Residual Shear Strength and Other Geotechnical Properties of Clay Mixed with Different Sand Ratios

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ABSTRACT

The current research investigates the residual shear strength of clay soils to which different percentages (5, 10, 15, and 20%) of sand are added, playing a pivotal role in determining the stability of steep slopes on these soils. The residual shear strength was compared with the shear strength calculated from the direct shear test and the unconfined compression strength test. According to the results, the clay soil's swelling ranged from medium to high, and its engineering characteristics were similar to that of all clay soils found in most sloped areas and hills in Mosul city. Also, a notable reduction was observed in the plasticity index with an increase in the sand percentage. In the residual shear test, a rise in shear coefficients (effective angle of internal friction (Φ') and cohesion(c')) was demonstrated with an increase in the percentage of sand addition up to a certain limit (15%), which is the same percentage that gave values for (c and Φ) in the direct shear test.

Keywords-slope stability; residual shear strength; clay soil; sand

I. INTRODUCTION

The drained residual strength of fine (cohesive) soils has been broadly investigated during the last 40 years. Various connections have been detected between the residual friction angle and index properties [1]. Slope failure is one of the geotechnical engineering problems induced by a rise in the groundwater table, long or heavy rain, and water leakage as a result of human intervention, causing slope saturation [2]. The residual strength of the soil is one of the most significant strength factors in assessing the stability of reactivated landslide slops [3]. It has been also used as an indicator to obtain the interface shear strength between the clay and geo-synthetic clay liners, utilized in the design and construction of municipal solid waste landfills [4].

The draining multiple reversal direct shear test or draining ring shear test are the most popular methods for estimating the drained residual shear strength of particular clayey soil types, such as stiff clays, shale, and mudstones [5]. The primary benefit of the residual shear test is that the specimen in the torsional ring shear apparatus is sheared in a single direction for any displacement magnitude. The torsional ring shear test results in the creation of a residual strength condition and a shear direction, with clay particles being reoriented parallel to it. One additional benefit of the ring shear apparatus is that it measures the shear surface's constant cross-sectional area during shear [6].

Generally, analyzing and solving soil stability problems, involving the bearing capacity of different types of foundations, retaining walls, dams, and embankment stability, depends on a vital for the geotechnical soil properties parameter, the shear strength [7]. Many researchers have studied the residual shear strength and have concluded that it is influenced by the shear displacement rate [3, 8]. In [9], it was reported that the residual stage is achieved by shear displacement with a high shear rate, larger than that of the low shear rate in the ring shear test. Authors in [10] claimed that the increase in clay content, especially the montmorillonite mineral, decreases the residual shear strength.

In [11], the effect of soil mineralogical composition on the soil residual shear strength was examined. Authors in [6] stated that the residual shear strength should only be defined by a residual friction angle, consisting of the frictional resistance of the face-to-face contacts of the oriented particles. In [5], it was discovered that the slip surface reaches the residual condition when the clay particles' shapes become to the greatest extent feasible, face-to-face, and parallel to the shearing direction under the working effective normal stress. Authors in [12] studied the shear strength characteristics at low effective normal stresses, with a range between 3 and 6 kPa. The loading assembly, shear measurement devices, and specimen container are some of the specific components of the residual test equipment that the authors modified for this purpose. The study's findings demonstrated that the soil's secant residual friction angle and interface residual friction angle decreased with an increasing liquid limit and clay-size fraction. Furthermore, in the zone of low effective normal stresses, the liquid limit, which indicates the clay particle type and shape, had a greater impact on the measured residual friction angle than the clay-size fraction, which is supposed to be a sign of the particle size and soil shearing mode. Authors in [13] considered the residual strength of 21 clay sets with different plasticity indexes in 10 different consolidation conditions. The effects of some important properties, like over-consolidation ratio, plasticity index, shear rate, and multi-stage shear mode, in the residual strength were investigated. The results showed that the shear rate and Over-Consolidation Ratio (OCR) have an insignificant effect on the residual strength. Also, the residual strength gradually decreases as the plasticity index of soils increases and under large deformation, the internal friction angle of drained clay decreases as the plasticity index increases. In contrast, authors in [14] specified that the OCR affects the shear strength of remolded clay specimens. The findings, especially those connected with the relation of the plasticity index and residual strength, are consistent with those in [15], where the influence of clay fractions and the addition of coarse sand on the behavior of residual shear strength of laterite soil was examined. The results revealed that increasing the percentages of low-plasticity clay and/or coarse sand increased internal friction angle and cohesion.

