Utilizing 3D printing for geomembrane fabrication in laboratory-scale geotechnical testing

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Abstract. This research investigates the innovative application of 3D printing technology in the production of geomembranes for laboratory-scale geotechnical experiments. Commonly, geotechnical research relies on the results of model testing. However, due to the high costs and complexity involved, full-scale model testing is rarely carried out. Geomembranes are essential components in various civil engineering projects, particularly in environmental containment and hydraulic barrier systems. In this research, the potential of 3D printing as an innovative method for producing geomembranes is carried out. Using a 3D printer, this research aims to prepare geosynthetic models with accurate geometric scales and tensile properties suitable for laboratory testing. A comparison was made between HDPE geomembranes and 3D printed geomembranes, to highlight their performance in a geotechnical laboratory environment. The research results show that 3D printed geomembranes show potential for applications in geotechnical research.

1 Introduction

Geosynthetics are artificial materials that function to increase stability in projects involving soil or rock, especially embankment construction work. Geosynthetics is a broad term that encompasses various products, including geotextiles, geogrids, geonets, geomembranes, geocells, geofoam, geocomposites, and more [1].

Geomembrane, geogrids, and other types of geosynthetics are commonly used in geotechnical engineering. For instance, the installation of geogrids in backfill for retaining walls improves the handling performance. The utilization of geogrids in embankment construction creates a much more improved composite material, considering that the shear strength of soil is often low [2-6].

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Therefore, laboratory-scale testing is more common since it can represent field conditions [7-9]. In laboratory-scale modeling, it's essential to use appropriate scaling laws in geotechnical testing, as shown in Table 1 [9]. The properties of geosynthetics (such as dimensions and tensile strength) used in laboratory-scale models need to be scaled down. For example, the tensile strength of the geosynthetics used in a laboratory-scale model should be $1/n^2$ of the full-scale geogrid when conducting tests, with that 'n' represents the model scale (e.g., 1:10, 1:100 etc.).

Table 1. Scale factors for laboratory geotechnical model [10].

Quantity	**Scale factors**
	lg
Mass density	1
Acceleration	1
Length	1/n
Stress	1/n
Force/unit length	$1/n^2$
Force	$1/n^3$
Stiffness	$1/n\alpha$
Strain	$1/n^{1-\alpha}$
Displacement	$1/n^{2-\alpha}$
Time (creep)	1

3D printing, since its emergence in the mid-1980s, has been a revolutionary technology. It is a form of additive manufacturing, differing from conventional techniques, such as CNC machining, which involves cutting desired objects from larger ones, as depicted in Figure 1 [10]. Currently, several 3D printing methods are available, including photopolymerization, extrusion, and lamination, with the choice of methods often depending on the desired object. In recent years, there have been numerous innovative applications of 3D printing, including successful efforts to create medical implants [11]. In the field of civil engineering, a bridge project in the Netherlands was completed using 3D printing in 2017 [12].

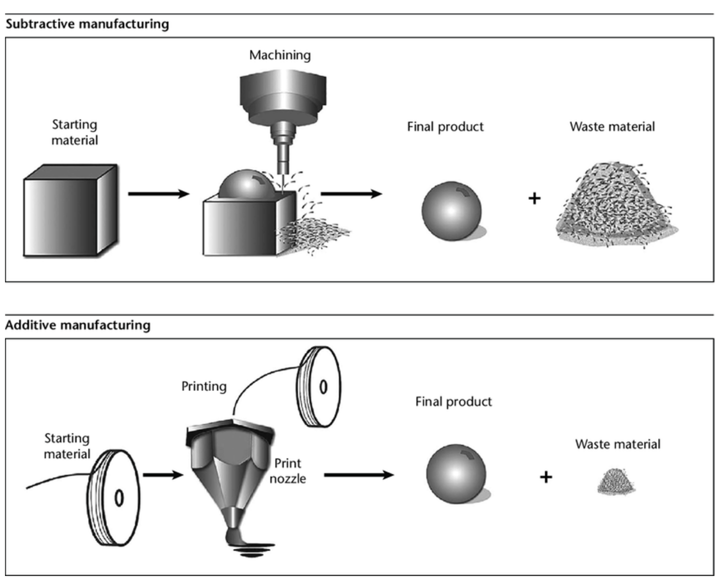

Fig. 1. Subtractive and additive manufacturing processes [10].

