Research Article

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Effect of surface roughness on the interface behavior of clayey soils

https://doi.org/10.1515/eng-2022-0578
received November 08, 2023; accepted December 22, 2023

Abstract: This study investigates the effect of surface roughness on the interface behavior between clayey soils and structural materials, aiming to determine the necessary parameters for soil-structural interaction. The research site, located in one of Iraq's seismically active regions, was selected for its significance. Experimental measurements were conducted using the SRT-6210 Digital Surface Roughness Tester to assess the roughness characteristics of steel and concrete samples. Four distinct roughness parameters were measured, and their correlation with shear parameters was analyzed. The shear behavior of clay-steel and clay-concrete interfaces was successfully described using the average roughness parameter (Ra), which exhibited the strongest correlation with shear parameters. Direct shear box and interface shear box tests were employed to identify soil's shear strength parameters and evaluate interface shear strength parameters. The experimental findings highlight the significant influence of surface roughness on the shear strength parameters of clay-steel and clay-concrete interfaces. The interface shear strength, friction angle, and adhesion exhibited an increasing trend with roughness. Notably, shear strength increased by approximately 29.76% when concrete sample roughness was below 20 μm and by 32.8% when steel sample roughness was below 30 μm. Moreover, increasing surface roughness improved the interface friction angle of clay-steel and clay-concrete samples by about 37.95 and 36.3%, respectively. Additionally, an increase in roughness led to a rise in the adhesion of concrete and steel samples by approximately 26.24 and 32%, respectively. These findings emphasize the significance of surface roughness in optimizing the interface behavior between clayey soils and structural materials. The results have important implications for enhancing the design and performance of soil-structural systems.

Keywords: adhesion, angle of internal friction, shear strength, surface roughness

1 Introduction

Understanding the behavior of interfaces between clayey soils and structural materials, such as steel or concrete, is crucial for optimizing the design and performance of soil structural systems. Surface roughness is a crucial factor in determining interface characteristics, including friction angles and shear behavior. Several studies have been carried out to explore the relationship between roughness parameters, interface friction angles, and shear behavior at the interface.

Ward provided a comprehensive summary of 23 international standard roughness measurements tailored to specific applications. These standardized measurements have facilitated the characterization of soil-steel interfaces and contributed to the development of normalized roughness analysis and surface topography calculations [1]. Uesugi and Kishida conducted laboratory tests to examine the frictional resistance between mild steel and dry sand. They introduced the concept of normalized roughness to assess the relative roughness of the sand-steel interface, which showed a strong correlation with the coefficient of friction at yield [2]. Studies have also explored the behavior of soil-structural interfaces under various conditions. Uesugi and Kishida observed sliding at the sand-steel interface prior to the peak in frictional resistance and demonstrated the influence of particle displacement on the friction test results [3]. Gadelmawla et al. provided definitions and mathematical formulas for multiple roughness parameters, enabling the calculation of 3D surface topography [4]. Researchers investigated the friction angles between soil and wall materials in direct shear tests, revealing variations depending on the contact surface roughness [5,6]. The mechanical behavior and shear strength of soil must be determined by different

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ways such as the statistical variation and the correlation models which were studied by Mohammed and Mahmood for gypsum rock soil [7].

The behavior of interfaces between Ottawa sand and steel samples with different roughness levels was examined by Alyounis and Desai [8], who found that higher surface roughness mobilized higher peak strength. Wang et al. investigated the influence of grouting volume on the shear characteristics of cohesive soil–concrete interfaces, observing an increase in interfacial apparent cohesion with higher grouting volume and roughness [9]. Li et al. studied the effects of soil water content, interface roughness, and normal stress on the shear mechanical behavior of silt–steel interfaces, revealing higher shear strength for rough interfaces compared to direct shear tests on silt [10]. However, previous studies have not adequately explored the effects of surface roughness on interface behavior under challenging conditions.

In this study, we focus on evaluating the surface roughness and its impact on the behavior of interfaces between clayey soils and steel or concrete. The selected research site, located in a seismically active region in Iraq [11,12], provides a relevant setting to investigate the interface behavior under challenging conditions. Experimental testing will measure the roughness characteristics of steel and concrete samples using the SRT-6210 Digital Surface Roughness Tester. Shear strength parameters will be determined through direct shear box tests and interface shear box tests. The results of this study will contribute to a better understanding of the interface behavior between clayey soils and structural materials and provide valuable insights for design and construction practices.

2 Materials and methods

2.1 Amplitude parameters of surface roughness

Surface topography, which represents the surface profile, is quantified as surface roughness. It has a significant influence on the behavior of interface shear in geologic materials. On the other side, roughness might promote adhesion. In the context of interface behavior, the following parameters are commonly used to describe interface roughness:

2.1.1 Average roughness (R_a)

The average absolute divergence from the mean line for a single sample length, as shown in (Figure 1) and equation (1),

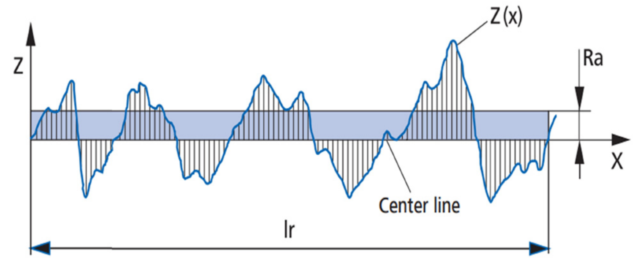


Figure 1: Average roughness (R_a) [4].

can be used to measure roughness irregularities. This parameter gives a good overview of the range of potential heights and is easy to define and measure [4].

$$R_a = \frac{\sum_{i=1}^{n} y_i}{n}, \tag{1}$$

where y_i is the height of each peak and n is the number of peaks.

