Influence of Matrix and the Fibre Orientation on the Mechanical Performance and Slope Protection of Three Dimensional Geosynthetic Cementitious Composite Mats

Manju R
Kumaraguru College of Technology
Sakthivel T (thanga.sakthivel@gmail.com)
PSG Institute of Technology and Applied Research
Sindhu Vaardini U
Kumaraguru College of Technology

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Abstract

Slope protection is necessary to prevent wave action from causing erosion on the upstream slope. In sufficient slope protection, an upstream slope might develop a major erosion problem. Slopes can be stabilized by adding a surface cover, digging and modifying (or regrading) the slope geometry, installing support structures to buttress the slope, or controlling groundwater in slope material through drainage. Though the types are typically involved in high manpower and time, In the recent past, Geosynthetic Cementitious Composite Mats (GCCMs) reinforced with spacer fabric has become increasingly popular because of its lightweight, high strength, and minimal contamination when compared to standard concrete. It is a potential material for use in various civil engineering disciplines, including water construction, pipelining, slope protection, military applications, and so on. In this study, CC slope protection's mechanical characteristics and stability are examined. First, the tensile strength and compressive strength of CC were tested. Short-term laboratory testing results show that the tensile and flexural strength of 3D spacer Geosynthetic Cementitious Composite Mats is relatively higher, and it is very durable. For Geosynthetic Cementitious Composite Mats, there was more constraint in the direction of the load applied, which caused the tensile stress and flexural strength that were created in the matrix to be higher.

1 INTRODUCTION

In the recent years, there has been a significant increase in research on Textile Reinforced Cementitious Composites (TRCC) as a novel field within alternative building materials, offering a replacement to conventional concrete (Awani et al., 2017). TRCC has exhibited remarkable characteristics, such as substantial load-bearing capability, resistance to corrosion, and greater durability (Daskiran et al., 2020; Rawat et. Al., 2022). The textile reinforcements may be classified into two main categories: two-dimensional (2D) fabric and three-dimensional (3D) fabric. 3D fabric is particularly notable for its high energy absorption efficiency and its ability to resist delamination. The use of spacer yarns in the thickness direction enhances the overall structural stability (Haik et al., 2017; Kadi et al., 2019; Prasad Gowda, Ravindra 2023).

Geosynthetic Cementitious Composite Mats (GCCMs) or Concrete Canvas is a 3D fabric reinforced cementitious material that is especially notable due to its high potential as a sustainable product in infrastructural projects. It has several advantages, including simple storage, quick transport, rapid strength growth, and minimum dust pollution). Unlike conventional TRCC which uses slurry-filling technology, GCCM involves the pre-filling of a cement-based powder into the spacer layer of the 3D fabric. Figure 1 (a) provides a typical 3D spacer fabric and its orientation. Moreover, GCCM may be easily shaped and distorted to fit a variety of working surfaces, such as canvas, and it can be immediately sprayed with water to solidify and mould it as seen in Fig. 1 (b). The solid surface of the GCCM then hardens with the addition of water to create a thin coating of concrete that is resilient to fire, watertight, and abrasion. As a building or component is being built, it may tightly cover any surface without the need of mixing tools, similar to soft fabric. Additionally, this prevents the necessity for conventional procedures such as blending, molding, and extracting (Li et al., 2019). The applications of this material vary from inflatable tents and ditch lining to slope protection, building restoration, and reinforcement (Ding et al.,2020; Jafari et al., 2020; Ding et al.,2022; Liu et al., 2023; Eller et al., 2023; Xiang et al., 2023. In comparison to traditional materials used for slope protection layers, such as shotcrete layers, GCCMs offers easier, and more cost-effective installation process, providing substantial benefits like reduced environmental impact, shortened construction periods, and lower labor costs. Furthermore, it is effectiveness in rapidly constructing slope protection, such as emergency slope protection or heavy rainfall (Li et al. 2016; Zhang 2020).

According to Bao (2013) and Han et al. (2014; 2016 (a); 2016 (b), the characteristics of the components, such as the kind of cement matrix, type of fibre, and geometric pattern of the fabric, directly influenced the mechanical strength and volume stability of GCCMs. The matrix of GCCMs after hydration is very dense due to the use of tiny particle cement powder and completely hydrated cement powder (Xu et al., 2018; Lin and Chen 2018; Lin et al., 2018; Lu et al., 2018). In comparison to shotcrete, GCCMs can prevent the creation of dust and reduce construction noise during slope protection, reducing the health risks to workers and the disruption of the surrounding environment. Construction is also more practical in CC due to the lesser requirements for equipment and labour expertise. Construction costs and building time are both greatly reduced because to GCCMs. A single structure may cover a slope, a drainage ditch at the top of the slope, and a drainage ditch at the bottom of the slope with excellent integrity since the revetment built using it consistent in thickness. Moreover, the reinforcing effect might increase the stability of a slope during seismic activity (Bao 2013; Zhou et al., 2019; Cheng et al., 2020).

