Interfacial characterization of soil-3D printing materials

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ABSTRACT

3D printing has emerged as a revolutionary technique for producing products with specific shapes and mechanical properties tailored to various needs. Its ability to fabricate intricate structures and forms has garnered considerable attention, leading to numerous research efforts exploring its potential benefits in geotechnical applications. These endeavours highlight the possibilities of utilizing 3D printing technology to create innovative and customized materials for soil reinforcement, such as geosynthetics, and fibres, as well as replicating soil particles, physical models of soil structures, and drainage systems in geo-structures. Additionally, beyond its role in geotechnical engineering, the interaction between geo-structures (foundations, retaining walls, embankments, tunnels, piles, infrastructures, etc.) and the surrounding soil under different loading and environmental conditions is of paramount importance. The interface between these structures and the soil plays a critical role in load transfer and overall stability. Therefore, this study focuses on investigating the interface between soil and 3D printed components through direct shear testing. The experimental campaign aims to examine how different factors, including the type of 3D printing materials, material rigidity, and surface texture of the printed components, influence the shear behaviour of the soil-3D printing material interface. The findings suggest that Young's modulus of the 3D printed materials plays a crucial role in determining the response of the soil-3D printed parts interface. Furthermore, an optimized design is proposed to achieve the desired shearing resistance at the interface. The insights gained from this investigation have practical implications for optimizing the design of 3D-printed components in geotechnical engineering applications.

Keywords: Three-dimensional (3D) printing technology, soil–3D printed parts interface, direct shear testing.

1. Introduction

The field of 3D printing, a technology that enables the production of physical objects from computer-designed models, has experienced significant advancements worldwide. It offers several notable advantages in product development, such as increased efficiency leading to time and cost savings, reduced human involvement, shortened product development cycles, and the ability to manufacture complex shapes that would be challenging using traditional machining techniques. In recent years, there has been a growing interest in the diverse applications of 3D printing across various fields, including medicine, aerospace, industrial manufacturing, civil engineering, among others (Wong & Hernandez, 2012; Wan Li Ma et al., 2014; Di Donna et al., 2016).

Among all fields mentioned, geotechnical engineering is a field that presents numerous opportunities for the application of 3D printing technology. Geotechnical engineering focuses on the design and construction of structures that interact with the ground, such as foundations, retaining walls, embankments, tunnels, and infrastructures (Fadaie & Veiskarami, 2020). Traditional construction methods for these structures can be time-consuming, costly, and challenging to execute with precision. However, the emergence of 3D printing technology has the potential to revolutionize geotechnical engineering by offering a more efficient and accurate construction process (Yin et al., 2021). Additionally, 3D printing technology provides greater design flexibility, enabling engineers to create complex shapes and structures that would be arduous or impossible to achieve using conventional construction techniques. This enhanced design flexibility holds promise for the development of more innovative and efficient geotechnical structures (Wu et al., 2020; Du et al., 2022; Ahmed & Martinez, 2020; Xu et al., 2022; Venkateswarlu et al., 2023).

There are multiple applications of 3D printing technology in geotechnical engineering. One such application involves using 3D printing to fabricate physical models of soil structures for laboratory testing (Dionysios et al., 2017; Kittu et al., 2019; Xia et al., 2020; Jaber et al., 2020; Tan & Wang, 2020; Ahmed & Martinez, 2020; Xia et al., 2021; Xu et al., 2022; Huang et al., 2023). Another significant use is the creation of innovative and customized materials for soil reinforcement, including geosynthetics (Dixon et al., 2006; Fowmes et al., 2017; Amurane et al., 2019; Maghool et al., 2020; Lashkari & Jamali, 2021; Liu et al., 2022; Ding et al., 2022; Wu et al., 2020; Du et al., 2022; Ahmed & Martinez, 2020; Xu et al., 2022; Venkateswarlu et al., 2023). These examples represent only a fraction of the potential applications of 3D printing in geotechnical engineering.

Additionally, the interface between soil and structures holds significant importance in assessing the stability of various geo-structures, including shallow and deep foundations, earth dams, retaining walls, nuclear waste disposal facilities, coal mine shafts, geothermal piles, and geogrid reinforcement. Therefore, it is imperative to

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characterize the properties and behaviour of this interface to guarantee the safety and dependability of these structures.