Sand improves the shear characteristics of highly problematic soil, like marl soil [16]. Authors in [17] stated that the shear strength of soil is greatly influenced by the shape of the sand, hence the angular grains provide greater soil interlock and shear resistance. Additionally, the shear resistance is impacted by the gradation and size of the sand. Using specialized equipment, authors in [18] examined the impact of temperature on residual shear strength and discovered that low-range temperature variations might be regarded as insignificant in terms of the residual shear strength parameters. In [19], the residual shear strength of natural sand and sand stabilized with fly ash were compared and it was found that shear strength rose with fly ash content and curing time at both the peak and residual states, but it decreased with soil saturation. Authors in [20] examined the residual shear strength of granulite residual soil and found the shear properties of the granulite by conducting both direct shear and ring shear tests.

Although interesting results were derived from the aforementioned studies, to the best of our knowledge, no work has examined the residual shear strength of clay mixed with different sand ratios. To fill this gap, the current study explores the residual shear strength of clay soils after varying sand additions to boost the residual shear strength.

Most of the lands of Mosul city are clay soils, which are undulating in nature and characterized by many slopes. The city is undergoing significant urban growth, with many structures having been built on sloping areas and deep excavations. Therefore, studying the shear properties, especially the residual parameters of clay soils is of vital importance.

II. MATERIALS

Brown high plasticity clayey soil (CH) was used for this investigation [21]. The clay was from a certain neighborhood in Mosul City (Al-Kafaat). The city's structural works frequently used sand soil, which was carried in from Mosul's river quarries as an addition. The chosen percentages of the sand used in the current study are the most common proportions naturally present in the clay soils of Mosul. Poorly graded sand (SP) is utilized in this study [21]. Table I presents the results of measuring and evaluating the clayey soil's and sand' properties.

TABLE I. NATURAL CLAY AND ADDITIVE SAND PROPERTIES

Soil properties		Soil type: Clayey soil	Soil type: Sandy soil
Specific gravity, Gs		2.7	2.66
Atterberg limits	Liquid limit, LL (%)	55	---
	Plastic limit, PL (%)	30	---
	Plasticity index (%)	25	Non. plastic
Grain size analysis	Sand (%)	5	100
	Silt (%)	43	0
	Clay (%)	52	0
Classification	Unified soil classification system (USCC)	CH	SP
	AASHTO	A-7-6(28)	A-3(0)

III. METHODOLOGY

A. Specimen Preparation

The clayey soil and sand utilized for the tests were oven-dried, cleaned, and passed the specified sieve for each test. For the direct shear test, sieve No.10 (2 mm) was used. The design mixtures consist of four percentages of sand (5%, 10%, 15%, and 20%) mixed with clayey soil by dry weight of the entire specimen, respectively, and compared with 0% sand (natural clay). A predetermined suitable volume of water was added to the dry mixtures for the compaction test. The specimens were prepared in suitable laboratory conditions.

B. Atterberg Limit Tests

The Atterberg limit tests were performed using a No. 40 (0.425 mm) sieve on the clayey soil and sand. All clayey soil and clayey soil-sand combinations were tested in accordance with [22].

C. Compaction Test and Apparatus

The modified Proctor compaction technique was applied to ascertain the compaction parameters of the clay and clay-sand mixes, which are their maximum dry density and optimum moisture content. An equal amount of sand and clayey soil in equal measure passed through sieve No. 4 (4.75 mm). Mixtures containing five or six distinct appropriate ranges of water contents were made. The produced mixture was compressed into the compaction mold in five layers using a (10 lb.) hummer with 55 blows for each layer. The specimens' surface was removed to guarantee leveling [23]. Following compaction, in each mixture, the maximum dry density and optimum moisture content were ascertained in accordance with [24].

D. Direct Shear Test and Apparatus

The sandy and clayey soil mixtures were run through sieve No. 10 (2 mm) in order to get them ready for the direct shear test. The samples were compacted into direct shear mold samples with square 60 mm dimensions and 20 mm thickness (H). The specimens were compacted statically at a fixed pace of 0.05 inch/min, or 0.02 mm/sec. Direct shear samples were made using the specific maximum dry density and optimum moisture content that was determined from the compaction curves of clayey soil and clayey soil-sand mixes. The test specimens were carried to direct shear cells statically at the same constant rate of 0.02 mm/sec or 0.05 inch/min. The tests were conducted based on the requirements presented in [25] for the combined drain category of direct shear tests. The relations between the shear and normal stress were drawn for clayey soil and clayey-sand mixes in order to obtain the direct shear test parameters (effective angle of internal friction (Φ') and cohesiveness (c')). For each specimen, the effective angle Φ' was found from the best-fit line between the three locations, while c' was found at the y-axis intercept.