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Using 3D printing, this research aims to prepare a geomembrane model with geometric scales and tensile strength properties that comply with scaling laws for geotechnical testing in the laboratory. Additionally, 3D printing enables rapid prototyping at lower costs, as geomembranes can be produced on a small scale.

2 3D printing and its application in civil engineering

3D printing is a manufacturing method that involves spreading plastic layer by layer to create a three-dimensional object based on a digital model. The use of 3D printing allows the creation of customized objects on a small scale that cannot be produced by other methods. With 3D printing the need for equipment and labor is reduced, and production waste can be reduced. Based on these advantages, 3D printing is increasingly being adopted in various fields, including medicine, automotive, aeronautics, civil engineering, and so on. This automated and accelerated process holds promise for civil structures such as buildings and bridges, which require extensive labor. If successful, 3D structural printing is expected to significantly reduce construction time and costs [13]. In the construction industry, 3D printing can be used to create components or even 'print' entire buildings. Currently, 3D Printing has been employed in construction, including housing, component manufacturing (panels, cladding, and columns), and even bridges [13].

However, the incorporation of geosynthetics into laboratory-scale model testing is not straightforward. For example, in Chen and Chiu, paper is utilized as reinforcement in a 1-g experiment, but the material's tensile strength of the reinforcement still unknown [14]. Tatsuoka et al. and Koseki et al. created geogrid models from phosphor-bronze strips for laboratory-scale testing to study the retaining walls dynamic response. The material was very elastic, but stress-strain curves were not available [16-18]. Therefore, it's challenging to assess whether the scaling laws for tensile properties were correctly matched in previous studies. While some research, like Patra et al., used a conventional geogrids in their laboratory-scale testing to investigate foundation stability under eccentric loads, it didn't adhere to scaling laws [18]. Hence, there's a need for reinforcement materials that can be used in laboratory-scale model testing and possess tensile strength/stiffness similar to prototypes to accurately represent real-world phenomena.

Currently, 3D printing has also found application in geotechnical engineering research. For instance, Miskin and Jaeger successfully produced structures from granular materials using a 3D printer and tested the stress-strain relationships for numerical simulations [19]. Similarly, Hanaor et al. and Matsumura et al. conducting triaxial tests on 3D-printed particles to investigate the soil behavior [20]. Jiang et al. created molds and replicated jointed rock structures using a 3D printer [21]. Stathas and Wang made modular block retaining walls for performance comparison with laboratory-scale model tests [22]. In their research, Dionysios Stathas, J.P. Wang, and Hoe I. Ling successfully used 3D printing to create a geogrid model with one-hundredth of the tensile strength of the prototype, suitable for 1:10 scale model testing under 1-g conditions [23].

3D Printing has seen increasing use in various fields of science. Architectural modeling is one of the primary areas that employ 3D printing to develop prototypes that facilitate communication between architects and clients. Architects can now print complex structures and even add color for better representation [13].

3 Research methods

To conduct the research as described in the introduction, a series of steps involving CAD modeling, slicing for 3D printing, manufacturing using a 3D printer, and tensile testing of the PLA geomembranes.

3.1 CAD modeling

Begin by designing the geomembrane using computer-aided design (CAD) software. Ensure that the design meets the required specifications and dimensions outlined in ASTM D 6693-03 as shown in Fig. 2 and Table 2. The thickness of models is 0.5 mm, 1.0 mm and 1.5 mm.