Over the years, numerous investigations have been carried out to evaluate the interaction between soil and structures (DeJong et al., 2003; Fowmes et al., 2017; Hu & Pu, 2004; Di Donna et al., 2015; Chen et al., 2015; Yavari et al., 2016; Martinez & Stutz, 2019; Laloui & Sutman, 2021; Gao et al., 2022; Zeng et al., 2023; Fang et al., 2023; Venkateswarlu et al., 2023; Venkateswarlu et al., 2023). These studies have provided valuable insights into the behaviour of soils under the influence of different types of structural loads. However, despite the extensive research conducted thus far, there remains a lack of comprehensive studies that thoroughly characterize the interaction between soil and structures fabricated using 3D printing technology, specifically in terms of determining an optimal design considering contributing parameters. Considering the potential advantages offered by 3D printing in the construction industry, it is crucial to conduct research on the interaction between soil and 3D-printed structures in order to bridge this knowledge gap.

In this study, the interface between soil and 3D-printed components was examined through direct shear testing to gain insight into how different factors, including the characteristics of 3D printing materials, material rigidity, and surface texture of the printed parts, influence the shear behaviour of the soil-3D printing material interface. A series of direct shear experiments were conducted to determine the equivalent shearing resistance for samples involving soil-on-soil and soil-on-3D printed material configurations. The authors' intention was to offer valuable practical insights that could be applied to have an optimal design of 3D-printed components specifically for geotechnical engineering applications.

2. Materials

2.1. Soil properties

In this research, the soil samples utilized were composed entirely of silica sand, specifically the variety known as Leighton Buzzard sand – see Fig. 1 – with sub angular to rounded grain shape, quartz composition, poorly-graded sand, and with specific gravity of 2.66 and the nominal effective size of 0.63–0.85 mm (Mehravar, et al., 2022).

A particle size distribution analysis was conducted based on British Standard Institution (BSI, 1999a). The outcome of this analysis is presented in Fig.1 (Fadaie, et al., 2022). It should be stated that from this point onwards, the term ‘soil’ refers to the type of sand that was used in this research. The properties of the soil are summarized in Table 1. C_u and C_c stand for the uniformity coefficient and coefficient of curvature, respectively.

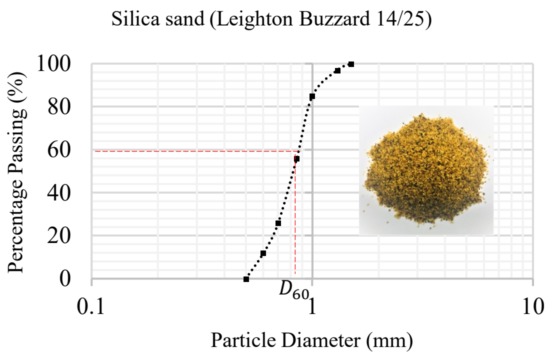


Figure 1. Soil particle size distribution curve – Leighton Buzzard sand used in present study

Table 1. Soil properties

D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c
0.62	0.73	0.86	1.38	0.99

2.2. 3D printing materials

Two different composites, PLA (Polylactic Acid), and TPU (Thermoplastic Polyurethane) produced by Markforged additive manufacturing company were employed to examine the interface between 3D printing materials and sandy soil. The features of 3D printing materials used in this research have been summarized in Table 2. These values are measured according to the American Society of Testing and Materials (ASTM, D790) (D790-17, 2017).

Table 2. 3D printing materials features used in present study

Composite Base	PLA	TPU
Tensile Modulus (GPa)	2.3	15.3
Tensile Stress at Yield (MPa)	31	-
Tensile Stress at Break (MPa)	18	26
Tensile Strain at Break (%)	27	550
Flexural Strength (MPa)	43	1.8
Flexural Modulus (MPa)	2.3	90
Density (g/cm^3)	1.3	1.2

3. Experimental approach

To assess the interface between soil and 3D printed parts, the experimental setup involved positioning the 3D printed parts within the lower section of a shear box, while the upper section was filled with sandy soil. The investigation of the soil-3D printed part interface was conducted using a direct shear apparatus manufactured by VJtech company. Throughout the study, experiments were performed under three distinct levels of normal stress (82, 164, and 328 kPa), during which measurements of shear stress and horizontal displacement were taken. The layout of interface friction measurement of soil-3D printed materials using direct shear test is illustrated in Fig. 2.

