

# Integrating 3D printing in fibre optic sensor packaging for soil strain measurement

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**ABSTRACT:** The functionality of global economies relies heavily on the effective maintenance of infrastructure and geo-structures. However, decades of continuous use result in the ageing and deterioration of civil infrastructure, posing substantial safety risks. This makes the continuous health monitoring of civil infrastructure in particular geo-structures critical for drawing on a timely rehabilitation and maintenance based on data. While conventional monitoring systems have long been used in civil engineering, their progress has been hindered by challenges such as sensor performance in harsh environmental conditions and limitations in dynamic monitoring. Fibre Optic Sensing (FOS) technology, particularly Fibre Bragg Grating (FBG) sensors, has emerged as a solution to these challenges. However, the fragility of optical fibres necessitates protective packaging, which can partially dissipate strain transfer from the host environment (in the context of this paper, soil) to the fibre core. This strain dissipation depends on factors such as material properties, packaging methods, and bonding length. When sensors are embedded or affixed to structures, strain is transmitted to the fibre core via shear forces at bonding interfaces. A key challenge is minimising strain loss to ensure the alignment of measured strain with the actual strain experienced by the structure. Strain transfer is influenced by the elasticity, interface properties, and layer thickness of sensing system components. In this context, 3D printing technology offers a promising approach to customise protective materials for FBG sensors, reducing strain loss and aligning material properties with the host environment. This study presents an initial design to embed bare FBG sensors in thermoplastic polyurethane (TPU) material, chosen based on experimental results. Using 3D printing, the packaging's mechanical properties will be tailored to enhance strain sensitivity and match the mechanical characteristics of the soil. This innovation holds potential for improving the performance and reliability of fibre optic sensing systems in health monitoring of geo-structures.

**KEYWORDS:** Geo-structural health monitoring, fibre optic sensing systems, 3D printing technology, fibre embedment, strain monitoring.

## 1 INTRODUCTION

3D printing technology has emerged as a ground-breaking method for producing products with desired geometric configurations and mechanical properties to suit various purposes. Recently, the versatility of 3D printing has gained significant attention owing to its capacity to fabricate complex shapes and structures. Numerous recent research endeavours have showcased the prospective advantages of utilizing 3D printing technology in geotechnical contexts, such as possibilities in terms of creating innovative and customized materials that can be used for soil reinforcement (such as geotextile, geogrids, geocells, and fibres, etc.), replicating soil particles, physical models of soil structures, and customised drainage systems in geo-structures, among others.

Effective monitoring of geo-structures is essential to ensure their long-term stability and safety. It's widely accepted that fibre optic-based strain sensors are well-suited for monitoring the health of geo-structures (Soga & Luo, 2018; Fadaie, et al., 2022; Mehravar, et al., 2022; Fadaie, et al., 2022). However, a significant challenge in the design of optical fibre strain sensing systems lies in minimizing the loss of strain as it travels from the host structure to the sensing fibre's core. Here, it's imperative to minimise any difference between the strain measured by the fibre optic sensing systems and the actual strain experienced by the host material or structure during monitoring or measurement. The transformation of strain is influenced by various factors, including the interface properties, layer thickness in different sensing system components, and their respective mechanical characteristics, in particular the material elasticity (Xu, et al., 2018; Fadaie, et al., 2023). In this context, 3D printing technology offers the potential to create innovative and customised materials for the packaging of fibre optic sensing systems, thus substantially reducing strain loss and tailoring the materials to match the mechanical properties

of the host environment. Consequently, there is an urgent need to gain a comprehensive understanding and characterise the mechanical properties of 3D-printed components to assess their suitability for specific applications.

