J Sustain Const Mater Technol, Vol. 8, Issue. 1, pp. 47–56, March 2023

Journal of Sustainable Construction Materials and Technologies
Web page info: https://jscmt.yildiz.edu.tr
DOI: 10.47481/jscmt.1207739

Journal of Sustainable Construction Materials and Technologies

Research Article

Pattern and filament optimization for 3D-printed reinforcements to enhance the flexural behavior of cement-based composites

Eren GÖDEK[1], Seyfi ŞEVİK[*2], Özgür ÖZDİLLİ[3]

[1]*Department of Construction Technology, Hitit University Vocational Faculty of Technical Sciences, Çorum, Türkiye*
[2]*Department of Electrical and Energy, Hitit University Vocational Faculty of Technical Sciences, Çorum, Türkiye*
[3]*Department of Machinery and Metal Technology, Hitit University Vocational Faculty of Technical Sciences, Çorum, Türkiye*

ARTICLE INFO

Article history
Received: 21 November 2022
Revised: 03 February 2023
Accepted: 23 February 2023

Key words:
Acrylonitrile butadiene styrene, cement, flexural performance, Polyamide, Polyethylene terephthalate glycol, 3D-printing

ABSTRACT

Cement-based materials are the world's most widely utilized construction materials due to their high compressive strength. However, they need reinforcement to withstand direct or indirect tensile forces. This study evaluated the potential use of 3D-printed polymers as an alternative reinforcement in cement-based composites. Polyethylene terephthalate glycol (PETG), Polyamide (PA), and Acrylonitrile butadiene styrene (ABS) based triangular and honeycomb-patterned 3D-printed reinforcements were incorporated into cement-based composites, and their mechanical performances were compared under three-point flexural tests by considering both polymer and pattern type. Both triangular and honeycomb patterns enhanced flexural behavior. Considering all filaments, the honeycomb pattern was found more effective than the triangular one for increasing flexural strength, deflection capacity, and toughness up to 46.80%, 251.85%, and 77.66%, respectively. In the case of filament type, 3D-printed PA-type filament in a honeycomb pattern preserved flexural strength, enhanced deflection capacity, and increased flexural toughness with pseudo-deflection hardening behavior. 3D-printed honeycomb patterned reinforcements produced by PA have the opportunity to be used in the manufacture of cement-based composites.

Cite this article as: Gödek, E., Şevik, S., & Özdilli, Ö. (2023). Pattern and filament optimization for 3D-printed reinforcements to enhance the flexural behavior of cement-based composites. *J Sustain Const Mater Technol*, 8(1), 47–56.

1. INTRODUCTION

Three-dimensional (3D) printing (also known as additive manufacturing (AM)) has been defined as the process of producing a 3D model product in which complex structures can be built using single or different raw materials. According to ASTM F2792-12 [1], AM was described as "a process of joining materials to make objects from 3D model data, usually layer upon layer". The 3D printing technology used metals, polymers, ceramics, concrete, food, living cells, and organs, while material forms included filaments, powder, paste, resins, and inks. In manufacturing objects, 3D printing technology

***Corresponding author.**
*E-mail address: seyfisvk@hotmail.com

Published by Yıldız Technical University Press, İstanbul, Türkiye

has introduced the creation of customized geometry, the possibility of making changes and detecting errors before manufacturing a product, and effective cost management. Hull [2] applied for a patent in 1984 to produce 3D objects using stereolithography (SLA) technology. Steven Scott Crump filed a patent in 1989 for another 3D-printing technology, fused deposition modeling (FDM) [3]. 3D-printing techniques developed rapidly. After the mid-2000s, with the rapid development of household products and affordable prices, 3D technology has been in incredible demand. It has enormous potential for new product fabrication, prototyping, hybrid applications, and structural reinforcement. 3D printing technology for cement-based applications is now generating considerable attention.