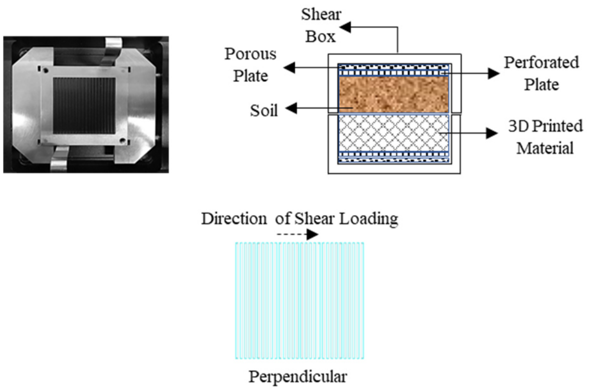


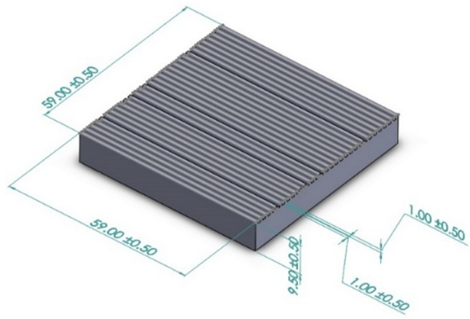
Figure 2. Layout of interface friction measurement of soil-3D printed materials using direct shear test

In this study, the 3D digital models were created using SolidWorks software. Subsequently, the slicing process was performed using Eiger software, developed by Markforged additive manufacturing company. Multiple digital models were generated to fulfil the specific requirements of direct shear interface testing. The research encompassed different scenarios, as outlined in Table 3. Firstly, soil-on-soil conditions were examined, followed by the assessment of soil-on-3D printing parts under both smooth and patterned conditions, incorporating grooves. To determine the shearing resistance of the soil and 3D printing materials, grooves with a depth of 1 mm and a width of 1 mm were designed, taking into consideration the D_{50} (median particle size) of the Leighton Buzzard (L.B.) soil, which measures 0.82 mm.

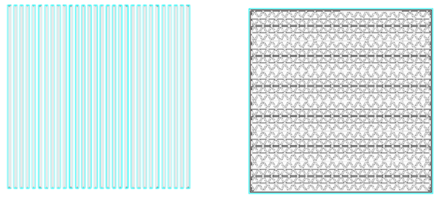
Table 3. Details of different scenarios defined in present study

Scenario	Material	Position to Shearing (°)	Pattern
1	PLA	-	without grooves
2	TPU	-	without grooves
3	PLA	90	with grooves

Design stages of 3D-printed parts with different scenarios to characterize the interface of soil and 3D printed parts in accordance with the direct shear testing are summarized in Fig. 3. It should be stated that the designed part for direct shear testing was created using SolidWorks. Subsequently, it was sliced into different layers using slicing software to prepare it for the 3D printing process. The schematic representation of the top and middle layers of the sample is shown in Fig. 3b.



a)



b)

Layer 95 and Layer 50

Figure 3. Design of 3D-printed parts according to the direct shear box, a. SolidWorks design, b. different layers of sample generated in slicing software, direction of Grooves Respected to Shear Loading (°): 90, Depth (mm) × Width (mm): 1 × 1

4. Results and discussions

To evaluate the shear behaviour of both the pure Leighton Buzzard sand and the soil-3D printed part specimens, the initial phase encompassed performing direct shear tests on the pure sandy soil sample. The shear stress-horizontal displacement curve of the pure sand sample is depicted in Fig. 4. It is noteworthy that, in order to ensure the reliability and consistency of the experimental results, all samples were subjected to three replications of the tests.

A formula, denoted as Eq. (1), has been derived to establish a correlation between shear strength and normal stress. This correlation is based on a well-defined Mohr-Coulomb criterion and the adoption of a frictional interface model.

$$\tau_f = \sigma_f \tan \varphi + c \tag{1}$$

where the variables τ_f and σ_f refer to the shear strength and normal stress, respectively, at the interface between soil and soil-3D printing materials when the material fails. The variable c signifies the equivalent cohesion of the interface, which is ascertained by the vertical intersection of the shear strength curve with the normal stress. Furthermore, the variable φ denotes the angle of shearing resistance at the contact surface between the soil and the soil-3D printing materials. This angle represents the inclination of the shear strength line.