In addition to its growing significance in geotechnical engineering, 3D printing technology is particularly well-suited for encasing fibre optic-based strain sensors used in the structural health monitoring of geo-structures (Fadaie, et al., 2023). Even though there are several studies on the application of 3D printing for the packaging of sensing systems (Fang, et al., 2016; Leal-Junior, et al., 2018; Hong, et al., 2019; Hong, et al., 2019; Ismail, et al., 2021; Presti, et al., 2022; Ahmad, et al., 2022; Hong, et al., 2023; Zhang, et al., 2023), there is no study regarding the characterisation of mechanical properties of 3D printing materials for geotechnical engineering applications. In other words, while a substantial amount of research effort has been dedicated to monitoring strain in geo-structures/infrastructures using sensing systems, spanning controlled laboratory settings and real-world field scenarios, these sensing systems have primarily been attached to or buried within the structures themselves. Consequently, there has been no study specifically focused on directly measuring the actual strain generated within a soil environment, a matter of potential significance within the field of geotechnical engineering. Therefore, soil strain monitoring holds significant importance in structural health monitoring and geotechnical engineering applications.

Employing 3D printing technology, the primary goal of this study is to determine the optimal design for the packaging of sensing systems, specifically fibre-optic sensing systems for monitoring the actual strain generated in soils. Additionally, the mechanical properties of 3D printed materials will be characterised to identify the best approach for assessing their suitability in specific applications. Therefore, the purpose of

this paper is to explore the mechanical properties of several 3D-printed specimens in order to identify the most suitable material and design for the utilisation of 3D printing technology in civil engineering, with the focus on the field of geo-structural health monitoring. For this purpose, this study utilises unconstrained compression testing to experimentally characterise the mechanical properties of various 3D-printed parts. The experimental campaign aims to understand how different factors, such as 3D printing materials, the direction of the printing process, infill density, and infill pattern, affect the mechanical behaviour of 3D printing materials.

## 2 MATERIAL

### 2.1 Soil

The aim of this study is to design packaging for the sensing systems that aligns with the compressive modulus of sandy soil with medium compaction, utilising 3D printing technology. Building on the authors' previous relevant studies, Leighton Buzzard sand was selected as the subject for this research and its mechanical properties were used as a reference to characterise the mechanical behaviour of 3D-printed materials. Table 1 presents the soil properties (Mehravari, et al., 2022).

Table 1. Soil properties

Type of soil	Soil classification	Size range (mm)	$D_{50}$ (mm)
Leighton Buzzard	SP	20	0.82

Moreover, a particle size distribution analysis was carried out based on British Standard Institution (BSI, 1999a). Figure 1 illustrates the outcome of this analysis and Scanning Electron Microscopic (SEM) photographs of Leighton Buzzard sand (Fadaie, et al., 2022).

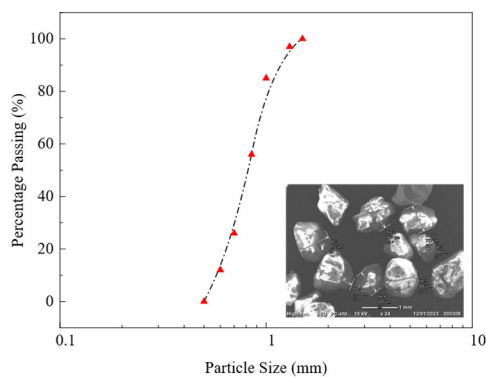


Figure 1. Particle size distribution analysis, and SEM photograph of Leighton Buzzard sand.

In addition, according to the Unified Soil Classification System (USCS), typical values of Young's modulus for poorly graded sands range from 10 to 80 MPa, depending on the degree of compaction (Kezdi, 1974) (Obrzud & Truty, 2012).

### 2.2 3D printing material

Two different composites, PLA (Polylactic Acid), and TPU (Thermoplastic Polyurethane) produced by Markforged 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 4 according to the data sheets prepared by the companies (Markforged 3D printers, 2023).