E. Unconfined Compressive Strength Test

The Unconfined Compressive Strength (UCS) test was performed using the same blends at the optimum water content for all specimens. The size of the clayey soil and sand utilized in the UCS test passed sieve No. 4 (4.75 mm) according to the specifications in [26].

F. Residual Shear Strength

The tests were performed according to the specifications in [27], aiming to obtain the values of the residual shear strength, represented by the effective angle of internal friction Φ', for the clayey soil and clayey soil-sand mixtures and compare them with those obtained by the direct shear test. For this purpose, the consolidated drain type of residual shear strength was used and the same normal stresses were applied. The natural soil specimen was prepared by mixing the dry clay with water to a certain liquid limit. The dry clay and sand additive mixtures were mixed with water content equal to the specific liquid limit for each mix.

IV. RESULTS AND DISCUSSION

The addition of four percentages of fine sand (5, 10, 15, and 20%) to clay soil was carried out to investigate the effect on the clay residual strength, represented by Φ' values and other geotechnical tests (compaction, unconfined compression, direct shear). The results are shown in Table II.

TABLE II. TEST RESULTS

Test	**Parameters**	**Sand percentage (%)**				
		0 (natural clay)	5	10	15	20
Atterbeρg limit	Liquid limit (w/c%)	55	50	44.5	46	44.3
	Plastic limit (w/c%)	30	30	26.5	25	23.2
	Plasticity index (w/c%)	25	20	18	21	21.1
U.S.C.S	Group symbol	CH	CH	CL	CL	CL
Compaction	Max. dry density (γ) (kN/m^3)	16.99	17.45	18.85	17.32	17.73
	Optimum water content (w/c%)	18.5	19.2	16.9	17.7	16.5
Unconfined compression	Stress (qu) (kN/m^2)	77.2	100	92.1	84.8	100.5
	Optimum water content (w/c%)	15.5	15.0	16.8	17.5	14.3
Direct shear	Cohesion (C) (kN/m^2)	6.1	13.5	40	83.5	33.5
	Eff. internal friction angle (Φ')	29	25	26.5	31.5	30
Residual Shear Strength	Eff. Internal friction angle (Φ')	15.4	18.7	18.3	19.9	25.1

The results of Atterberg limits (consistency limits) of natural clay and clayey soil-sand mixtures, demonstrate a general decrease in all limits, especially in liquid limits and plasticity index with increasing sand percentage as a result of adding non-plastic material to clayey soil, as illustrated in Table II and Figure 1. The decreasing plasticity index leads to changes in the behavior of natural clay. It acts as low-plasticity clay in the unified soil classification system which indicates some improvement in the geotechnical properties of clay.

The compaction test results, depicted in Table II, reveal that the maximum dry density increases and the optimum moisture content decreases at low sand percentages like 5 and 10%. When the sand percentages increase up to 15 and 20%, the maximum dry density begins to decrease, as can be seen in Figures 2 and 3.

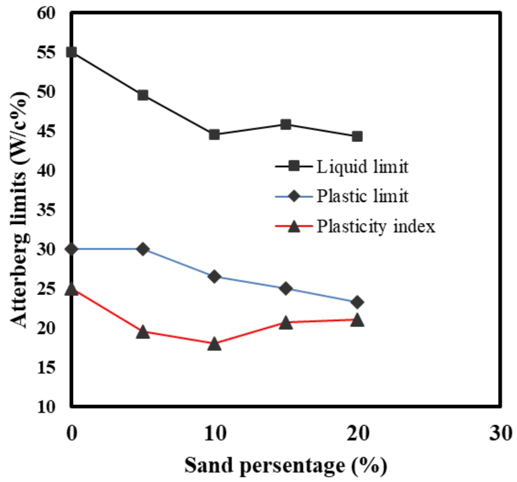

Fig. 1. Variation of Atterberg limits with sand addition.

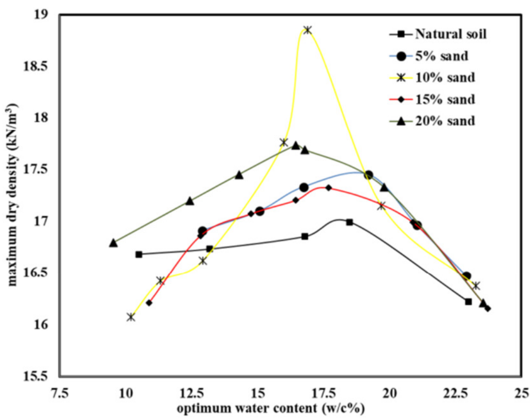

Fig. 2. Compaction characteristics of natural clay and clayey soil-sand mixtures.