The angle of mobilized interface friction, δ, can be calculated using Eq. (2) that is analogous to the angle of internal friction, φ, obtained through direct shear tests on granular materials.

$$\delta = \tan^{-1} \frac{\tau_f}{\sigma_f} \tag{2}$$

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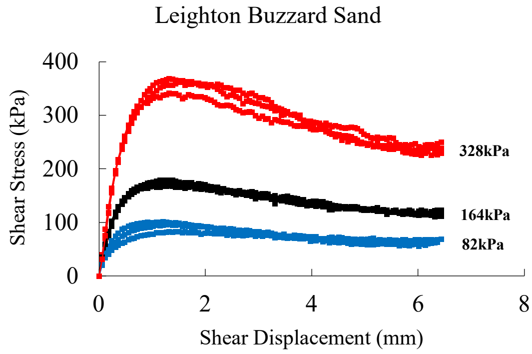

Figure 4. Shear stress-horizontal displacement curve of Leighton Buzzard sandy soil

Fig. 5 provide evidence of the linear relationship between shear strength and the initial normal stress of the samples.

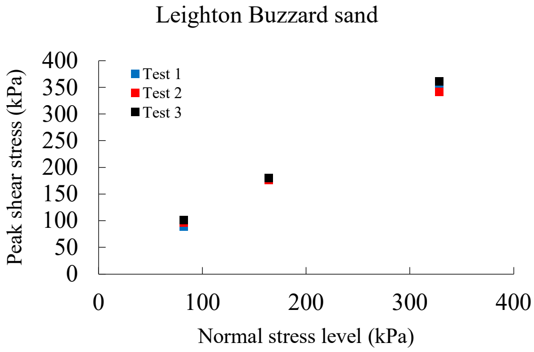

Figure 5. Peak shear stress against normal stress of sandy soil

To conduct a comparative analysis of the shear characteristics displayed by the pure soil samples and the samples comprising soil-3D printed parts, direct shear tests were conducted on the latter as well. The relevant results are depicted in Fig. 6 and Fig. 7. TPU and PLA materials were chosen based on their flexible and rigid behaviours, taking into account the values of their Young's modulus, as presented in Table 2. The surface patterns of the 3D printed parts were designed without incorporating grooves.

The linear trends of the shear strength against initial normal stress for the samples under different conditions are depicted in Fig. 7.

The results are summarized in Table 4. According to the results obtained, it is evident that the equivalent angle of shearing resistance of the soil-3D printed part interface is lower than that of the pure soil, as observed from the direct shear tests. A significant point drawn from the results is that TPU material as a hypo-elastic material exhibits behaviour more similar to pure sandy soil when compared to other 3D printing materials (Onyx, Nylon, and PLA) with a high Young's modulus.

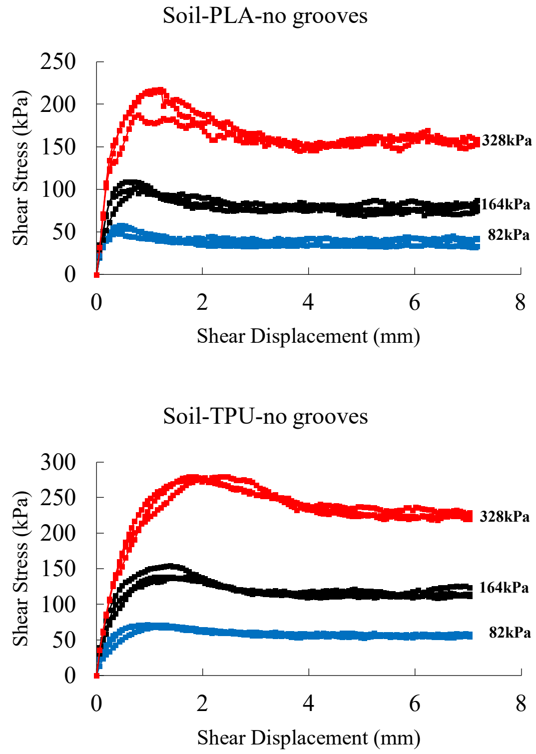

Figure 6. Shear stress-horizontal displacement curves of sandy soil – PLA – no grooves, and sandy soil –TPU – no grooves