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

Composite Base	PLA	TPU
Tensile Modulus	2.3 (GPa)	15.3 (MPa)
Tensile Stress at Yield (MPa)	31	-
Tensile Stress at Break (MPa)	18	26
Flexural Strength (MPa)	43	1.8
Flexural Modulus	2.3 (GPa)	90 (MPa)

## 3 METHODOLOGY

Due to the intrinsic fragile mechanical properties of optical fibres, particularly silica sensor, appropriate packaging is required to enhance their survivability under typical civil engineering conditions. Moreover, it is also worth mentioning that using an uncoated fibre, assuming it survives installation, would likely result in very poor strain coupling between the soil and the fibre. Therefore, the main goal of this study is to find out the best material and structural design compatible with 3D printing which can improve the sensing properties and its measurements.

Depending on the application of sensing systems, different characteristics should be considered in the development process of sensors. To elucidate the process of strain transfer from the structure to the fibre core, it is important to note that when the sensors are affixed or embedded within the structure, strain propagates through the fibre core via shear forces along the bonding interfaces of different layers. This sequence begins from the structure, proceeding through the jacket, cladding, and ultimately reaching the core. Therefore, the initial design proposal aimed to enhance strain sensitivity by tailoring the mechanical properties of the sensor's packaging. As previously noted, strain transfer losses arise from the varying mechanical properties across the sensor's layers.

Specifically, 3D printing is a promising tool to reduce the packaging interlayer strain transfer losses, overcoming this issue through the tailoring of the physical properties of the 3D printed part to meet specific requirements. Consequently, selecting an appropriate packaging solution for the strain sensors, developed using 3D printing technology, becomes a crucial initial step from the perspective of geotechnical engineering applications. Therefore, it is essential to determine the Young's modulus of different types of 3D printed parts. For this purpose, compression testing procedure was employed in the present study.

## 4 ANALYSES AND RESULTS

### 4.1 Design of samples and compression tests

To identify the optimal infill material and printing pattern for a novel packaging design of a fibre optic sensor for strain monitoring in geo-structure, two distinct 3D printing materials were chosen, with their printing specification being given in Table 3.

Table 3. Features of different 3D printed specimens.

Material	Features of Printing
PLA	Concentric, Circular, Horizontal, 50% Infill Density
TPU	Concentric, Circular, Horizontal, 50% Infill Density

A cylindrical-shaped specimen was designed for packaging purposes using SolidWorks software (see Figure 2). The specimen size was 50 mm in length and 10 mm in diameter and were 3D printed. Five specimens were prepared for each type of material. Unconstrained compression experiments were conducted on the cylindrical specimens at a recommended speed of 5 mm/min, as specified in ISO 604A (ISO 604, 2002).

The unconstrained compression tests conducted on the 3D-printed specimens are intended to evaluate the materials' elastic properties, which play a significant role in strain transfer mechanisms and the overall stability of the composite system of the sensor. In this paper, efforts have been made to tailor the mechanical properties of the sensing system packaging to mimic the behaviour of soil. Compression testing was therefore selected, as soils are primarily subjected to compressive loading and must withstand such stresses effectively.

For the purpose of facilitating comparative analysis, all aspects of the printing process were kept consistent. A horizontal printing orientation and 50% infill density were employed for all created specimens. It should be stated that in this section, C. stands for Concentric infill pattern, T. stands for Triangular infill pattern, H. stands for Horizontal printing direction, V. stands for Vertical printing direction, and I.D. stands for Infill Density.

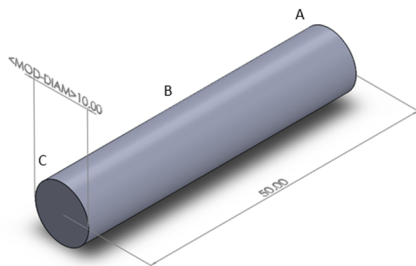


Figure 2. The cylindrical-shaped samples (length: 50mm, diameter: 10mm).

In accordance with the ISO 604A standard (ISO 604, 2002), five specimens were tested using an Instron machine equipped with a 5 kN load cell. The force (kN) – displacement (mm) curves of different materials directly obtained from the machine are presented in Figure 3.