2.1.2 Root mean square roughness (R_q)

The Root mean square roughness measures the standard deviation of the height of asperities above and below the reference plane, as described by equations (2) and (3). This parameter is more responsive to significant deviations from the mean line than the arithmetic average height (R_a) [4].

$$R_q = \sqrt{\frac{1}{l}\int_0^l \{y(x)\}^2 dx}, \tag{2}$$

or

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}, \tag{3}$$

where R_q is the root mean square roughness. $y_i = y(x)$ is the height of each peak. l is the length measured by the Digital Surface Roughness Tester. n is thenumber of peaks.

2.1.3 Maximum height of the profile (R_t or R_{max})

This parameter exhibits high sensitivity to high peaks or deep scratches. Rt is the vertical distance along the profile's assessment length between its highest peak and the lowest valley [4]. The parameter is depicted in Figure 2 and equation (4).

$$R_t = R_p + R_v = R_{p3} + R_{v4}, \tag{4}$$

where R_p is the maximum height of peaks. R_v is the maximum depth of valleys.

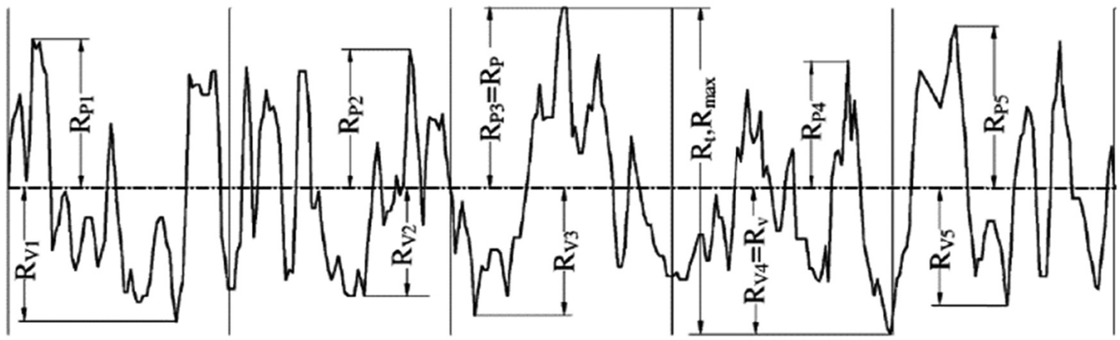


Figure 2: The diagram of the parameter, R_t (R_{max}) [4].

2.1.4 Ten-point height (Rz)

This parameter is more sensitive to occasional high peaks or deep valleys than R_a, which is shown in Figure 3. It is defined by the International ISO system (ISO 13565-1) as the difference in height between the average of the five highest peaks and the five lowest valleys along the assessment length of the profile. This measurement indicates the fluctuation in surface topography and helps quantify the extent of elevation changes within the profile [4].

$$R_{Z(ISO)} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i - \sum_{i=1}^{n} v_i\right), \tag{5}$$

where n is the total number of measurements taken along the length.

2.2 Interface testing devices

To study the interface behavior between clayey soil and structural members, which are usually made of concrete or steel, shear tests were carried out between soil and samples of steel and concrete with different roughness. Ten samples of steel and concrete samples were used in this study. Steel samples were sprayed with water regularly to corrode their surfaces until the desired roughness was attained. The smooth surface of concrete samples was attained using a smooth contact surface when casting. Jam paper of varied roughness was put on the cast surface for samples to get the necessary roughness for the remaining samples.

The roughness profiles of the steel and concrete were measured using Contact Profilometer Digital Surface Roughness Tester SRT-6210, as shown in Figure 4. The roughness profiles directly measured by the profilometer with a cutoff length of 2.5 mm. Table 1 summarizes the measured roughness parameters (R_a, R_z, R_q, and R_t) for the steel and concrete samples used in this study where

Figure 4: Digital Surface Roughness Tester SRT-6210.

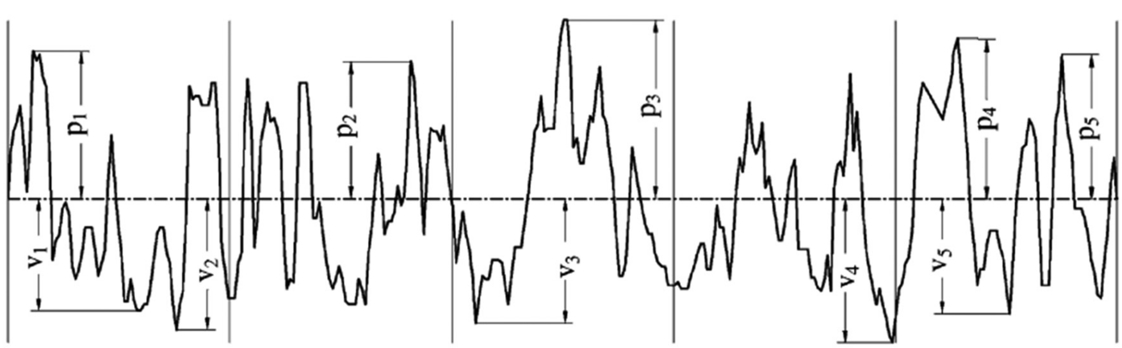


Figure 3: The diagram of the ten-point height parameter $R_{z(ISO)}$ [4].