This behavior can be explained from the fact that for the low sand addition, the sand particles in the soil-sand mixture are full of void spaces. After that, when the sand percentage increases, it starts creating segregation in the mix, which decreases its maximum dry density. Also, the addition of sand imparted a continuous reduction in the general trend of the optimum moisture content because of the sand's coarse-grained nature [28].

The UCS test results, listed in Table II, showed a variable increase in the unconfined compression values when the percentage of sand was increased, as evidenced in Figures 4 and 5. Some researchers indicated that the sand can improve the UCS up to specific (optimum) sand contents [28].

The findings of the direct shear test for the effective cohesion c' and effective angle of internal friction Φ', displayed in Table II, demonstrate that a 15% sand addition yields the greatest values of c' and Φ', with minor changes observed, particularly in Φ', as portrayed in Figures 6 and 7. The nature of the direct shear test is one of the probable reasons for these results. A predefined plane of failure is present in the test in the middle of the soil sample. The strength characteristics of soil, Φ' and c', will be affected by the concentration of sand particles in the plane of failure. The shearing mechanism in the direct shear equipment has a major role in providing a plausible explanation for these findings. The type of particle fluctuation in the predetermined plane of failure in the direct shear test will affect the results [29-31].

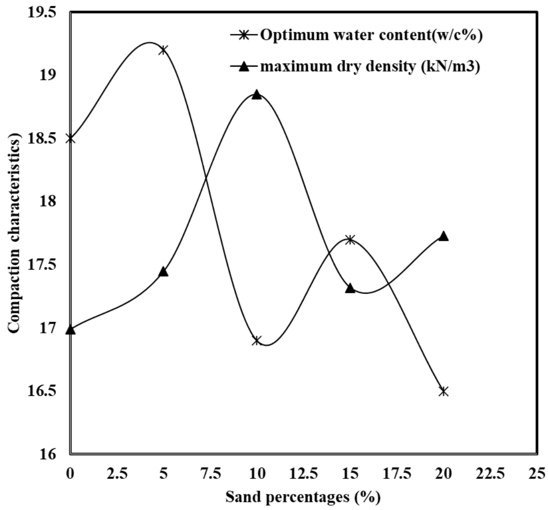

Fig. 3. Variation of compaction characteristics with sand addition.

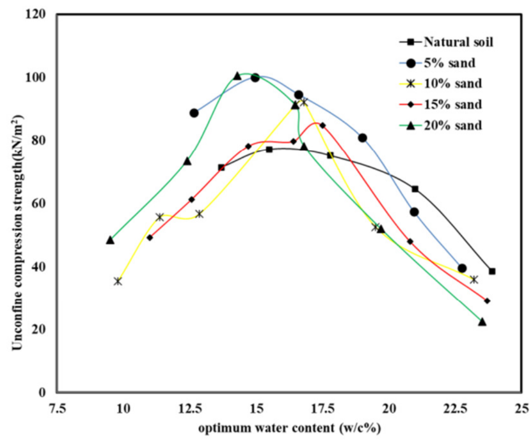

Fig. 4. UCS of natural clay and clayey soil-sand mixtures.

The quantity of sand particles concentrated in the middle plan of the soil sample, which is the predetermined plane of failure in the direct shear test, will change, almost increasing the strength parameters of soil, Φ' and c'. The results for the residual shear strength, which are represented by the residual internal friction angle Φ', as illustrated in Table II, indicate a notable increase in the Φ' values with increasing the sand content. The values of Φ' are less than the one from the direct shear test, as shown in Figure 8. The increasing roughness in the pre-sheared plane of the residual shear test caused an increase in the residual internal friction angle Φ'. The general trend of improving clayey soil by sand addition has been confirmed by many researchers [29-31].

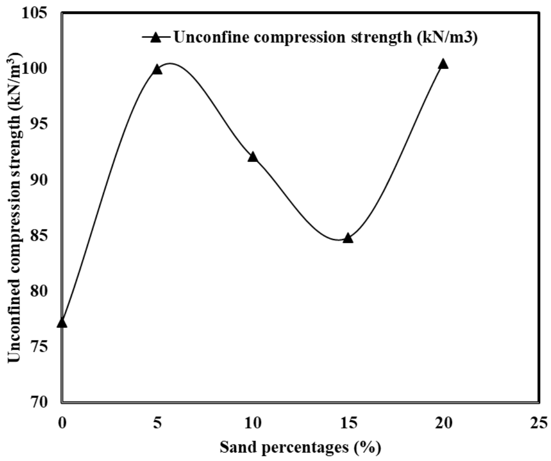

Fig. 5. Variation of compaction characteristics with sand addition.

