Varying Moisture Content

The relationship between shear stress and the corresponding deformation of all three locally available sands by varying moisture content is presented in Fig. 7. The shear stress and deformation are presented for three stress levels of 12.361 kPa, 24.721 kPa, and 37.109 kPa by considering the same three moisture content values, i.e. (i) At OMC; (ii) At 5% above the OMC and (iii) At 5% below the OMC of sands.

The results showed that when the stress level increased to 37.093 kPa, the maximum resisting stress of Ravi, Chenab, and Lawrencepur sand was revealed to be 32.390 kPa, 33.389 kPa, and 37.112 kPa, respectively, at OMC. The maximum resisting stress at 5% below the OMC was 30.91 kPa, 31.56 kPa, and 40.82 kPa for Ravi, Chenab, and Lawrencepur sand, respectively. Furthermore, at 5% above the OMC, the maximum resisting shear stress of 21.99 kPa, 28.99 kPa, and 27.21 kPa were observed for Ravi sand, Chenab sand, and Lawrencepur sand, respectively. The summary of obtained maximum resisting shear stress obtained at all stress levels for three locally available sands is summarised in Table 3.

The investigation of shear stress and deformation plots of all three sands led to an interesting observation that the maximum value of resisting shear stress was obtained at OMC for all three locally available sands. Nominal decrease in the values of resisting shear stress at 5% below the OMC was noted for all three locally available sands. However, significant reductions in the resisting shear stress were observed at 5% above the OMC. By comparing the resisting shear stress of the three locally available sands, the result highlighted

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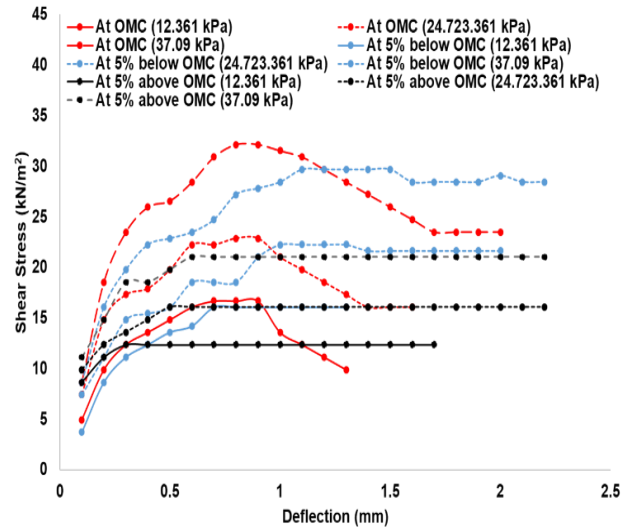
that Lawrencepur sand possessed the maximum resisting shear strength as compared to the other two sandy soils. This is because Lawrencepur sand has the highest density among all three types of sandy soil. Owing to this, the soil exhibits a higher capacity when compared with other soils. Comparable findings were documented in the already published research study [25]

Table 3

Summary of Resisting Shear Stress by Varying Moisture Content

Sand Type	Stress Levels (kPa)	Resisting Shear at OMC	Resisting Shear at 5% below OMC	Resisting Shear at 5% above OMC
Ravi Sand	12.361	18.54	16.06	13.00
	24.721	23.86	23.48	16.88
	37.109	32.39	30.91	21.99
Chenab Sand	12.361	17.00	16.0	16.99
	24.721	31.00	23.11	24.73
	37.109	33.39	31.56	28.99
Lawrencepur Sand	12.361	25.90	23.06	16.00
	24.721	34.99	31.53	21.03
	37.109	37.11	40.82	27.21



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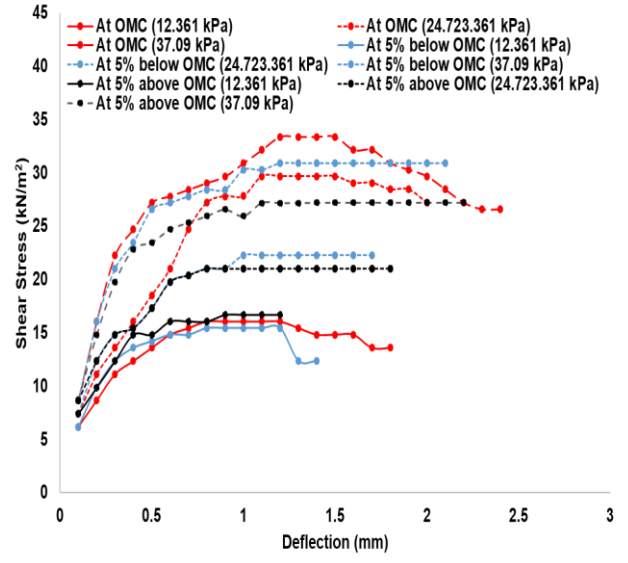