Table 1: Measured roughness parameters (R_a, R_z, R_q, and R_t) for steel and concrete samples

Samples	R_a (μm)	R_z (μm)	R_q (μm)	R_t (μm)
Steel samples				
1	1.173	14.65	1.3	12.5
2	3.81	15	3.2	20
3	7.675	76	7	80
4	12.96	97	11	95
5	27.51	109	25.3	113
Concrete samples				
1	3.151	48	5.2	51
2	6.871	58	7.95	53.64
3	11.05	69.4	13.2	79
4	15.19	80.5	18.78	85
5	19.01	95	20.3	93

R_a is the average roughness parameter, R_z is the ten-point height, R_q is the Root mean square roughness, and R_t is the maximum height of the profile.

The steel and concrete sample surfaces are shown in Figures 5 and 6, respectively. The device is calibrated using a standard roughness glass piece shown in Figure 7 before starting the measurements.

2.3 Physical characterization of the soils

Soil properties in any location must be determined either by laboratory tests or by correlation between different physical and mechanical properties of soil [13,14]. The soil samples are classified according to the Unified soil Classification system as silty clay and sometimes with sand with low plasticity (CL). It presents a Liquid Limit of 45 and a Plastic Limit of 22. The soil has a dry unit weight of 17.3 kN/m^3, a bulk unit weight of 19.7 kN/m^3, and a natural moisture content of 14% [15].

2.3.1 Shear strength parameters of clay soil

Shear tests were used to calculate the shear strength of the clayey soil. The direct shear box test was conducted in the Geotechnical Engineering Laboratory at the University of Thi-Qar. The direct shear device is shown in Figure 8. The upper and lower shear boxes are square in cross-section with dimensions of 60 mm × 60 mm × 30 mm (length × width × height). The soil samples would be remolded at the natural moisture content (14%). During the test, each sample was subjected to three levels of normal stress: 5.45, 10.9, and 21.8 kPa. The horizontal displacement after applying normal loads on the hanger was measured. Results are given in Table 2 and (Figure 9). From the direct shear box test, the value of cohesion is 17.7 kPa, and the angle of internal friction is 21.8°.

2.3.2 Shear strength parameters of interfaces

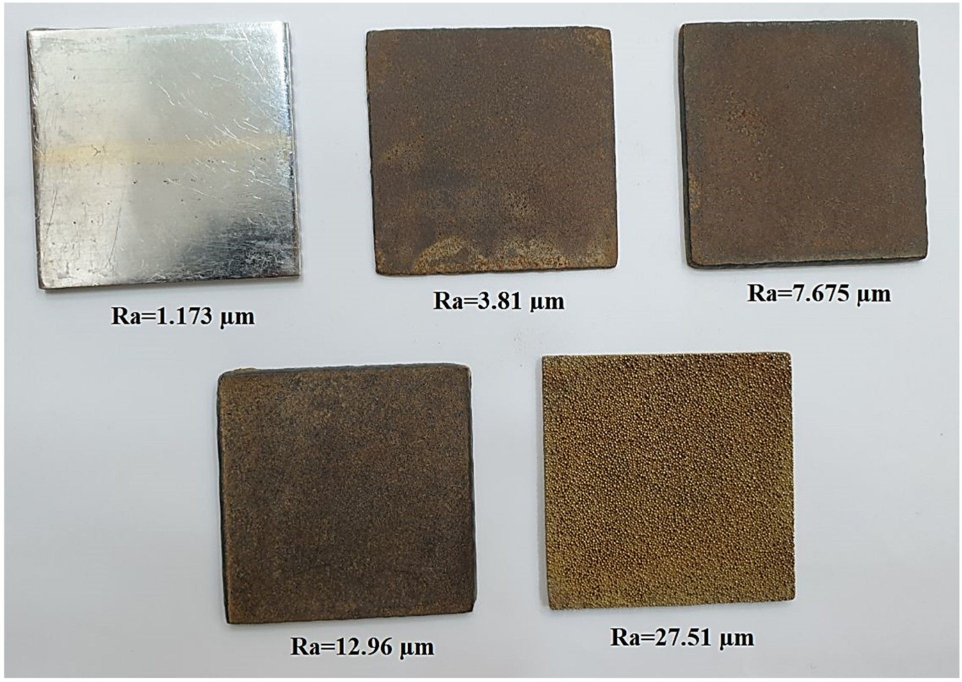
Ten shear box tests were carried out: five samples for the clay-steel interface and five for the clay-concrete interface. The main variable among the tests is the surface roughness of the structural material (steel or concrete). Steel (or concrete) sample was placed at the lower part of the shear box so that the upper half of the box would move freely over the lower half, and then the upper half of the box is filled with a soil, as shown in Figure 10. The peak shear stress vs the corresponding normal stress curves were plotted for each test to determine the interface shear parameters.

3 Results and discussion

3.1 Interface friction angle and interface adhesion

Figures 11 and 12 demonstrate the variation in adhesion (Ca) and interface friction angle (δ), respectively, with the roughness of concrete samples. Figures 13 and 14 show the variation in adhesion (Ca) and interface friction angle (δ) with the steel samples' roughness. Table 3 summarizes the correlation factor (r^2) values for different roughness parameters (R_a, R_z, R_q, and R_t) for clay-steel and clay-concrete interfaces. The average roughness parameter (R_a) is used in this study since it offers the best correlation; its fitting correlation coefficient ranges from 0.9577 to 0.9837 as shown in the figures. The data presented in Figures 11 and 13 demonstrate a positive correlation between roughness and interface adhesion. Specifically, an increase in roughness resulted in a corresponding increase in adhesion. Notably, the adhesion values for the concrete interface exhibited an overall increase of 26.24%, while the steel samples experienced a 32% increase in adhesion.

According to the data presented in Figures 12 and 14, it can be observed that the interface friction angle demonstrated an upward trend as the roughness increased. Specifically, the concrete–clay interface experienced a 36.3% increase, while the steel–clay interface exhibited a 37.95% increase. Simultaneously, when comparing the physical and mechanical parameters of the soil, it becomes evident



(a)

(b)

Figure 5: Roughness of the steel samples. (a) Steel samples in two dimensions and (b) steel samples in three dimensions.