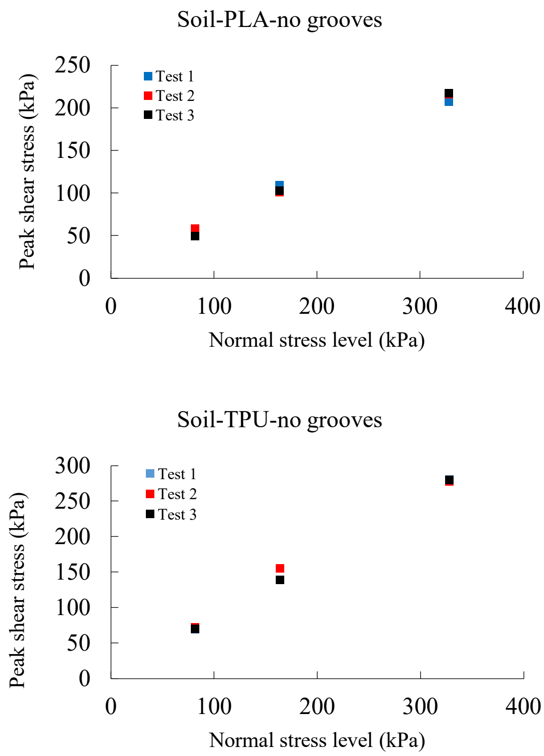

Figure 7. Peak shear stress against normal stress of sandy soil – PLA – no grooves, and sandy soil – TPU – no grooves

Table 4. Angle of shearing resistance at different conditions obtained from interfacial characterization testing

Sample	Angle of Shearing Resistance			
	Test 1	Test 2	Test 3	Average
L. B. Sand	44.9	46.0	45.5	45.5
L. B.-PLA	31.9	34.4	33.8	33.4
L. B.-TPU	40.5	40.9	40.4	40.7

L.B.: Leighton Buzzard

According to Martinez and Frost (2017), the dominant perspective regarding interfacial properties suggests that particles can move along the interface either by sliding or rolling. The level of shear resistance exhibited by soil-structure interfaces differs based on the surface features of the interface. Therefore, in order to enhance the interaction between the soil and 3D printing materials, the design of grooves was implemented, considering the median particle size (D_{50}) of Leighton Buzzard (L.B.) soil particles. For this particular phase, PLA material was chosen. The grooves with dimensions of 1mm in depth and width were developed to evaluate the shear resistance between the L.B. soil and the 3D printing material. It should be stated that the D_{50} of the L. B. soil is 0.82 mm.

The angle of the grooves was set perpendicular to the shear loading in direct shear testing. The relationship between interfacial shear stress and displacement, as well as the peak stress values obtained from each curve on a normal stress – shear stress graph, are plotted and depicted in Fig. 8 and Fig. 9, respectively.

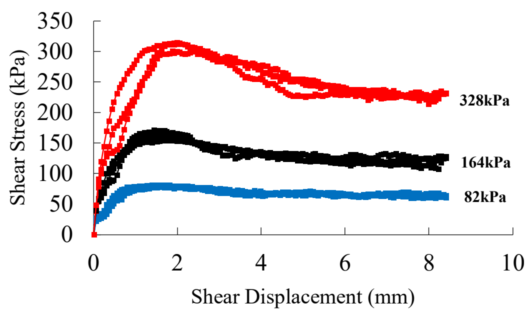

Figure 8. Shear stress-horizontal displacement curves of sandy soil – PLA – with grooves

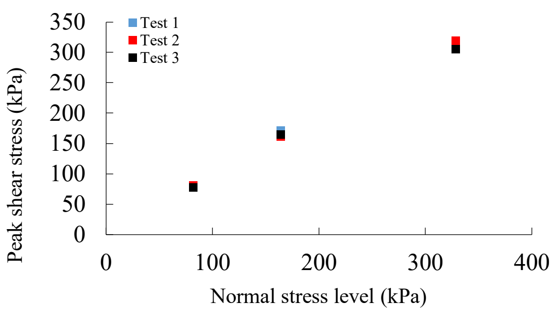

Figure 9. Peak shear stress against normal stress of sandy soil – PLA – with grooves

The results of this stage are presented in Table 5. It is evident from Table 6 that the equivalent angle of shearing resistance of the soil-3D printed part interface with grooves in the perpendicular position to shearing is greater than that of the condition with no grooves resulting from the direct shear tests. This is due to the interlocking of soil particles embedded into the prefabricated grooves. It is worth stating the results unambiguously demonstrate that positioning the grooves perpendicular to the shearing load yields interface strength roughly close to the angle of shearing resistance in pure soil samples (see Table 5).