While infrastructure building is accelerating, the execution of some projects is prone to causing extra complications. A difficult one among them is an extensive bare slope, which readily causes shallow landslides, soil erosion water runoff etc. (Zhang et al., 2017). Nevertheless, with the development of GCCMs, it has steadily evolved into an eco-friendly building material for effective slope protection due because of its reduced in dust and quick construction (Haik et al., 2017), as provided in Fig. 2.

Slope protection necessitates a high level of stability and stress resistance. Studies have been started to evaluate the seismic response of reinforced CC to study the impacts of varying CC tilt degrees with a series of shaking table tests (Haik et al., 2017). Because of its high tensile and shear strengths strength, FRP-reinforced CC safeguard against the risk of landslides in complex situations and greatly enhanced the safety factor (Li et al., 2019). The flexural and tensile characteristics of reinforced CCs were studied using uni - axial tensile and bending tests in the weft and warp directions. According to (Haik et al., 2017) tensile and flexural parameters, were increased significantly in reinforced CC samples. The influence of 3D fabric orientation on the flexural characteristics was greater in the warp direction. Amzaleg et al. (2013) studied the flexural strength of CC reinforced with 3D warp knitted cloths and found that the flexural strength and elongation at break of 3D fabric made of aramid yarns was stronger than that of 3D polyester fabric. The mechanical characteristics of 3D warp knitted fabric reinforced cementitious composites. They adopted a modified ultra-high molecular weight polyethylene layer incorporating carbon nanotubes to enhance the tensile strength. Mechtcherine et al. (2018) investigated the tensile and flexural characteristics of 3D-reinforced CC. They observed that the spacer yarns had no effect on the tensile performance. Comparing GCCM to conventional concrete processes results in considerable carbon savings. According to Concrete Canvas Ltd.'s CO_2 Footprint Study (2022), one square metre of GCCM used for channel lining will contain 45% of the embodied carbon of an equal square metre of traditional poured concrete. Two 17-tonne ready-mix concrete trucks may be simply replaced by one pallet of CC. It is furthermore offered as man-portable, pre-cut batched rolls. This significantly minimise the number of vehicle transfers while making it much easier to carry and use. The 3D matrix traps the speciality cementitious material, preventing material loss during installation. As a solution, CC may be laid and hydrated within active watercourses with a low loss of fines of roughly 3% as opposed to the typical of 10–15% seen when utilising specialised underwater concretes. Particularly in applications for channel lining, slope protection as seen in Fig. 3 where the surface is typically damp and offers the ideal circumstances for development, the fibrous top surface layer of CC is the ideal surface for the growth of moss and algae.

In summary, the use of 3D spacer fabric in slope protection, particularly in Cementitious Composite, offers reinforcement in the thickness direction. This characteristic proves advantageous in reducing de-bonding failure when compared to the conventional two-dimensional geotextiles employed in slope protection. Consequently, GCCMs exhibits significant capabilities and is continuously evolving to address the challenges in slope protection. On one hand, the environmental protection scenario is worsening due to pollution from traditional building materials like cement and gravel, limiting manufacturing and transportation options. Conversely, its simple operation and low labor intensity present effective solutions to issues such as labor reduction and inconsistent employee qualities in slope protection. Simultaneously, it is imperative to enhance the capabilities and expand its usage by exploring new materials and introducing innovative customization approaches.

2 EXPERIMENTAL WORK AND TEST METHODOLOGY

Geosynthetic Cementitious Composite Mats is made out of cement powder packed in between a 3D spacer fabric, as shown in Fig. 4 (a) was used in the present work. The manufacturing technique as well as the basic material have a significant impact on the mechanical characteristics. The 3D spacer fabric is essential for establishing a space for the cement powder infill and improving the composite's tensile strength. The thickness of 3D spacer fabric ranges from 8 to 20 mm, with a maximum thickness of 60 mm depending on the type of weaving machinery used. Table 1 provides the dimensions and properties of the GCCM used in the current study. Tests such as tensile strength with cement matrix filled and without cement matrix in a parallel and perpendicular direction According to ASTM D-5035, the uni-axial tensile strength of the concrete fabric was tested in various alignments (X and Y). Six specimens, each 30 x 120 mm in size, were used for the test, three of which will be cut perpendicular to the fibers and the remaining three parallel. Using the ravelled strip and cut strip methods of testing, ASTM D5035 offers a testing process for measuring the maximum force and elongation at maximum force of different textiles. The experimental setup for evaluating the tensile strength of Geosynthetic Cementitious Composite Mats is shown in Fig. 4 (b). The experiment adhered to the ISO standard [24] guidelines, Previous research [13] involved puncture tests on GCCM materials, which are valuable for simulating real-world scenarios, particularly in instances where the GCCM layer lacks support (e.g., railway tracks, localized failures). In this experiment, samples measuring 250×250 mm^2 were prepared and affixed to two circular profiles with a minimum diameter of 150 mm. The samples were unsupported from below, while a 50 mm diameter plunger applied the load. Loading continued until the initial crack appeared, followed by continuous loading until both the textile and PVC layers were torn

Table 1
Dimension and properties of Geosynthetic Cementitious Composite Mats.