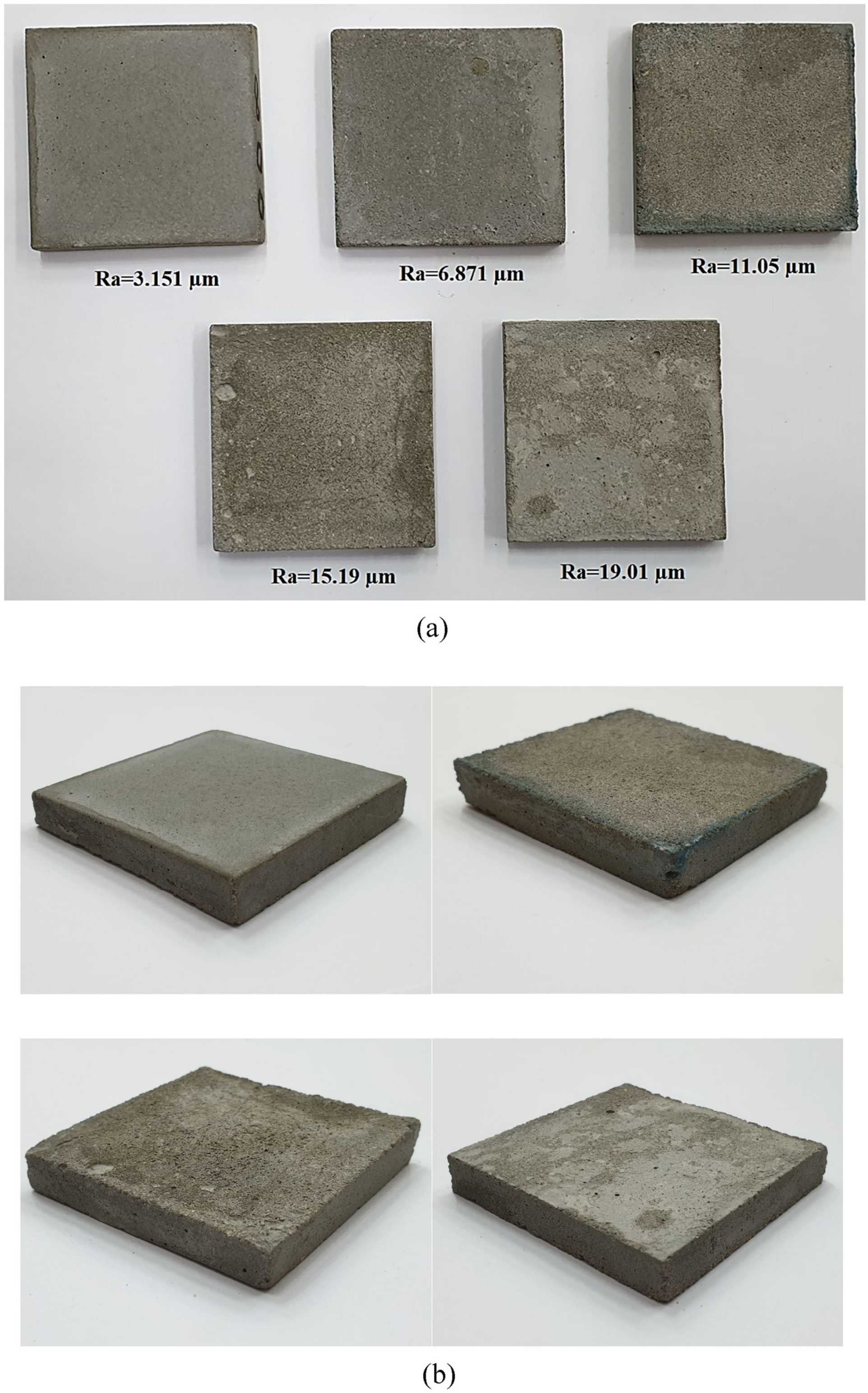


Figure 6: Roughness of the concrete samples. (a) Concrete samples in two dimensions and (b) Concrete samples in three dimensions.

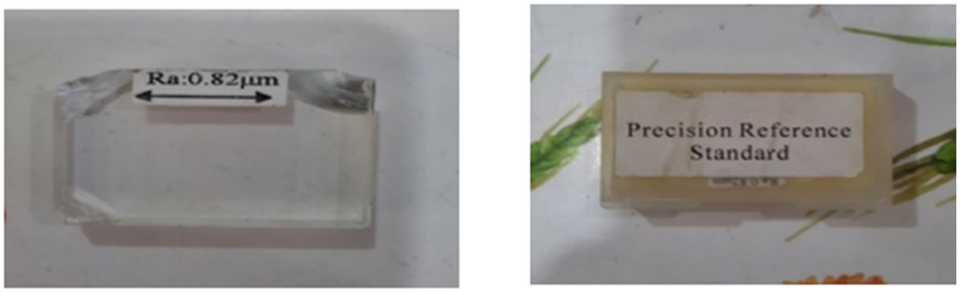


Figure 7: Precision reference standard.

Figure 8: Shear box test.