Table 5. Angle of shearing resistance at perpendicular position respected to the shear loading obtained from interfacial characterization testing

Sample	Angle of Shearing Resistance			
	Test 1	Test 2	Test 3	Average
L. B. Sand	44.9	46.0	45.5	45.5
L. B.-PLA-Perpendicular to shearing	44.5	44.3	43.4	44.1

Another significant aspect that demands attention is the impact of groove dimensions on the interfacial properties between soil and 3D printing materials. Existing literature indicates that the interfacial shear strength of the soil when in contact with 3D printing materials is typically lower compared to that of the pure soil. Consequently, this examination holds significance in improving the surface characteristics for the fabrication of 3D printed components, with the objective of attaining the angle of shearing resistance exhibited by the pure soil.

In order to elucidate the impact of surface pattern alterations in 3D-printed components on shear failure characteristics, the results of direct shear tests, performed with different conditions at a desired initial normal stress of 82 kPa, are presented in Fig. 10. The inclusion of grooves, taking into account the median size of soil particles, resulted in higher shear stress failures. It is worth noting that the presence of grooves also led to increased shear displacement values. The enhanced interface strength can be attributed to the activation of passive resistances, which in turn generate concurrent shear-compression loading conditions within the soil.

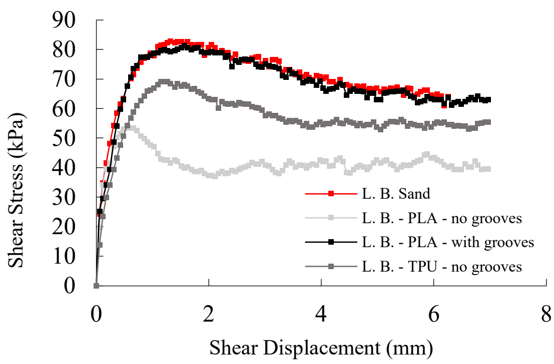

Figure 10. Shear stress–shear displacement curves at different conditions under 82 kPa normal stress

In order to perform a comparative examination of the interfacial properties displayed by the soil samples without any 3D printed parts and the samples containing soil-3D printed components, the outcomes of the direct shear tests are provided in Table 6. This table presents the Interfacial Index (II) corresponding to the various scenarios investigated in this study. The Interfacial Index is defined as the ratio between the equivalent maximum shearing resistance of the soil-3D printing material and the equivalent shearing resistance of the pristine soil obtained from different direct shear testing. A value of 1 indicates the scenario involving pure sandy soils.

Table 6. Summary of Interfacial Index for different scenarios

Scenario	Interfacial Index
L. B. Sand	1.00
L.B.-PLA	0.73
L. B.-TPU	0.89
L.B.-PLA, perpendicular to shearing, with grooves	0.97

5. Conclusions

This research aimed to investigate the interfacial characterization between soil and 3D-printed components using direct shear testing. The objective was to gain a comprehensive understanding of how various factors, such as the characteristics of 3D printing materials, the mechanical properties of the material, and surface texture of the printed parts, affect the shear behaviour of the soil-3D printing material interface. A series of direct shear experiments were conducted to determine the equivalent shearing resistance of soil-on-soil and soil-on-3D printed material samples. Drawing upon the findings derived from the present investigation, the following conclusions can be inferred:

- The equivalent shearing resistance of the soil-3D printed samples with no grooves on their interface is less than those of the pure soil resulting from the direct shear testing.
- The outcomes of the study clearly demonstrate the significant influence of Young's modulus on the characterization of soil-3D printing material interfaces. It is observed that the equivalent angle of interfacial shearing resistance for soil-on-3D printed parts exhibiting rigid behaviour, owing to a high Young's modulus, is considerably lower compared to that of soil-on-3D printed parts displaying flexible behaviour, attributed to a low Young's modulus.
- According to the results obtained, the presence of grooves on the surface of the 3D printed parts plays a significant role in the interface strength of soil-on-3D printed parts, considering D_{50} of soils.

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