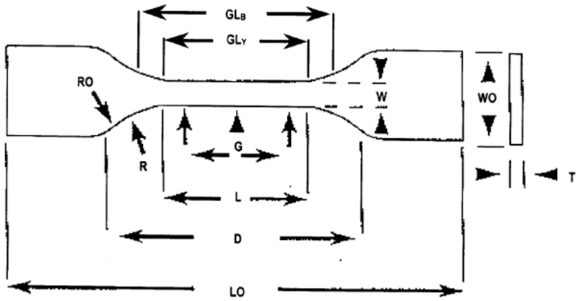

Fig. 2. Geometry of dog bone tensile test sample based on ASTM D 6693-03.

Table 2. Dimensions of tensile test samples based on ASTM D 6693-03.

Description	Dimension, mm	Tolerances, mm
W	6	±0.5
L	33	±0.5
GLY	33	±0.5
GLa	50	±0.5
WO	19	±6.4
LO	115	No max, No min
G	25	±0.5
D	65	±0.13
R	14	±1
RO	25	±1

3.2 Slicing for 3D printing

Import the CAD model into slicing software compatible with your 3D printer. Configure slicing parameters such as layer height, infill density, and print speed according to the PLA (Polylactic Acid) material and the desired properties of the geomembrane. G-code files were generated, which contain instructions or program for the 3D printer to create the physical object layer by layer. During the slicing process, several settings need to be configured, including Layer Thickness, Print Speed, Print Temperature, and Infill.

3.3 Manufacturing using 3D printer

The 3D printing process used utilizes a 3D printer of the FFF (Fused Filament Fabrication) type, which is an extrusion process where objects are built by depositing molten material layer by layer. The plastic used is the same thermoplastic material found in conventional manufacturing processes, as depicted in Figure 3. FFF has led to the proliferation of desktop 3D printers and is now the most widely adopted 3D printing technology, primarily due to its low initial investment requirements, the multitude of application possibilities it offers, and the relatively minimal specialized knowledge required for successful utilization of this technology [24].

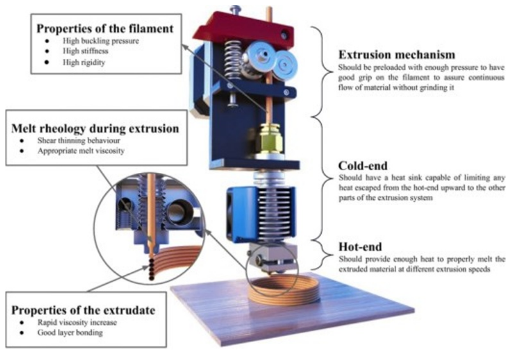

Fig. 3. FFF 3D printer [24].

Load the PLA filament into the 3D printer's extruder and ensure the printer is calibrated and properly leveled. Transfer the G-code files to the 3D printer and start the printing process. Monitor the printing to ensure there are no defects or errors in the geomembrane's fabrication. After printing is complete, remove the 3D-printed geomembrane from the printer's build plate. Perform any necessary post-processing steps, such as sanding or smoothing, to achieve the desired surface finish. Figure 4 is a finished sample for tensile test using 3D printing.

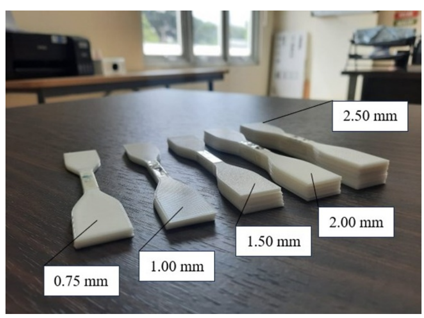

Fig. 4. Results of tensile test samples using 3D printing.

3.4 Tensile testing

Prepare samples from both conventionally manufactured geomembranes and 3D-printed geomembranes, ensuring they meet the ASTM D 6693-03 specifications for testing. Set up a tensile testing machine capable of measuring properties like tensile strength, elongation at break, and modulus of elasticity. Conduct tensile tests on the samples, recording the relevant mechanical properties, as shown in Figure 5. Compare the mechanical properties of the 3D-printed geomembranes with those of conventionally manufactured geomembranes to evaluate their performance in geotechnical laboratory settings.