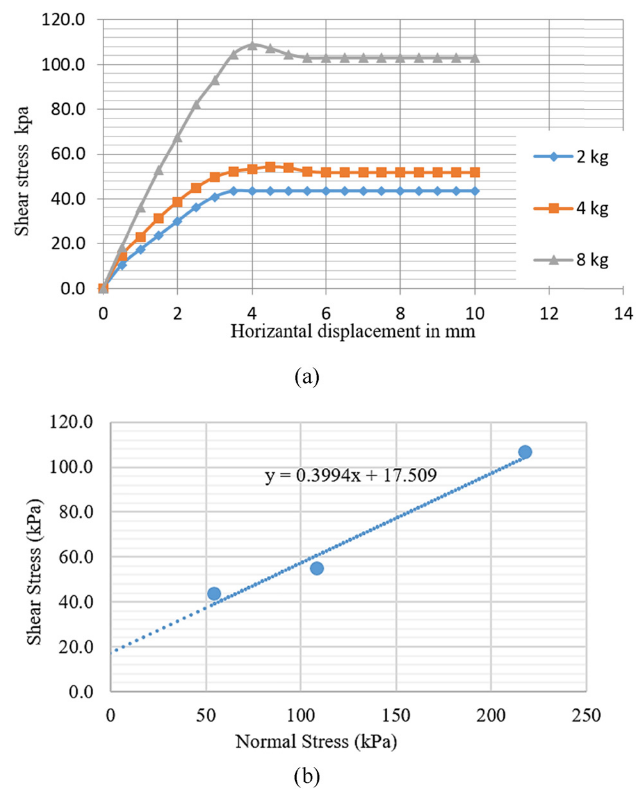


Figure 9: Direct shear box test for clayey soil: (a) shear stress vs horizontal displacement and (b) normal stress vs shear stress.

Table 2: Direct shear box test for clay soil

Shear stress τ_f (kPa)	Normal stress (kPa)
43.4	5.45
54.9	10.9
106.6	21.8

that both the interface adhesion and the interface friction angle have lower values compared with those observed in the soil.

3.2 Interface shear strength

Based on the obtained test results, it is possible to construct the shear strength variation curve for the steel–soil and concrete–soil interfaces with varying degrees of roughness, illustrated in Figures 15 and 16, respectively. It is evident that, under constant normal stress conditions, the shear strength exhibited an upward trend corresponding to an increase in roughness.

When the normal stress σ equals 21.8 kPa, the interface shear strength increases from 18.3 to 23.75 kPa as the roughness increases from 3.151 to 19.01 µm. This corresponded to a relative increase in 29.76% for concrete samples. Similarly, the interface shear strength for steel samples increased from 18.11 to 24.36 kPa as the roughness increased from 1.173 to 27.51 µm, resulting in a relative

Figure 10: Preparation of the soil sample (interface test).

increase of 32.8%. These findings suggest that the roughness of the clay–steel (or concrete) interface significantly impacts the shear strength.

Figures 17 and 18 depict the relation of shear strength and normal stress for concrete and steel samples, respectively, under the condition of equal roughness. It is obvious that under similar roughness conditions, the relationship involving shear strength with normal stress tends to be approximated as a linear progression. The frictional resistance observed at the interface between clay and concrete exhibited similarities to the shear strength of soil, as referred to by equation (6).

$$q_{\mathrm{u}} = \sigma \tan \delta + \mathrm{Ca}, \tag{6}$$

where q is the ultimate friction resistance at the construction material steel– or concrete–soil interface, σ is the normal stress at the interface, δ is the friction angle at the construction material–soil interface, and Ca is the adhesion factor of the construction material–soil interface.

4 Discussion

In the experimental setup aimed at investigating the impact of roughness, the interface's shear characteristics between silty clay and concrete or steel samples are primarily influenced by the roughness of the contact surface. The significance of this influence remains when the interface's normal stress and moisture content are kept constant, as stated by Chen et al. [16]. The shear strength of the interface consists of two main elements: adhesion and frictional resistance, both of which are caused by interface slip. The friction angle is a key factor influencing the level of frictional resistance. Cohesion, which represents the cementation and presence of a water film that connects soil particles on a macroscopic level, plays a vital role in the adhesion of fine soil particles. In this experimental study, the soil sample consists of clay soil, which exhibits substantial cohesion, thereby significantly contributing to its shear strength. The shear strength of the interface under varying roughness conditions ranges