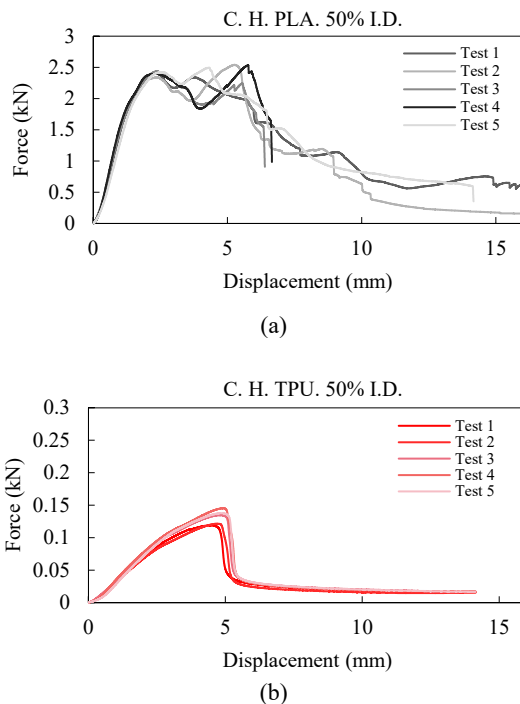


Figure 3. The force (kN) – displacement (mm) curves of different materials with 50% infill density and horizontal printing direction and the relevant specimens after failure, (a) PLA, (b) TPU.

The compressive modulus of five specimens related to each material are summarized in Table 4.

Table 4. Compressive modulus of different 3D printed specimens.

Materials and Infill Pattern	Compressive Modulus (MPa)	
	Average	Standard Deviation
PLA	2310.25	144.15
TPU	54.25	3.34

As can be seen, PLA exhibits the highest values of compressive modulus with an average of 2310.2 MPa, while TPU demonstrates the lowest values with an average of 54.2 MPa. Based on the results obtained, TPU displays flexible behaviour due to its lower compressive modulus. It should be noted that two specimens of PLA material experienced fast fracture. In addition, the results of the TPU exhibit a greater degree of consistency when compared to the results of PLA material. Considering the range of compressive modulus values of various types of soils, particularly in sandy soils, the compressive moduli exhibited by TPU samples demonstrate its promise as an effective packaging material for the fibre optic strain sensor in geotechnical engineering applications, specifically for the health monitoring of geo-structures. In order to facilitate result comparison, the average values of the five specimens printed with two materials were calculated, and the resulting curves are presented in Figure 4.

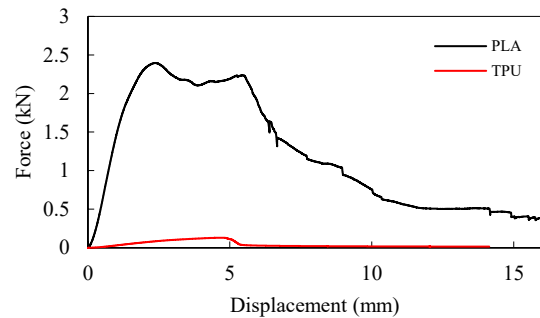


Figure 4. The force (kN) – displacement (mm) curves: average values of the five specimens printed.

#### 4.2 Effect of infill pattern and printing orientation

As different parameters such as infill pattern, direction of printing, infill density, etc., play a role in the values of compressive modulus of 3D printed specimens, it is essential to assess the influence of these parameters on the compressive modulus to discover the best design. Therefore, three different rounds of compression testing were defined. For the first round, four different infill patterns were examined to evaluate the influence of infill pattern and printing direction on the mechanical properties of the samples. In general, 20 specimens (5 for each pattern modelled according to the standard, ISO 604A), were printed using the Industrial Series X7 3D printer equipment (Markforged, 2024). After 15 minutes, the compression tests were repeated on the last three samples. The third round was conducted after waiting for an additional 15 minutes, again using the last three specimens. This study employed triangular and concentric infill patterns for the cylindrical-shaped samples with both vertical and horizontal printing directions.

Figure 5 presents a comparison of compressive modulus of different tests conducted under different scenarios defined.