Thickness (mm)	Size of batch roll (m2)	Width of the roll (m)	Density (kg/m3)	Mass (kg/m2)
8	10	1.10	1500 ± 50	10

Three-point tests was adopted to determine the flexural behaviour of GCCM and the test was performed in accordance to ASTM D8058-19 with six identical samples with dimensions of 50 ×125 mm (X and Y directions). The specimen with a rectangular section was placed on a steel support base as given in Fig. 5, the span is adjusted, and a vertical force is given to the specimen's centre location until the failure. Although there is undoubtedly a concentration of stress at the site of loading, three-point bending results in a uniform bending moment and pure bending loading. The support span, displacement rate, and bending load all have an impact on the bending strength of GCCM. The size of the specimens determines the support span, the displacement rate is fixed as 0.5 mm/min, and the bending load is kept within the load capacity range. To test the compressive strength, a 300 x 300 mm square specimens were used in accordance with the ASTM D8329 standards. The specimens were loaded for ultimate load and the displacement was noted.

3 RESULTS AND DISCUSSIONS

Figure 6 (a) and Fig. 7 (a) depicts the tensile properties of 3D textiles in terms of warp and weft orientations. The fabric stress-strain curves show a significant strain under the preload at the start of the tensile test due to deformation in the GCCM fibre and elongation. The width of sample in the transverse (perpendicular) direction to the tensile axis decreased as the expanding process progressed and withstood tensile tension, and the force. The findings confirmed that the tensile strength is differed due to the materials' different structures. Figure 6 (b) Fig. 7 (b) illustrates the tensile performance of the composites with cement matrix. The parts were stretched at the start of the test, and afterward, the top layer of 3D fabric was not torn, but the bottom layer, along with the layer impregnated with the adhesive and the 3D fabric spacer yarns, was torn; this behaviour was observed for all specimens irrespective of the orientation of the fabric. The form of GCCMs changes during the tensile test based on the type of stitch structure and the fabric's warp or weft direction. The ultimate tensile stress with parallel orientation in filled with cement mortar was in the range of 1.86 MPa whereas; the same has been increased as around 4 MPa. This is clearly indicating that the fibres make a full contribution in the tensile performance of the GCCMs. In the case of perpendicular alignment, the tensile strength was 5 MPa and 6 MPa for Composite Mats with out and with cement in filled. This could be a reason that the in filled has not been influenced in the tensile properties. Table 2, provides the various mechanical properties of the GCCMs studied in this present work. Similarly, the flexural properties were provided in Table 3.

Table 2
Tension test performance of Geosynthetic Cementitious Composite Mats (GCCMs).

Test performed	orientation of GCCMs	Specimen Nos.	Ultimate Tensile Stress (MPa)	Young's modulus (MPa)	Maximum Force (kN)	Tensile stress at Yield (MPa)	Displacement at Yield (mm)	Tensile strain at Tensile strength (%)
Tension	Parallel without Cement Matrix	1	4.29	20.71	0.57	3.94	15.08	33.34
		2	3.72	18.89	0.49	3.41	13.22	27.69
		3	3.78	17.94	0.50	3.48	11.99	28.10
	Parallel with Cement Matrix	1	6.97	4805.5	1.30	4.99	0.17	15.05
		2	4.76	4208.1	0.90	2.88	0.17	9.74
		3	6.69	6041.6	1.25	5.05	0.16	14.93
	Perpendicular without Cement Matrix	1	1.90	6.10	0.27	1.69	37.56	66.46
		2	1.85	5.84	0.26	1.85	36.92	60.99
		3	1.84	4.88	0.26	1.72	35.98	70.17
	Perpendicular with Cement Matrix	1	4.49	3310.8	0.78	3.18	0.18	24.46
		2	4.45	3193.6	0.78	3.07	0.18	9.67
		3	4.50	4523.8	0.78	3.77	0.18	9.06

Under flexural load, the GCCMs fails due to a flexure mechanism in the parallel direction, whereas shear and a flexure mechanism in the perpendicular direction produce failure. Hence, the test was performed in parallel direction with cement mortar. The load-deformation curve includes elastic and numerous fracture stages. The former is caused by a break in the cement matrix, whereas the latter is caused by the structure of the spacer fabric. The hardness of CC is much higher than that of pure cement matrix. The average flexural strength was 21 MPa which supports that the values are in the acceptable range. Compressive strength of the Geosynthetic Cementitious Composite Mats was presented in Fig. 9 and it was found that the strength was around 38 MPa at the end of 2 days of curing. Also, it has been noted that the s Composite Mats attained the maximum strength at the early age and there was not any significant increase in the strength at 14 and 28 days.

Table 3
Flexural performance of Geosynthetic Cementitious Composite Mats in perpendicular and parallel orientation

Test performed	orientation of CC	Specimen Nos.	Flexural Stress (MPa)	Young's modulus (MPa)	Maximum Force (kN)	Flexural stress at Yield (MPa)	Flexural strain at Yield (%)
Flexural	**Perpendicular**	1	21.36	3329.71	0.37	10.49	3.80
		2	24.11	2207.68	0.41	11.48	2.86
		3	20.26	2187.94	0.35	10.56	2.61
	Parallel	1	15.65	2065.03	0.20	07.65	1.62
		2	18.65	1920.68	0.30	06.20	2.02
		3	15.03	2010.20	0.29	06.89	1.98

CONCLUSION

Based on the tested conducted on the Geosynthetic Cementitious Composite Mats, the following conclusion has been derived.