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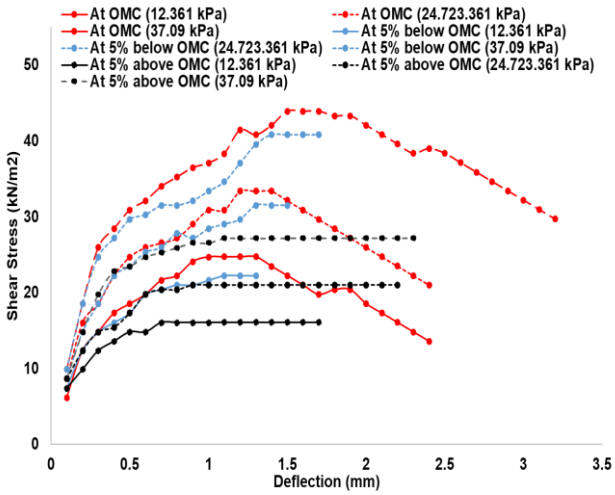

(c)

Fig. 7. Relationship between Normal and Shear Stress by Varying Moisture Content (a) Ravi Sand, (b) Chenab Sand, (c) Lawrencepur Sand

3.4 Effect on Frictional Angle by Varying Degree of Saturation

The effect of soil saturation on the angle of internal friction was investigated by performing a series of DSTs by considering three values of degree of saturation, i.e., 20%, 40%, and 60%. At least 3 samples were tested for all three locally available sands, and the frictional angle was evaluated using the relationship between the normal and shear stress for all three locally available sands. The relationship between average normal stress and average shear stress is presented in Figs. 8, 9, and 10 for the degree of saturation of 20%, 40%, and 60%, respectively.

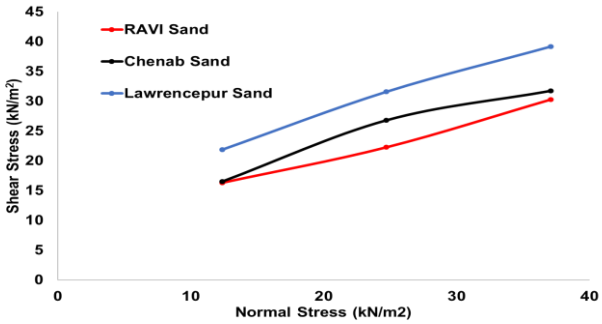

Fig. 8. Relationship between Normal and Shear Stress at 20% Degree of Saturation

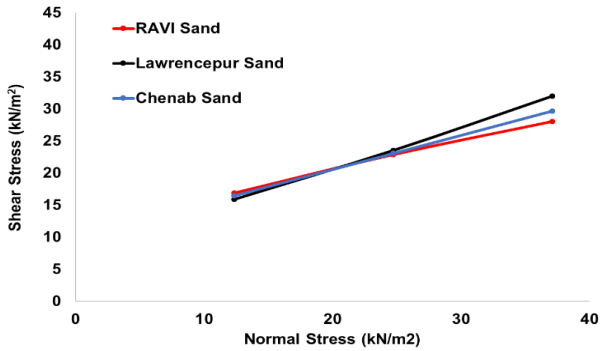

Fig 9. Relationship between Normal and Shear Stress at 40% Degree of Saturation

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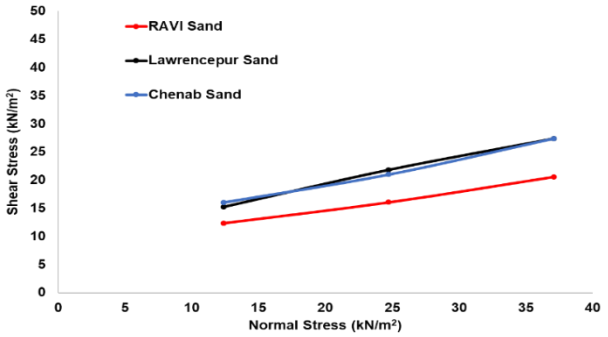


Fig 10. Relationship between Normal and Shear Stress at 60% Degree of Saturation

The frictional angles of Ravi, Chenab, and Lawrencepur sand at 20% degree of saturation were revealed to be 29.54 degrees, 32.99 degrees, and 35 degrees, respectively. Furthermore, the frictional angles of Ravi, Chenab, and Lawrencepur sand at 40 % degree of saturation were observed to be 25.79 degrees, 28 degrees, and 31 degrees, respectively. Whereas the angle of internal friction of Ravi, Chenab, and Lawrencepur sand at 60% degree of saturation were 18.43 degrees, 24.6 degrees, and 26.17 degrees, respectively. The fluctuation of the frictional angle with an increase in the degree of saturation is summarised in Fig.11.