Due to their low strength under tensile loads, cement-based construction materials need reinforcements such as steel reinforcing bars [4,5], polymeric and metallic fiber reinforcements [6], and various fiber types [7-8]. Başsürücü et al. [5] stated that the concretes incorporating long hooked-end steel fibers exhibited deflection hardening behavior, while the short straight steel fiber and polypropylene synthetic fibers incorporating concretes exhibited deflection softening. Zhang et al. [7] investigated the flexural behavior of engineered cementitious composites incorporating polyvinyl alcohol and polyethylene fibers and enhanced the flexural strengths by up to 247.2% compared to reference composite. Doğan et al. [8] studied concrete with carbon fiber incorporating recycled ferrochrome slag aggregate. They reported that reinforced concrete with recycled ferrochrome slag aggregate provides superior mechanical and electrical properties to regular concrete, providing lower production costs and energy savings. There has been a recent search for different products for more effective solutions. In literature, applications for 3D-printing with different materials such as bio-inspired polymeric reinforcement, composites, silica sol, ceramic, concrete, steel fiber, polypropylene synthetic fibers, and wax have been used [9,10]. Rosewitz et al. [9] examined the mechanical performances of their new design products in terms of flexural strength, flexibility, toughness, and compressive strength. When the literature is examined, it is seen that although there are significant changes in performance according to the characteristics of the reinforcement product, most of the products used as reinforcement products provide specific improvements on the concrete.

Studies on 3D-printed reinforcements for cement-based materials are limited. In the studies, metallic materials, Acrylonitrile butadiene styrene (ABS) reinforcement, Polyethylene terephthalate-glycol (PETG) structures, and Polylactic acid (PLA) were used as 3D-printed reinforcement materials for cement-based materials [5,6,11-18]. Xu and Šavija [11] tested both bending and tensile performances and achieved significant performance improvements. Shweiki et al. [12] printed PLA and PETG-based products as reinforcements and observed bending behaviors. PETG-reinforced samples showed better flexural behavior than PLA-reinforced samples in terms of ultimate loads and deformations, which was almost double, and the deformation of PETG samples at final loads was found to be three times that of PLA samples. Salazar et al. [15] investigated the use of 3D octet lattice structures made of PLA and ABS materials instead of steel reinforcement. Flexural test results showed that all truss-reinforced beams exhibit strain hardening up to peak load. In addition, multiple cracking and crack expansion were observed in the samples up to the peak load [15]. Xu et al. [16] used ABS-based octet lattice structures for reinforcement. They stated that the refined products did not meet the steady-state cracking criteria; however, they suggested increasing the strength of the reinforcement material by 40%. Santana et al. [18] studied composites reinforced with homogeneous or graded PETG structures and compared the PLA and PETG. Even though PLA natural polymer outperformed PETG in terms of mechanical properties, it lost around 50% of its tensile strength and elastic modulus after exposure to alkali solutions. The above studies have shown that the products generally used in 3D-printing technology have advantages and disadvantages against each other due to their material content.

The honeycomb structure's application fields have significantly increased since the discovery of its unique geometry. The honeycomb construction and its structural usage started in 1914 with a patent of Hofler and Renyi [19]. Honeycomb core's first use in the modern sense was carried out on aircraft in the 1940s to reduce weight and increase flight distance and payload. However, its usage areas are expanding rapidly. Due to the structural opportunities it offers, the honeycomb structure has been widely applied in a variety of fields, including mechanical engineering (e.g., to increase the heat storage efficiency in the solar collector [20]), architecture (to reduce the weight of structures, absorb vibrations and provide thermal and acoustic insulation) and aviation industry (to reduce weight and increase payload and flight distance). Habib et al. [21] conducted a simulation study on nine different honeycomb types and stated that the unit cell geometry and arrangement seriously affect the compression response of the honeycombs and ensure different energy absorption properties. Katzer and Szatkiewicz [14] printed the honeycomb geometry using ABS filament to reinforce the concrete beams. The F_{max} values in some specimens were equal from 74% to 98% of pure mortar; however, the reinforced mortar beam with H=20 mm and D=2.00 mm was equivalent to 184% of the pure mortar. In our previous pioneering work, honeycomb-shaped reinforcements of two different thicknesses (1 and 2 mm) with a combination of protrusions (flat and protruded) were produced by the use of PLA filament and used as reinforcement in cement-based composites [17]. Three-point bending tests were performed to determine the flexural behavior of these composites. The results showed that the flexural performance of composites changed depending on the thickness and protrusion combinations, and accordingly, the flexural strengths, deflection capacities, and toughness values ranged between 2.30-3.04 MPa, 0.045-0.588 mm, and 15.92-652.37 N.mm, respectively. The 2 mm thick and protruding specimens showed significant improvement in the spurious deflection hardening behavior, which is considered an essential criterion for performance improvement [17].