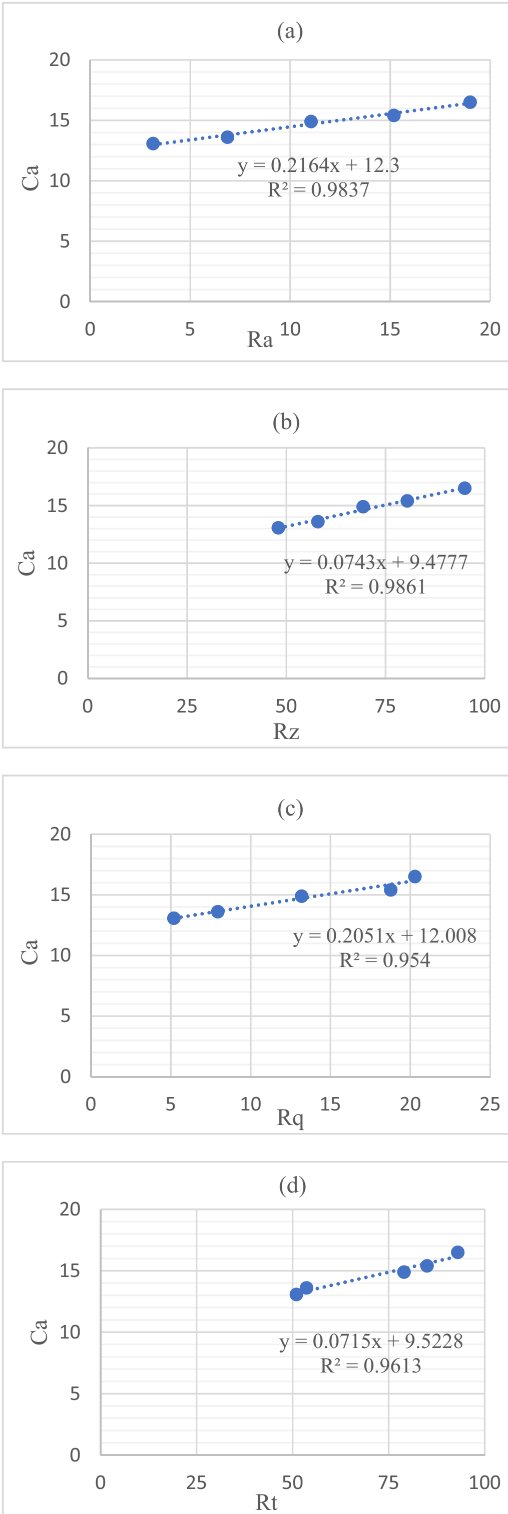


Figure 11: Variation in adhesion factor (Ca) with roughness parameters for clay–concrete interface. (a) R_a, (b) R_z, (c) R_q, and (d) R_t.

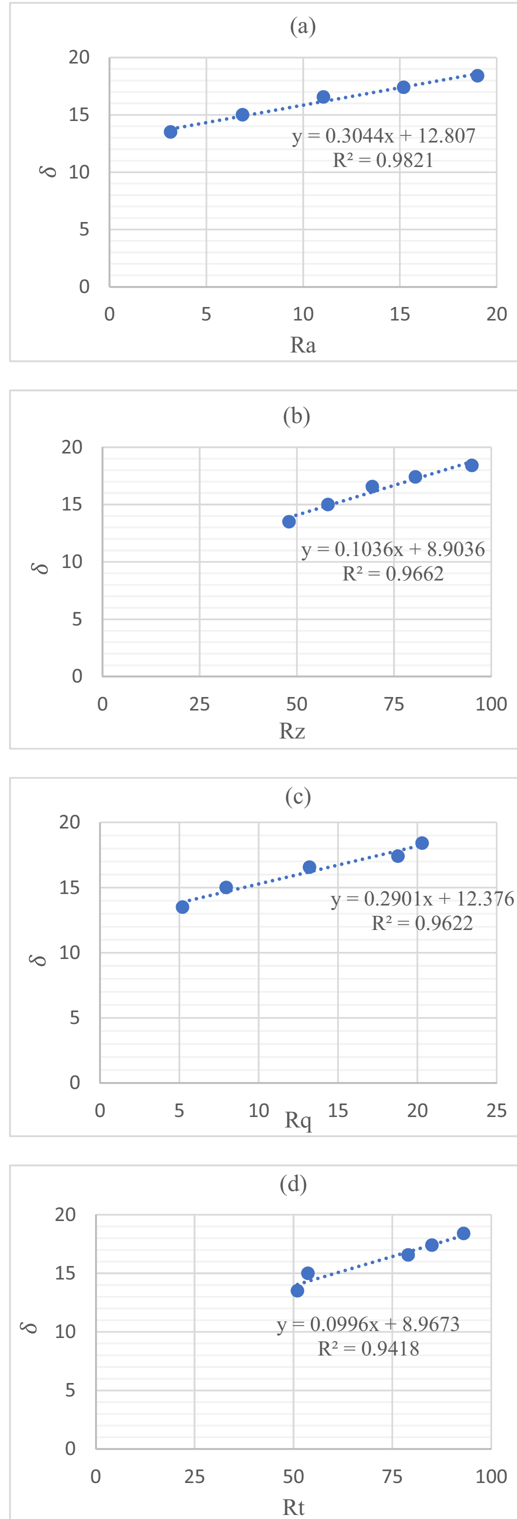


Figure 12: Variation in interface friction angle (δ) with roughness parameters for clay–concrete interface. (a) R_a, (b) R_z, (c) R_q, and (d) R_t.

from 18.3 to 23.75 kPa for concrete samples, while the interface adhesion ranges from 13.07 to 16.5 kPa.

Similarly, for steel samples, the shear strength of the interface ranges from 18.11 to 24.36 kPa, and the interface

Table 3: Correlation factor (r^2) for the relations between surface roughness parameters and interface parameters (δ and Ca)

Roughness	Steel samples		Concrete samples	
	δ	Ca	δ	Ca
Ra	0.9577	0.9621	0.9821	0.9837
Rz	0.8204	0.8136	0.9662	0.9861
Rq	0.9377	0.943	0.9622	0.954
Rt	0.8365	0.8307	0.9418	0.9613

adhesion ranges from 12.8 to 16.9 kPa. It was observed that the shear strength increased by approximately 29.76% when the roughness of concrete samples was below 20 µm and by 32.8% when the roughness of steel samples was below 30 µm. This illustrates that increased surface roughness promotes improved shear strength between soil and structural materials.

As the degree of roughness increases, there is a gradual reduction in the contact area between construction materials, such as steel or concrete, and the soil. Consequently, the ratio of frictional resistance gradually increases, leading to a corresponding enlargement of the influence of shear strength. The frictional resistance at the interface results from the frictional interaction between the soil particles and the surfaces of the concrete or steel specimens. When the roughness of the interface increases, it primarily affects the friction within the soil particles near the interface and the interface surface. Additionally, the frictional resistance is directly related to the friction angle. In other words, increasing surface roughness improved the interface friction angle of clay-steel and clay-concrete samples by about 37.95 and 36.3%, respectively. This suggests that higher surface roughness enhances the frictional resistance at the interface. Additionally, an increase in roughness increased the adhesion of concrete and steel samples by approximately 26.24 and 32%, respectively. This demonstrates that greater surface roughness promotes better adhesion between the soil and structural materials.