- The study finding highlight that the Geosynthetic Cementitious Composite Mats are exceptionally well-suited for providing support under static stresses, effectively protecting the slope of any structural member. The material demonstrates the ability to be loaded to achieve optimal form, and subsequent application of Geosynthetic Cementitious Composite Mats, helps drive the material down to the supportive protection layer.
- In terms of mechanical properties, it was found that GCCMs exhibit superior tensile strength and lower strain in the weft direction compared to the warp direction. This observation held true both with and without the presence of a cement matrix, indicating a consistent pattern of performance.
- The Young's modulus in the parallel direction was found to be approximately 10% higher than that in the perpendicular direction during testing. This distinction in modulus values was consistently observed in both patterns, emphasizing the directional dependence of the material's mechanical behaviour.
- Notably, when the Geosynthetic Cementitious Composite Mats was oriented perpendicularly, it enhanced flexural strength. The study showed a 25% increase in strength compared to the parallel direction, highlighting the influence of orientation on the flexural performance.
- The compressive strength of GCCMs was found to be around 40 MPa, and notably, this strength was achieved at the early age of 2 days. This promising result suggests that it holds considerable potential for use in slope protection, providing early and robust support for various infrastructure engineering applications.

Declarations

Author Contribution

Manju, R., Idae, Concept, Sakthivel, Writing, Testing, Experimentation; Sindhu Vaadhini, Testing, Experimentation

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Figures

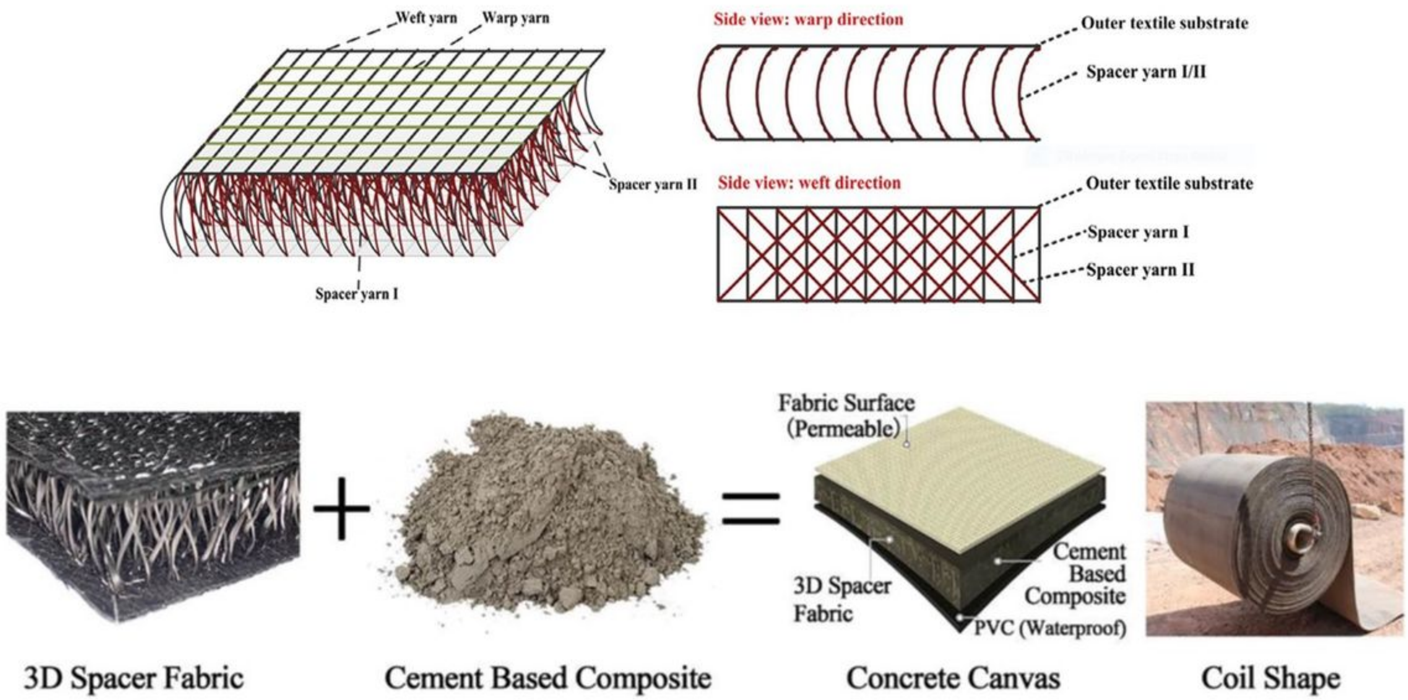


Figure 1

(a) A typical 3D spacer fabric (Han et al., 2014)

(b) A typical process of making a Geosynthetic Cementitious Composite Mats.