As seen from the literature, different designs and different products have been studied, and significant contributions have been made to the literature, but issues such as printing geometry or polymer type still need to be investigated. Based on the recent literature, it has been seen that the most common polymer types used in studies are PLA, PETG, and ABS. This study analyzes the possibility of using 3D-printed reinforcements as an alternative reinforcement element in cement-based composites. In addition to the literature, the effect on the performance of different designs of well-known geometries, such as triangles and honeycombs, and three different printing material types (PETG, ABS, and PA) are investigated. Therefore, triangle-patterned and honeycomb-patterned 3D-printed reinforcements were formed using PETG, ABS, and PA, added to the cement mortars as a reinforcement, and mechanical performances of cement-based composites were compared under three-point flexural tests by taking both printing geometries and polymer type into consideration.

2. MATERIALS AND METHODS

Cement mortars with a cement:aggregate: water ratio of 1:3:0.50 was prepared using CEM I 42.5 R type cement and micro silica powder below <400µm. The chemical, physical and mechanical properties of cement are given in Table 1. This combination is known as a reference mortar in TS EN 196-1 standard [22]. In this study, the mixture was modified by replacing micro silica sand with standard sand, and a superplasticizer of 0.1% of cement by weight was used to achieve proper workability for casting.

Due to the balance between strength and ease of printing, Table 2 shows the characteristics of the ABS and PA nylon. PETG and ABS are the most consumed materials in 3D printing, with good mechanical properties. Both materials have good shock resistance. The ABS is the plastic par excellence at the time of creating parts of all kinds in the industry. The ABS offers hardness, resistance to some chemical elements, rigidity, and stability at a high temperature like 100 °C. Since PETG has a certain flexibility, products with greater hardness and strength can be obtained. However, the ABS presents can be machined without deformation. PETG is more resistant to sun, rain, and cold and less prone to cracking deformations than ABS. The PA is more resistant to chemical products and has good impact resistance and low friction properties than the ABS. The ABS has better thermal conductivity properties than the PA. Three materials (ABS, PA, and PETG) being compared need similar extrusion temperatures, usually in the wide range of 210-260 °C. Two materials (ABS and PETG) being compared need similar extrusion temperatures, usually in the range of 230-260 °C. Compared to the ABS (1.04 g/cm³), the PA (1.14 g/cm³) has a higher density. The difference in density is about 9%. Blok et al. [23] compared the machinability and performance of four different filaments and stated that PA began to lose mass at about 100 °C and lost 7% of its mass at 300 °C,

Table 1. Chemical, physical and mechanical properties of cement

Chemical Properties (%)		Physical Properties	
SiO_2	17.62	Specific gravity	3.11
Al_2O_3	5.01	Blaine (cm²/kg)	3485
Fe_2O_3	3.17	Retaining on 90 µm sieve (%)	0.6
CaO	63.78	Retaining on 45 µm sieve (%)	17.4
MgO	0.97	Mechanical Properties (MPa)	
Na_2O	0.39	Compressive strength at two day	28.3
K_2O	0.77	Compressive strength at seven day	40.1
SO_3	3.10	Compressive strength at 28 day	49.9
Loss on ignition	2.48		
Cl-	0.006		
Insoluble residue	0.19		
Free CaO	1.09		

Table 2. Characteristics of the ABS, PA, and PETG nylon (Data obtained by manufacturer of filaments)