Several factors influence the shear properties of the interface between clay and either concrete or steel. Factors such as applied stresses, soil type, the qualities of the contact surface (whether it is concrete or steel), and the roughness of the contact surface interface have been identified as important considerations.

These findings underscore the significance of surface roughness in optimizing the interface behavior between clayey soils and structural materials. They provide important implications for enhancing the design and performance of soil structural systems, contributing to safer and more resilient structures in seismically active regions.

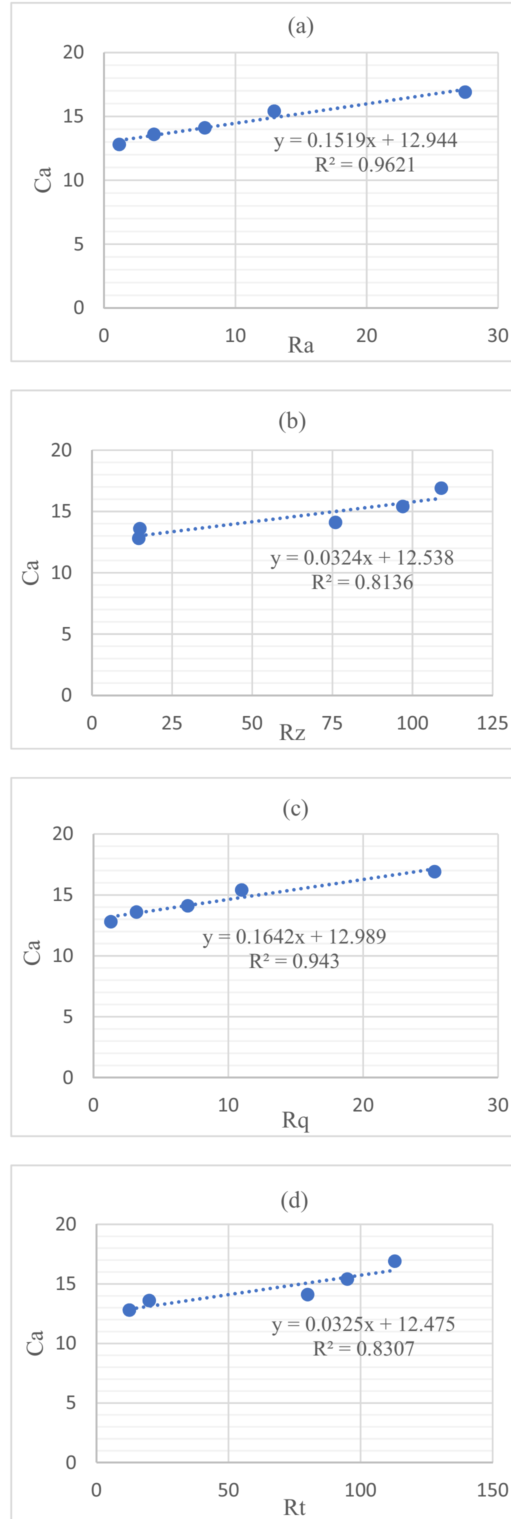


Figure 13: Variation in Adhesion factor (Ca) with roughness parameters for clay–steel interface. (a) R_a, (b) R_z, (c) R_q, and (d): R_t.

Moreover, the results align with the research conducted by Wang et al. [17]

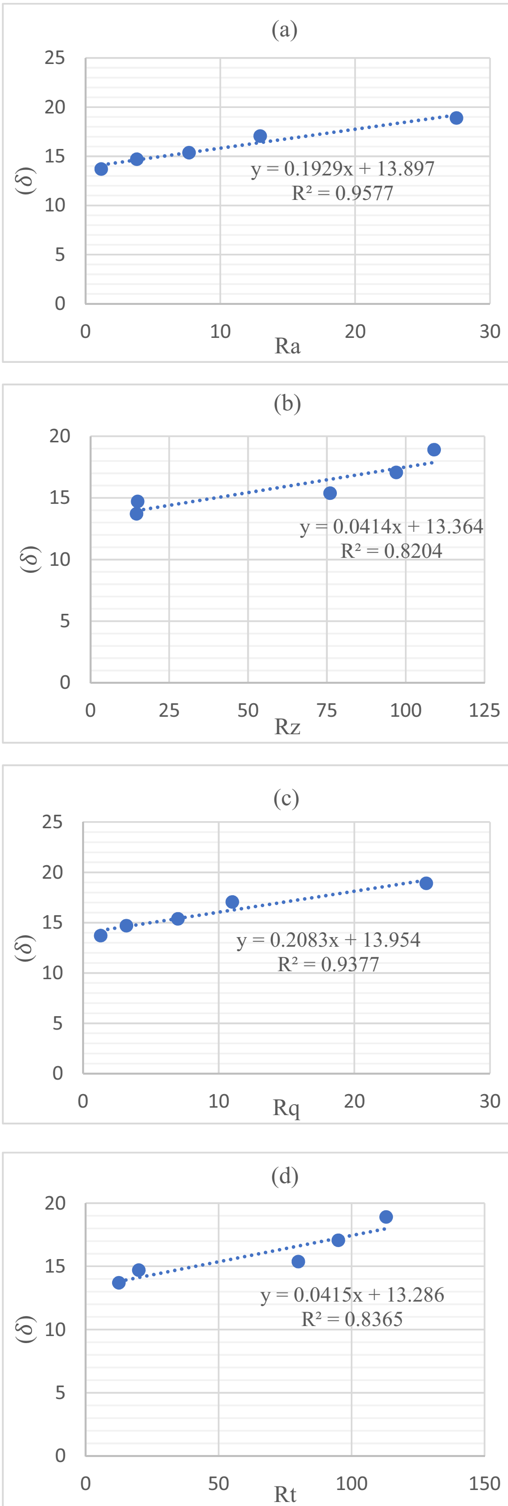


Figure 14: Variation in interface friction angle (δ) with roughness parameters for clay–steel interface. (a) R_a, (b) R_z, (c) R_q, and (d) R_t.