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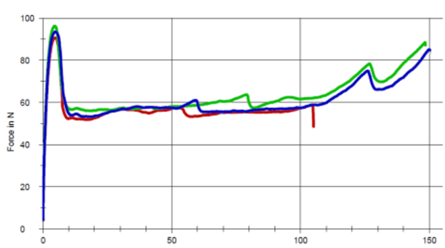
Fig. 5. Testing of tensile strength for HDPE and PLA geomembranes.

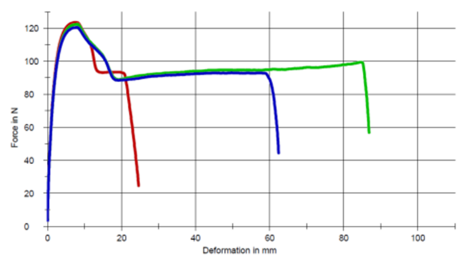
4 Test results

4.1 Tensile test result of HDPE geomembrane

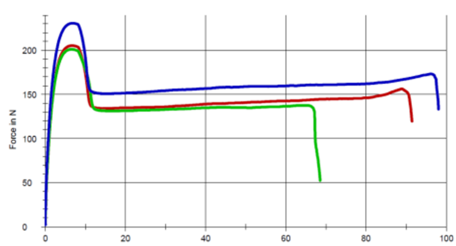
The results of the tensile test for HDPE geomembrane material with thicknesses of 0.5 mm, 1.0 mm, and 1.5 mm. Based on the Tensile Test results, the average maximum tensile force for each thickness as shown in Fig. 6 and Tabel 3. It shows that the tensile strength of geomembrane increases the thicker the geomembrane.



(a) 0.5 mm



(b) 1.0 mm



(c) 1.5 mm

Fig. 6. Tensile test force-deformation curve of HDPE geomembrane.

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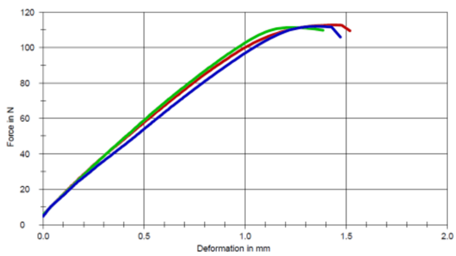
Table 3. Tensile strength of HDPE geomembrane.

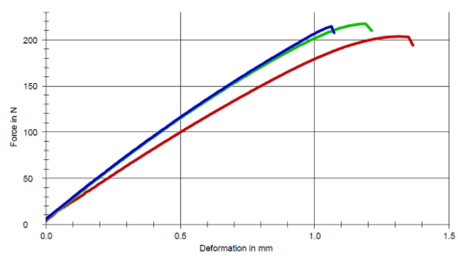
Thickness (mm)	**Tensile Force (N)**	**Tensile Strength (N/mm-width)**
0.5	93,35	15,56
1.0	122,03	20,34
1.5	212,44	35,41

4.2 Tensile test result of 3D printed geomembrane

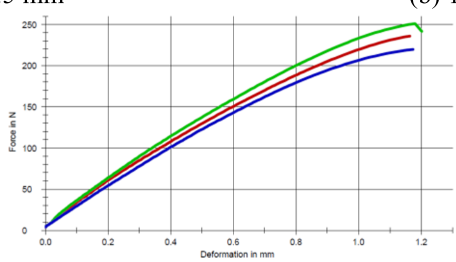
Here are the results of the Tensile Test for PLA geomembrane material manufactured using 3D Printing with thicknesses of 0.5 mm, 1.0 mm, and 1.5 mm. Based on the Tensile Test results, the average maximum tensile force for each thickness as shown in Fig. 7 and Table 4.



(a) 0.5 mm



(b) 1.0 mm



(c) 1.5 mm

Fig. 7. Tensile test force-deformation curve of 3D printed PLA geomembrane.

Table 4. Tensile strength of 3D printed PLA geomembrane.