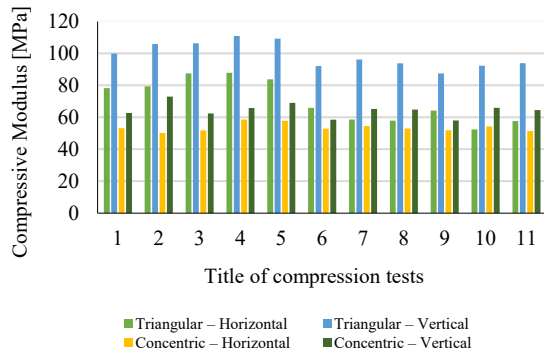


Figure 5. Comparison of compressive modulus of different tests – TPU material – 50% infill density.

Based on the results from the second and third rounds of testing, concentric infill patterns and horizontal printing directions show a small decrease in performance. For example, the percentage decrease from the first to the second round is 1.53% for the concentric infill pattern. This suggests that the concentric pattern maintains its structural integrity more consistently over repeated tests.

All captured results related to the specimens with TPU material with 50% infill density, concentric infill patterns and horizontal printing directions are presented in Figure 6.

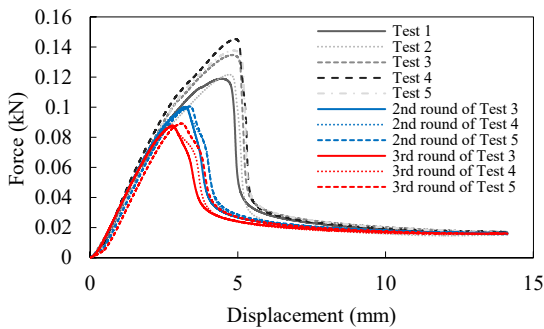


Figure 6. Results of compression tests on 3D printed specimens with TPU material with 50% infill density, concentric infill patterns and horizontal printing directions.

Beyond considering the range of compressive moduli in specimens, it's crucial to incorporate practical perspectives. In this context, since the primary application of 3D printing technology for this stage of the study involves utilising it for packaging FBG-based strain sensors, it's necessary to embed the fibres within the packaging during the printing process. Consequently, the horizontal printing direction emerges as the most suitable choice from a practical standpoint.

#### 4.3 Effect of infill density

In addition to infill pattern, it is important to find the optimal infill density considering the range of compressive modulus of typical sandy soil studied in this research. Since 50% infill density has already been evaluated in the previous stage, we will now focus on assessing infill densities of 25%, 75%, and 100% for this step.

According to the literature (Jung, et al., 2023), it was expected that a rise in infill density generally results in an increase in the compressive modulus of the specimens. Interestingly, the results confirmed the findings in the literature, indicating that an increase in infill density typically leads to a

higher compressive modulus in the specimens. The average values of compressive moduli of different specimens under various infill densities with a concentric infill pattern and a horizontal printing orientation are presented in Figure 7.

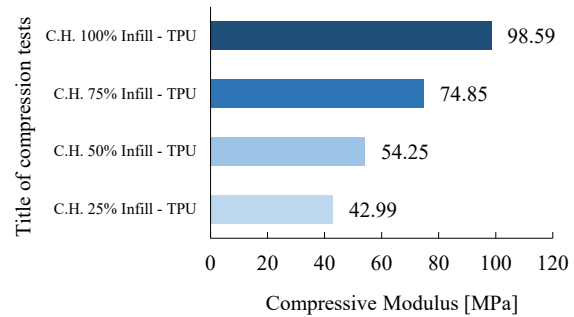


Figure 7. Comparison of average values of compressive modulus of the TPU specimens with concentric infill pattern, horizontal printing direction, and different infill densities.