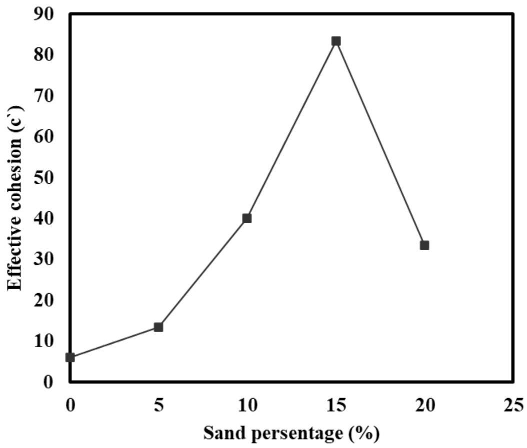

Fig. 6. Variation of effective cohesion with sand addition.

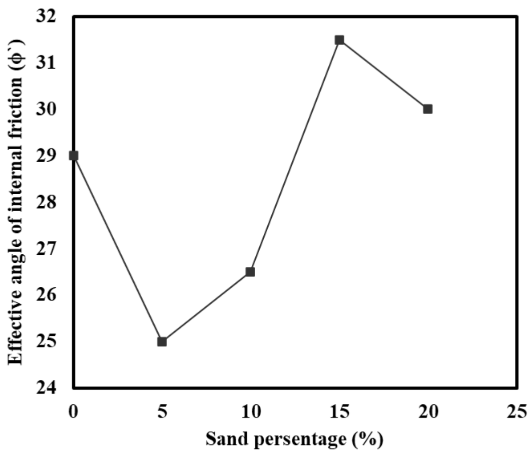

Fig. 7. Variation of effective internal friction angle with sand addition in the direct shear test.

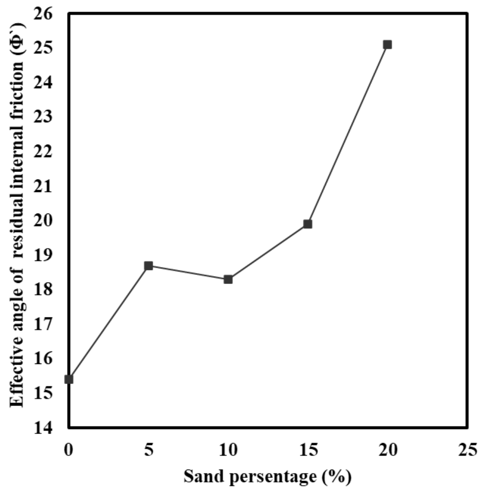

Fig. 8. Variation of residual effective internal friction angle with sand addition in residual shear test.

V. CONCLUSION

In this paper, addition of sand in percentages of 5, 10, 15, and 20% in clayey soil was carried out to investigate the residual shear strength and other geotechnical properties, such as Atterberg limits, compaction characteristics, unconfined compression, and direct shear test, of the Mosul city clayey soils. This study can be considered the first attempt to address the residual shear strength of clayey soil, specifically in the city of Mosul. From the testing process, the following conclusions were drawn:

- Increasing the sand addition to high-plasticity soil decreases the liquid limit and reduces the plasticity index.
- The addition of sand to clayey soil increases the maximum dry density to a certain point, after which the maximum dry density starts to decrease with an increasing sand addition.
- The results of the Unconfined Compressive Strength (UCS) test followed a pattern almost similar to the effect of sand addition on the compaction properties of clay soil.
- The direct shear test results showed a general increase in the effective cohesion value (c'), especially at the sample with a sand addition of 15%. That offset by a discrepancy in the results of the effective internal friction angle (Φ'). It can be concluded that 15% of the added sand provided a clear optimization.
- The results of the residual shear test, represented by the effective residual internal friction angle, exhibited a notable increase in the angle value when the added sand percentage increased.
- Increasing the proportions of sand in the clay soils, which exist in slope areas in Mosul city, gives values for the effective angle of internal friction close to their normal values (from direct shear testing), and this, in turn, increases the bearing capacity of the soil.

The findings of this study demonstrated that further research is needed to determine the addition of many materials, such as cement, lime, and asphalt, to the residual shear strength of clay soil. Also, the residual shear strength of different Mosul soil types, like gypseous, organic, and fill, needs to be investigated.

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