Figure 2

Application of Geosynthetic Cementitious Composite Mats as slope protection (Li et al., 2019)

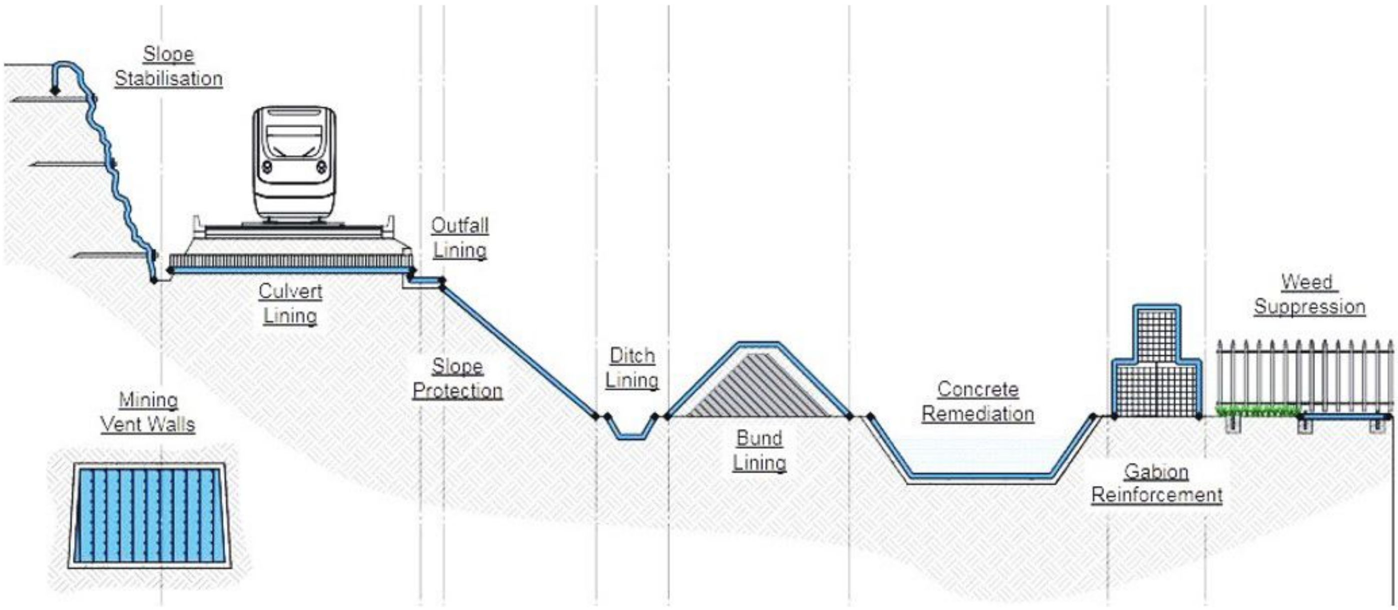


Figure 3

Geosynthetic Cementitious Composite Mats in different engineering applications.