Feature	ABS	PA Nylon	PETG
Melting temperature (°C)	170-220	220	220-245
Printing temperature (°C)	210-250	230-250	230-260
Printing bed temperature (°C)	80-110	>110	80-90
Density (g/cm³)	1.04	1.14	1.27
Specific heat capability (J/g °C)	1.6-2.13	1.6	1.47-1.53
Thermal conductivity (W/m K)	0.128-0.187	0.25	0.162-0.225
Thermal expansion coefficient	Good	Very good	Good
Strength	Good	Very good	Very good
Flexibility	Medium	Very good	Good
Heat resistance	Good	Good	Medium
Cold resistance	Medium	Medium	Good
Water resistance	Medium	Good	Good
Chemical resistance	Medium	Very good	Good
Machinable	Very good	Good	Medium
Stiffness	Good	Medium	Good
Durability	Good	Very good	Good

ABS: Acrylonitrile butadiene styrene; PA: Polyamide; PETG: polyethylene terephthalate glycol.

while ABS lost less than 1% of its mass. Compared to ABS (1.04 g/cm³), PETG (1.27 g/cm³) has a higher density. The difference in density is about 20%.

Two different geometries, honeycomb, and triangle were used. In addition to these geometries, the protruding structure was created, and the protrusions were applied in the same direction. Honeycomb and triangular patterned reinforcements were designed with a thickness of 4 mm protrusions and printed by using the three types of filaments. These designs were selected based on the previous study of authors [17]. In addition, support pieces have been added at the bottom of the mesh to centralize the printed mesh in the mold for insertion into the mold. 3D schematics of reinforcement designs are presented in Figure 1.

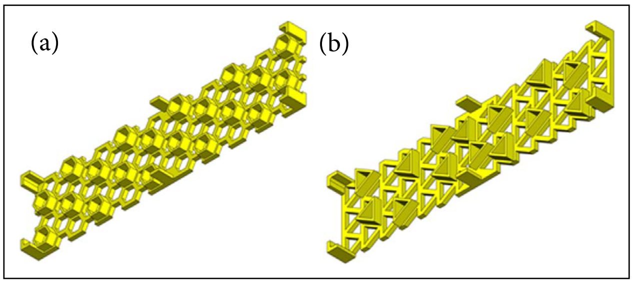

Figure 1. 3D schematics of reinforcement designs **(a)** Honeycomb patterned, **(b)** Triangular patterned

The product idea is transformed into digital data employing CAD; multifunctional material systems with complex shapes are transformed into a CAD-guided 3D product; a virtual object is created, which is digitally sliced; layered data is transferred to a 3D printer; and finally, manufacturing of the model or product is printed with the 3Dprinter but at a slower rate than conventional polymer processing. The 3D-printed part with FDM has visible layer lines. However, the SLA has sharp edges, a smooth surface finish, and minimal visible layer lines. Therefore, FDM is more effective in adhering to concrete than SLA.

In the 3D-printing process, the ZAXE Z1 model 3D filament printer was used. Figure 2 shows the 3D printing process of the reinforcements and their printed versions. Figure 2a shows the step of reinforcement printing in the 3D printer. Support legs were added at six different points to keep the reinforcements at a certain level in the mortar. Three replicates of each design were produced for three replications. Figure 2b shows the PETG reinforcement products printed with a 3D printer.

PA filament was processed at 250 °C at 0.15 microns. Its high yarn structure makes it difficult to produce small micron sizes in ABS filament. Therefore, ABS nylon filament was processed at 240 °C at 0.3 microns. The PETG filament was processed at 0.1 microns and 245 °C. As a hybrid of the two materials, PETG is somewhat more heat resistant than PLA and a little bit stronger than ABS. FDM printing parameters for ABS, PA, and PETG specimens are given in Table 3.