Thickness (mm)	**Tensile Force (N)**	**Tensile Strength (N/mm-width)**
0.5	111,89	18,65
1.0	211,76	35,29
1.5	235,37	39,23

4.3 Tensile test comparison analysis

The tensile strength results of the geomembrane manufactured using a 3D printer with PLA material are then compared to the actual geomembrane made from HDPE material to obtain the correct geometric scale and tensile behavior for laboratory-scale model testing. This allows for the testing of the use of geosynthetics in geotechnical modeling at a laboratory scale that accurately represents real-world phenomena.

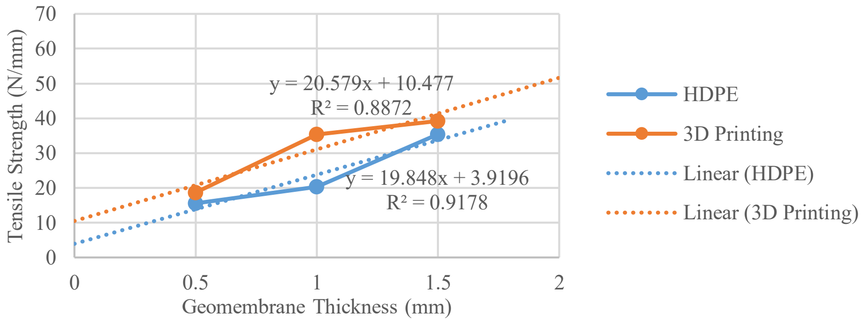


Fig. 8. Comparison analysis of HDPE and 3D printed PLA geomembranes.

Based on the test results between HDPE geomembrane and 3D Printing, the following results were obtained. With a geometric scale of 1:10, it was expected that the tensile strength of the 3D printing material would be 1:100 of the HDPE material. The tensile strength of the HDPE geomembrane at a thickness of 1.00 mm was 20.34 N/mm, whereas the tensile strength of the 3D printing material geomembrane at a thickness of 0.10 mm (1:10 geometric scale) was 12.53 N/mm, or approximately 61.6% of the strength of the actual geomembrane. Therefore, it may not be suitable for geotechnical modeling at a 1:10 scale in the laboratory. Test results indicate the potential use of geomembranes produced via 3D Printing in the context of geotechnical modeling in laboratory environments. Based on the results of a comparison of the tensile strength between geomembranes produced by 3D printing and conventional geomembranes, it shows that geomembranes produced by 3D printing produce higher tensile strengths, thus contradicting the hypothesis.

This is because the 3D printing method produces a denser and more homogeneous material structure compared to the conventional extrusion method used for HDPE geomembranes, resulting in a geomembrane with better mechanical properties. Geomembranes produced by 3D printing have a more consistent thickness than conventional geomembranes, which can be influenced by variability in the extrusion process. The 3D printing process allows better control of fiber orientation in PLA materials. Optimal fiber orientation can also increase the tensile strength of the geomembrane. The research results show that the tensile strength of 3D printed geomembranes exceeds that of HDPE geomembranes, which has the potential for further research, especially regarding other geomembrane characteristics, such as surface roughness or interface properties.

5 Conclusion

At a geometric scale of 1:10 based on the scaling law of laboratory geotechnical models, it is estimated that the tensile strength of 3D printed material will be comparable to 1:100 of HDPE material. Based on the tensile strength test results between HDPE geomembrane and 3D printed geomembrane, the tensile strength of HDPE geomembrane at a thickness of 1.00 mm was 20.34 N/mm. Meanwhile, the tensile strength of 3D printed geomembrane with a thickness of 0.10 mm (geometric scale 1:10) is around 12.53 N/mm or around 61.6% of the strength of the original geomembrane. Therefore, the use of 3D printing for geomembrane manufacturing may not be suitable for geotechnical modeling at 1:10 scale in the laboratory. These results illustrate the potential use of geomembranes produced via 3D Printing in laboratory scale geotechnical testing. Test results show that the tensile strength of 3D printed geomembranes is close to or even exceeds the strength of HDPE geomembranes, opening opportunities for further research, especially in terms of other characteristics such as surface roughness or geomembrane interface properties.

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