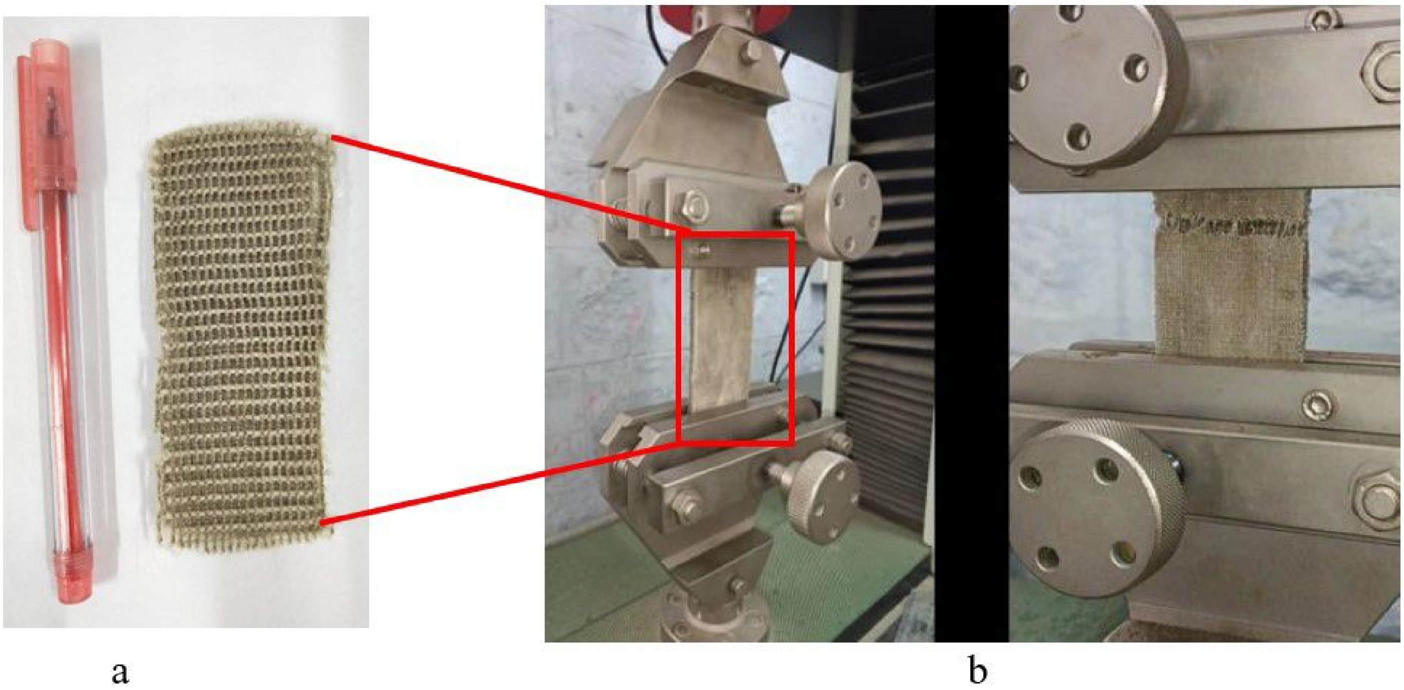


Figure 4

(a) Geosynthetic Cementitious Composite Mats

(b) Testing of Geosynthetic Cementitious Composite Mats for tensile strength

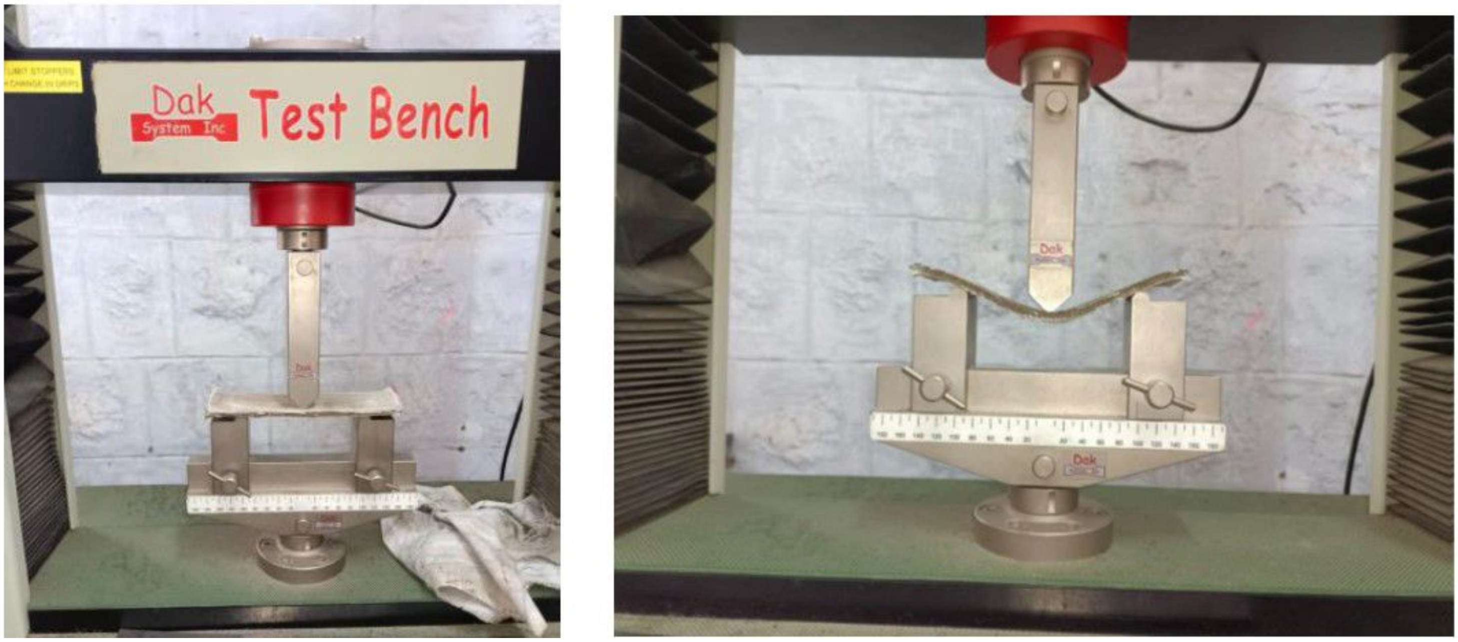


Figure 5

Experimental setup for flexural strength of Geosynthetic Cementitious Composite Mats