First, 3D-printed reinforcements were placed into 40×40×160 mm steel molds. Then, the cement mortar was prepared in a laboratory-type mixer confirming with TS EN 196-1 [22] and filled into molds. Reference specimens and three specimens for each series were molded, and 21

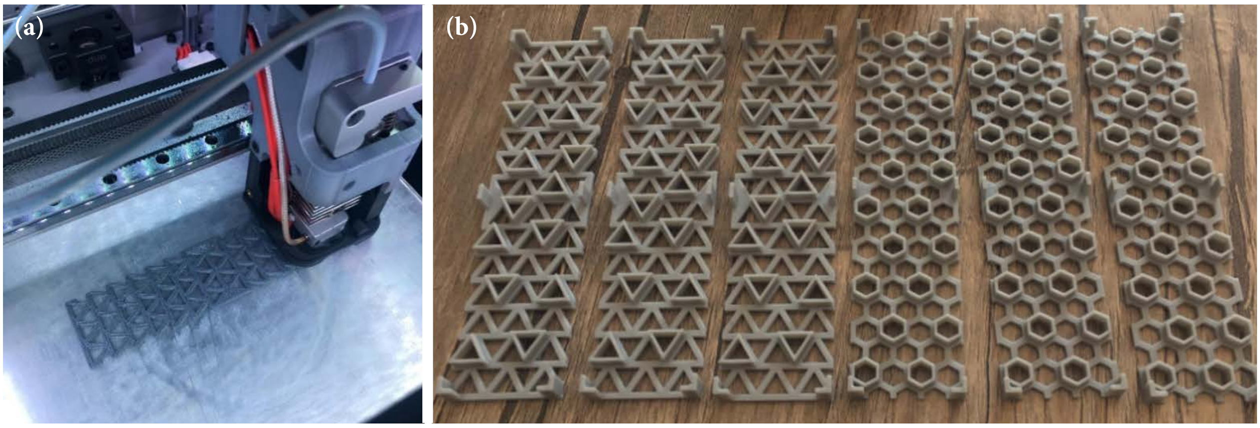

Figure 2. 3D printing of reinforcements and their printed versions. **(a)** The 3D-printing process of reinforcements, **(b)** 3D-printed triangular and honeycomb-patterned reinforcements (Photo of PETG reinforcements).

Table 3. FDM printing parameters for ABS, PA, and PETG filaments

Parameters	ABS	PA	PETG
Printing speed (mm/s)	50	10	60
Printing thickness (μ)	0.3	0.15	0.1
Infill density (%)	90	90	90
Diameter (mm)	1.75	1.75	1.75
Nozzle diameter (mm)	0.4	0.4	0.4
Nozzle temperature (°C)	250	240	245
Environment temperature (°C)	22	22	22
Bed temperature (°C)	100	90	70

Fused deposition modeling; ABS: Acrylonitrile butadiene styrene; PA: Polyamide; PETG: polyethylene terephthalate glycol.

specimens were obtained. Mechanical performances of specimens were determined under deflection-controlled three-point flexural tests with a loading rate of 0.5 mm/min. Load and deflection values were saved, and flexural load-mid span deflection curves were drawn for three specimens for each series.

During flexural loading, two prominent cases occur. The load gradually increases. When a crack is formed on the specimen, the load dramatically decreases. The stress calculated using this first cracking load is called the first cracking strength. At this critical moment, if the reinforcement in the cracked section cannot transfer the load, stress accumulation occurs on the reinforcement, and the reinforcement breaks, which is named as deflection softening behavior (Figure 3a). If the reinforcement in the cracked section effectively transfers the load to the uncracked sections, the load tends to increase, exceeds the load on the first cracking stage, and may create new cracks. This behavior is called pseudo-deflection hardening (Figure 3b). The maximum load value was determined and accepted as the peak load in the curves, and flexural strengths were calculated using these values. Corresponding deflection values to the peak loads were determined as deflection capacities. Finally, the area under the curve up to 1.5 mm deflection was calculated and named the relative toughness ($T_{1.5}$) (note that this value is the typical value obtained from all curves, which ensures a practical comparison).

The failure of 3D printed reinforcement was also investigated at the cracked sections of determined specimens using a digital optical microscope. Images were taken between 200-240x magnification levels, where the images became apparent, and results were discussed.

3. RESULTS AND DISCUSSIONS

3.1. Flexural Load – Mid-Span Deflection Curves

Flexural load – mid-span deflection curves of specimens are given in Figure 4. It was clear from the graphics that mechanical performances were remarkably enhanced by the use of 3D-printed reinforcements when compared to reference specimens. In general observation, it has been determined that using honeycomb reinforcing elements is more effective in increasing the flexural performance of composites than triangular patterns (Figure 4b-4d-4f; Figure 4c-4e-g). Detailed comparisons for mechanical parameters will be discussed in the following sections.