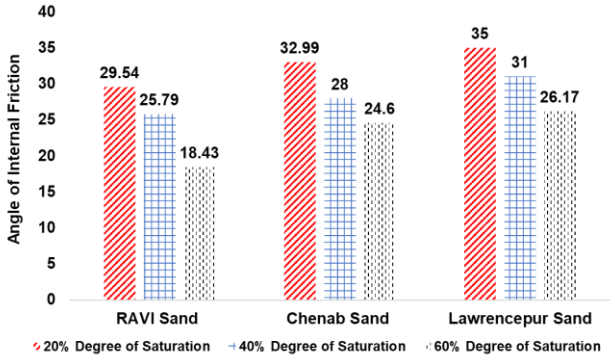


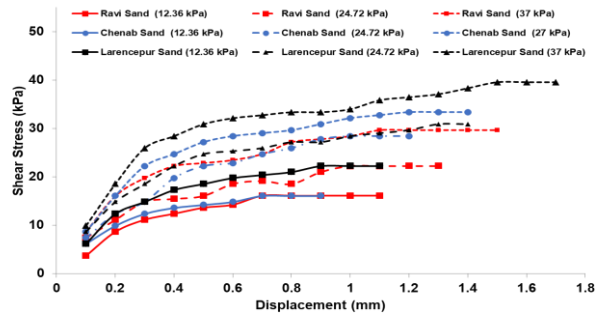
Fig. 11. Angle of Internal Friction of all Three Types of Soil by Varying Degrees of Saturation

The results showed an inverse relationship between frictional angle and saturation for all three locally available sandy soils. An increase in soil saturation results in a reduction of the frictional angle. The percentage of decline in the frictional angle of Ravi sand at 40% and 60% degrees of saturation was estimated to be 12.69% and 37.6 %, respectively. Furthermore, the percentage of drop in the frictional angle of Chenab sand at 40% and 60% degrees of saturation was assessed to be 15.12% and 25.43%, respectively, whereas the contraction of the frictional angle of Lawrencepur sand at 40% and 60% degrees of saturation was 11.42% and 25.22%, respectively.

The sandy soil is considered to be a drained material that exhibits high permeability compared to cohesionless soil. Due to the higher permeability, there is an ease in the flow of water through particles as compared to cohesionless soil, such as clay or silt. The increase in saturation results in higher moisture in the soil, which leads to higher flow between the soil particles. Due to this flow, the interlocking between the particles becomes weak, which causes a reduction in the frictional angle and shear strength of the soil. The abovementioned results are in agreement with the conclusions made in published research work [25].

3.5 Effect on Stress-Strain Response by Varying Degrees of Saturation

The correlation between shear stress and the corresponding deformation of all three locally available sands by considering variation in the saturation is presented in Fig. 12. The same three stress levels of 12.361 kPa, 230 24.721 kPa, and 37.109 kPa were considered, and the relationship between shear stress and deformation were graphically plotted for the same values of degree of saturation (i) 20%; (ii) 40% and; (iii) 60%.



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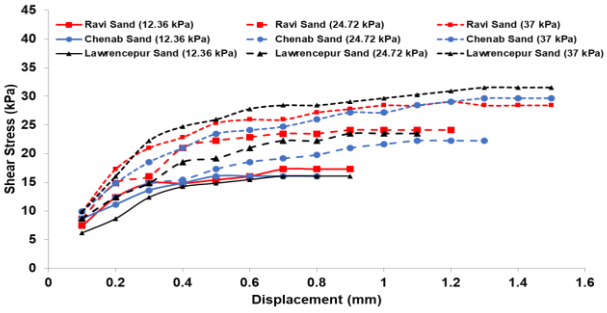

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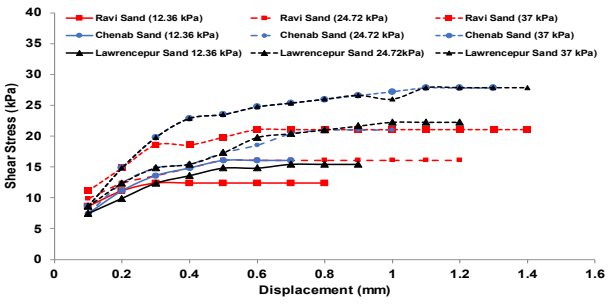

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Fig 12. Shear Stress-Displacement Curves with Varying Degree of Saturation (a) 20% Degree of Saturation (b) 40% Degree of Saturation (c) 60% Degree of Saturation.