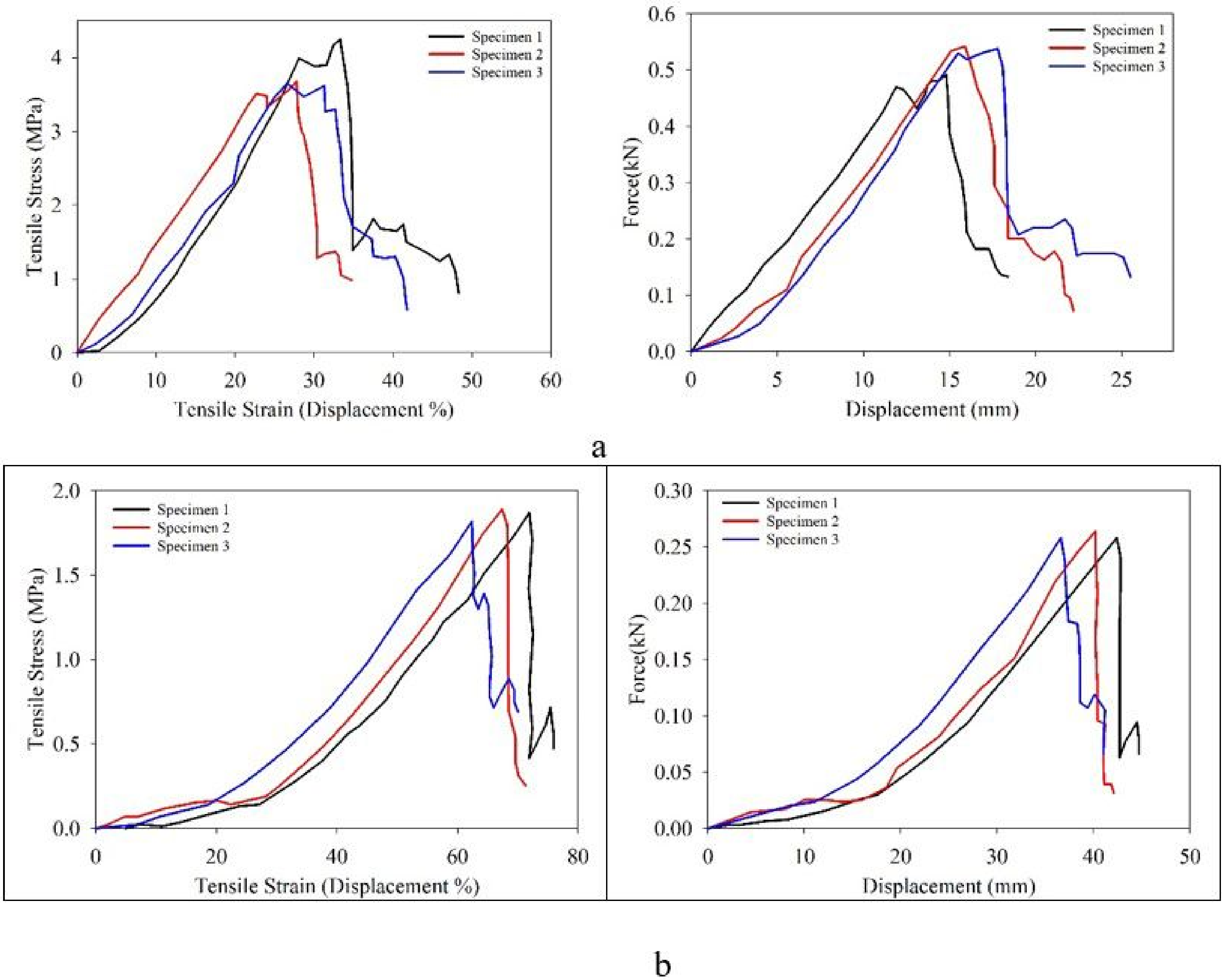
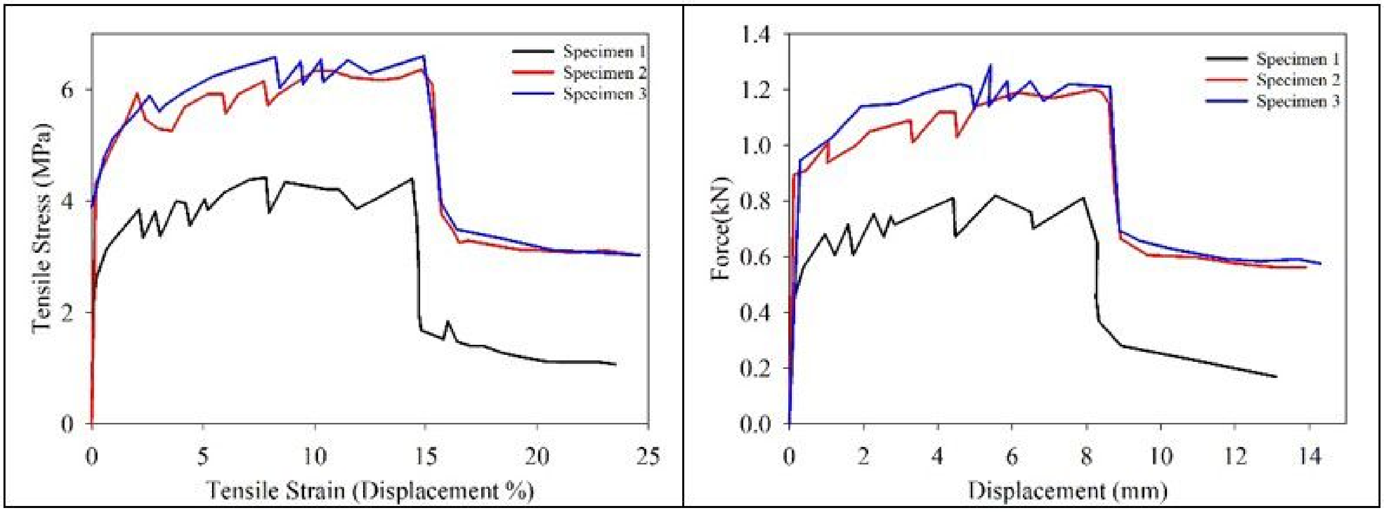