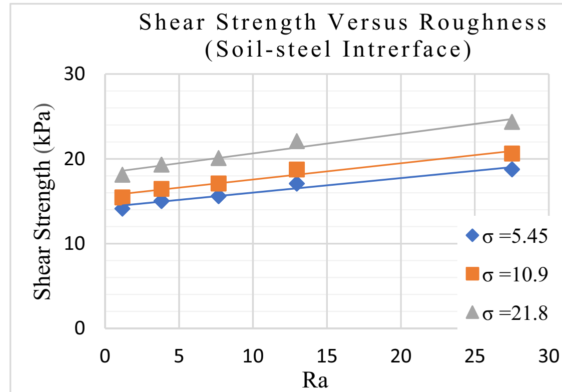


Figure 15: Relationship between shear strength of interface and roughness for steel samples.

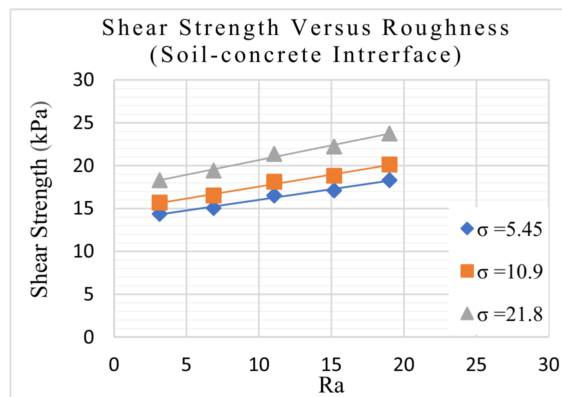


Figure 16: Relationship between shear strength of interface and roughness for concrete samples.

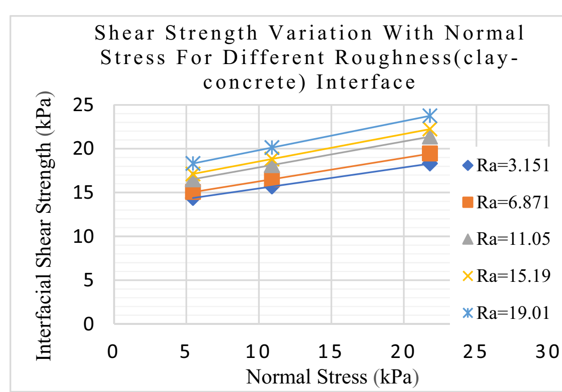


Figure 17: Variation in shear strength with normal stress for different roughness (clay–concrete interface).

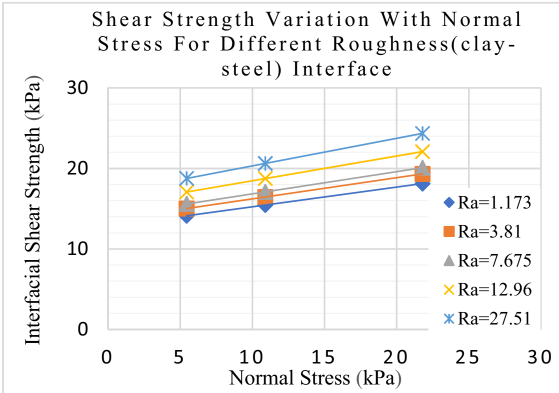


Figure 18: Variation in shear strength with normal stress for different roughness (clay–steel interface).

5 Conclusion

This study investigated the effect of surface roughness on the interface behavior between clayey soils and structural materials, aiming to determine the necessary parameters for soil structural interaction. The experimental measurements using the SRT-6210 Digital Surface Roughness Tester provided valuable insights into the roughness characteristics of steel and concrete samples. The correlation analysis revealed that the average roughness parameter (Ra) exhibited the strongest correlation with shear parameters, making it a significant factor in describing the shear behavior of clay–steel and clay–concrete interfaces.

The direct shear box and interface shear box tests effectively identified the shear strength parameters of the soil and evaluated the interface shear strength parameters, respectively. The experimental findings highlighted the significant influence of surface roughness on the shear strength parameters of clay–steel and clay–concrete interfaces. The shear strength increased by approximately 29.76% when the concrete sample roughness was below 20 µm and 32.8% when the steel sample roughness was below 30 µm. Furthermore, increasing surface roughness improved the interface friction angle of clay–steel and clay–concrete samples by about 37.95 and 36.3%, respectively. An increase in roughness also led to a rise in the adhesion of concrete and steel samples by approximately 26.24 and 32%, respectively.

The findings of this study emphasize the significance of surface roughness in optimizing the interface behavior between clayey soils and structural materials. The results have important implications for enhancing the design and performance of soil structural systems. The identified correlations between roughness parameters and shear behavior provide valuable guidance for engineers and researchers involved in soil structural interaction studies. The understanding gained from this research can contribute to developing improved design guidelines and techniques for such systems.

While this study has provided valuable insights into the effect of surface roughness on interface behavior, it is important to acknowledge its limitations. The research was conducted at a specific site in one of Iraq's seismically active regions, and the findings may not be directly applicable to other locations. Additionally, the study focused on clay–steel and clay–concrete interfaces, and further investigations are needed to explore the behavior of other soil structural material combinations. Future studies should also consider the influence of other factors, such as moisture content and compaction, on the interface behavior.

Funding information: The manuscript was done depending on the personal effort of the authors, and there is no funding effort from any side or organization.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most of the datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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