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The results showed that at a maximum stress level of 37.093 kPa, the maximum resisting stress of Ravi, Chenab, and Lawrencepur sand was 31.0 kPa, 32.33 kPa, and 39.17 kPa, respectively, at 20% degree of saturation. The maximum resisting stress at 40% degrees of saturation was 30.38kPa, 29.50kPa, and 32.0kPa, respectively, for Ravi, Chenab, and Lawrencepur sand. Furthermore, at a 60% degree of saturation, the maximum resisting shear stress of 20.5kPa, 27.33kPa, and 27.17kPa were observed for Ravi, Chenab, and Lawrencepur sand, respectively. The summary of obtained maximum resisting shear stress obtained at all stress levels for the three locally available sands is summarised in Table 4.

An analysis of shear stress and deformation plots of all three locally available sands led to a thought-provoking observation that the maximum value of resisting shear stress decreased with enhancement in saturation for all three locally available sands. By comparing the resisting shear stress of the three locally available sands, the results highlighted that Lawrencepur sand contained higher shear stress capacity compared to other types of locally available sands because of higher density and uniform gradation. The abovementioned results are consistent with the results reported in an already published research study[25].

Table 4

Summary of Resisting Shear Stress by Varying Degrees of Saturation

Sand Type	Stress Levels (kPa)	Resisting Shear Stress at 20% Degree of Saturation	Resisting Shear Stress at 40% Degree of Saturation	Resisting Shear Stress at 60% Degree of Saturation
Ravi Sand	12.361	16.33	17.00	11.83
	24.721	19.50	23.60	16.00
	37.109	31.00	30.38	20.50
Chenab Sand	12.361	16.33	16.34	16.00
	24.721	27.66	23.00	21.00
	37.109	32.33	29.50	27.33
Lawrencepur Sand	12.361	22.00	15.83	15.00
	24.721	31.50	23.40	21.66
	37.109	39.17	32.00	27.19

The present study provided a complete picture of the index and shear strength characteristics of the three main locally available sandy soils, i.e., (i) Ravi sand; (ii) Chenab sand; and (iii) Lawrencepur sand, in Pakistan. The shear-resisting capacity of sandy soil was primarily governed by the frictional angle. Since Pakistan lies in semi-arid regions where the soil moisture content changes as per season in one calendar year, therefore, it is vital to understand the effect of moisture on the frictional angle of the three locally available sandy soils.

The results highlighted that an increase in the moisture content of the sandy soil resulted in a decrease in the shear resisting capacity of all three types of soil, mainly because of an alteration in the overall structure of the soil, which led to reductions in friction in the particles. Similar observations were recorded while examining the impact of soil saturation on the frictional angle in the present study. The results of the present study provided insight and useful information for practice engineers in Pakistan, as the engineers have to deal with one of the locally available sandy soils during their professional careers. In most cases, one of these sandy soils will be used for construction activities in the country.

4. Conclusion

This study provided a comprehensive analysis of the mechanical behaviour of three types of locally available sandy soils in Pakistan—Ravi, Chenab, and Lawrencepur sand—, extensively used in the construction industry, under varying moisture content and degrees of saturation. The following conclusions are drawn from the present study:

- Corresponding to the Index properties, Ravi and Chenab sand were classified as poorly graded soil, while Lawrencepur sand was classified as well-graded soil.
- The results concluded that maximum dry density and the minimum void ratio of Lawrencepur sand, representing a dense and firm structure as compared to other two types of sands.
- Noteworthy reductions in shear strength characteristics are concluded when the soil moisture deviates from OMC for all three sandy soil particularly in Lawrencepur which showed maximum shear strength characteristics.
- The results highlighted better strength characteristics and lower reduction in angle of internal friction with an increase in soil saturation as compared other two types of sands

The outcomes of the study in hand accentuate the fact the soil moisture dynamics have significant impact on the shear strength characteristics of the sandy soil. The study also reinforces the need for detailed soil testing and analysis to ensure the safe and cost-effective use of local materials in the construction industry.

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