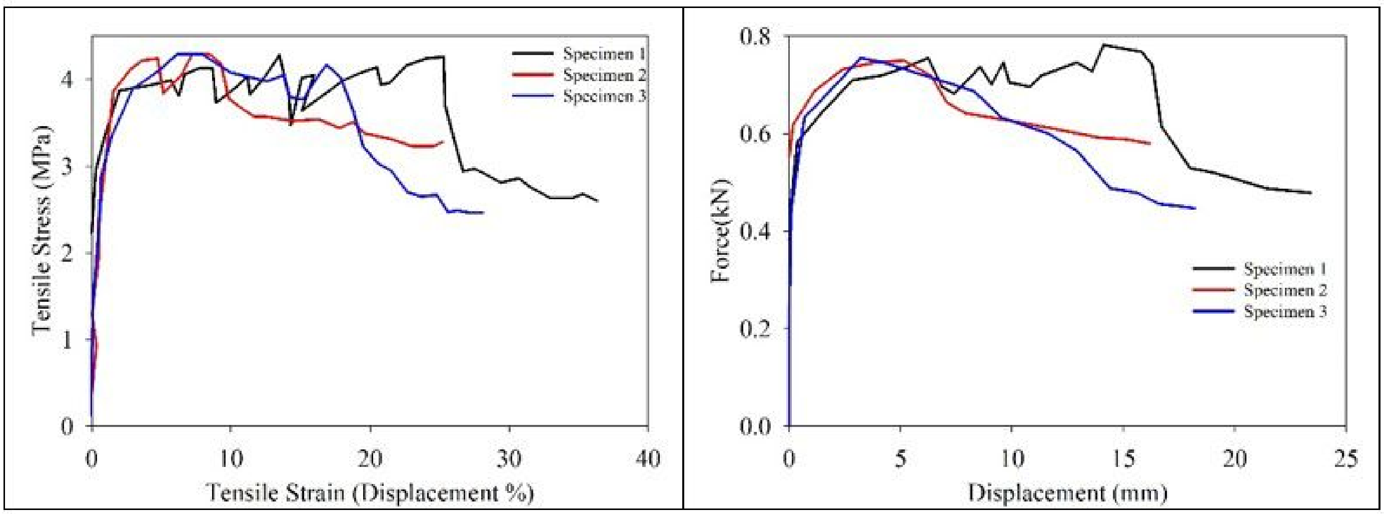
Figure 6

(a). Stress Vs Strain and Force Vs Displacement of GCCM without cement matrix in parallel to the direction of weaving.

(b). Stress Vs Strain and Force Vs Displacement of GCCM without cement matrix in perpendicular to the direction of weaving.



a



b

Figure 7

(a). Stress Vs Strain and Force Vs Displacement of GCCM with cement matrix in parallel to the direction of weaving.

(a). Stress Vs Strain and Force Vs Displacement of GCCM with cement matrix in parallel to the direction of weaving.

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Figure 8

Flexural performance of Geosynthetic Cementitious Composite Mats in perpendicular and parallel orientation

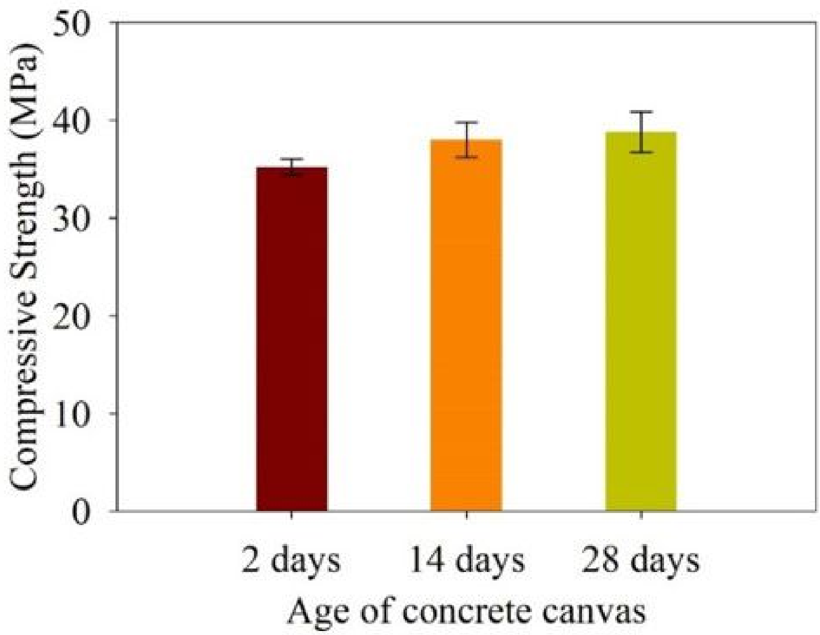

Figure 9

Compressive strength of Geosynthetic Cementitious Composite Mats.