Various infill densities could be suitable in the context of geotechnical engineering, given the range of compressive moduli across different soil types. However, the concentric pattern stands out as the most practical option. Specifically, for geo-structural health monitoring, the concentric pattern offers an ideal foundation to embed bare fibres within the designed packaging using TPU material. It's worth noting that selecting a 50% infill density as a baseline, while accounting for the range of compressive moduli in sandy soil, would be the initial recommendation due to its more consistent behaviour and best match with typical soil modulus. Therefore, even though matching the modulus of the 3D-printed parts to that of the soil is more important than the infill pattern or density, using a concentric infill with a horizontal printing orientation provides a compressive modulus that is more closely aligned with that of the soil.

#### 4.4 Water absorption of TPU

The presence of water and the degree of saturation of the soil play a significant role in the stability of geo-structures. Given that this particular type of 3D printing material (TPU) has been selected for geotechnical engineering applications, it must come into direct or indirect contact with the soil environment. Therefore, it is essential to determine its water absorption. In order to determine the water absorption (also called moisture absorption) – the capacity of a polymer to absorb moisture from its environment – of TPU material, a cylindrical sample of 50 (Heights) × 10 (Diameter) mm was considered. ASTM D570 and ISO 62 are recognized as the predominant standards utilized for assessing the water absorption characteristics of plastic materials (ASTM D570, 2018). Having followed the standards, the dried 3D-printed sample was initially weighed. Then, it was kept immersed in distilled water in the laboratory environment for 24 hours at 23±1 °C. During this process, the temperature of the water was constantly monitored by a mercury-in-glass thermometer and seen to vary from 22.5 to 23.5 degrees Celsius during the test (see Figure 8).

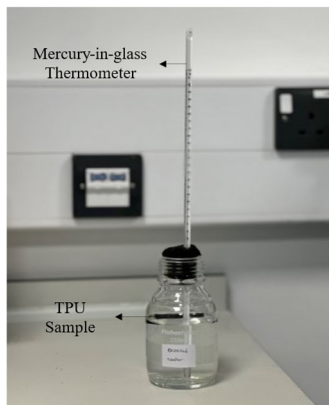


Figure 8. Setup for TPU sample immersion during the water absorption test.

## 5 CONCLUSIONS

Based on the results obtained in the current research, the following conclusions can be made:

- The use of 3D printing in the geotechnical engineering field offers numerous advantages, such as the ability to create products tailored to specific soil conditions and site requirements, by varying the contributing parameters of the 3D printing process.
- Based on the results obtained, TPU displayed flexible behaviour due to its low compressive modulus.
- The results of the TPU exhibited a greater degree of consistency when compared to the results of PLA. This consistent pattern suggests that the TPU consistently performs in a predictable manner under various conditions, making it a promising choice for geotechnical engineering applications.
- Considering the range of compressive modulus values observed in various types of soils, particularly in sandy soils for geotechnical engineering purposes, the compressive modulus exhibited by TPU samples demonstrated their effectiveness in geotechnical engineering applications.
- The experimental assessment of TPU material printed specimens revealed that the compressive modulus varied based on the infill patterns and printing directions. The triangular infill with vertical printing showed the highest modulus, while the concentric infill with horizontal printing exhibited the lowest. Despite the latter's lower modulus, it demonstrated more consistent behaviour under loading, with smaller decreases during subsequent rounds of testing. Consequently, the concentric pattern with horizontal printing is considered a more preferable option over the triangular pattern for its consistent performance and slight decrease in values over subsequent rounds.
- It can be clearly observed from the results that an increase in infill density typically leads to a higher value for the compressive moduli of the specimens.
- Due to significant role of water and the degree of saturation of the soil in stability of geo-structures, a water absorption (also called moisture absorption) test was conducted on the TPU material. The 3D-printed sample with TPU material (concentric infill, horizontal printing direction, 50% infill density) absorbed roughly 0.37% moisture when saturated in the distilled water at  $23 \pm 1$  °C.

However, further experimental investigations at laboratory and field scales are needed to ensure the reliable performance of 3D printing material, specifically the TPU material, in the geotechnical engineering context under different conditions,

including different soil types. Moreover, further work is necessary to establish the reliability of TPU material for housing the sensing systems in soil environment, thereby reducing strain dissipation.

## 6 ACKNOWLEDGEMENTS

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