3.2. Flexural Strengths

The flexural strengths of composites are given in Figure 5. The dashed line in the graph represents the average strength of reference specimens. Since the reference specimens lacked reinforcement, they abruptly collapsed when the composites achieved their load-bearing capability. Their average bending strength was calculated as 1.84

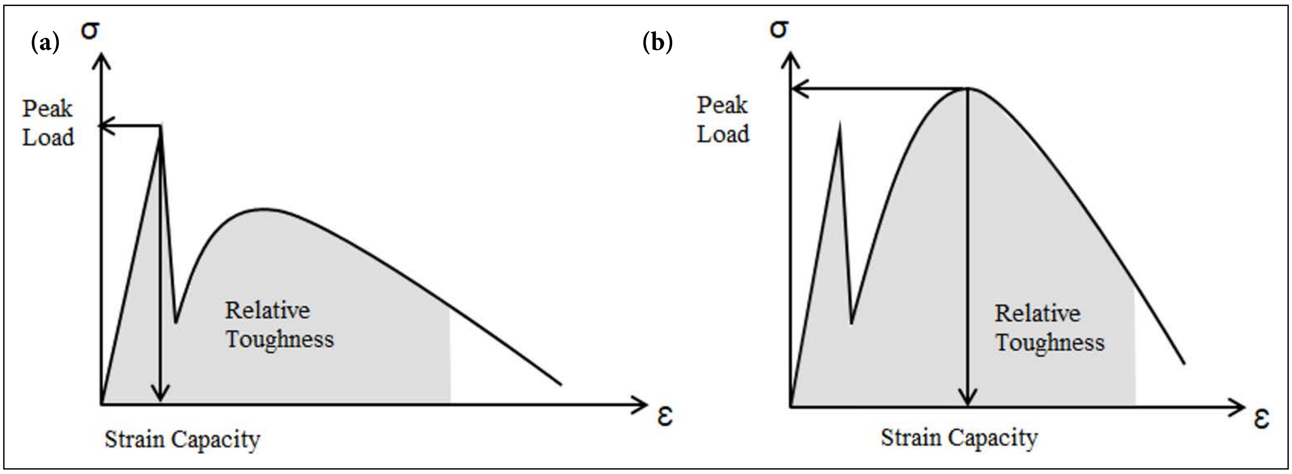

Figure 3. Curves of **(a)** deflection softening, **(b)** pseudo deflection hardening (adopted from the [17]).

MPa. In terms of flexural strengths, all series exhibited higher flexural strength than reference, thanks to reinforcement. When triangular patterned 3D reinforcements were used, PA performed 41.38% and 49.48% higher flexural strength than PETG and ABS, respectively. In using honeycomb-patterned 3D reinforcements, the flexural strength of PETG increased from 2.03 MPa to 2.98 MPa (by 46.80%). Similarly, the flexural strength of ABS increased from 1.92 MPa to 2.47 MPa (by 28.65%). A negligible decrease in flexural strength was observed in the case of PA, which is still higher than ABS.

3.3. Deflection Capacities

The average deflection capacities of specimens are given in Figure 6. As mentioned in the previous section, the dashed line indicated the mean deflection capacity of the reference specimens. Therefore, it was found that the deflection capacities were greatly enhanced compared to the reference. This rate was calculated between 107-730%, approximately. In the case of triangular patterned 3D reinforcement, higher deflection capacity was obtained from PETG (0.52 mm) compared to PA (0.39 mm) and ABS (0.27 mm). However, when the pattern type changed to honeycomb, the deflection capacity of PETG was preserved the same, while the deflection capacities of PA increased by 176.92% to 1.08 mm and ABS increased by 251.85% to 0.95 mm.

3.4. Relative Toughness ($T_{1.5}$)

The average relative toughness values of specimens are given in Figure 7. Similar to previous results, toughness values were significantly increased in all series because of 3D-printed reinforcement (from 35 to 70 times greater than reference). Although the toughness depended on the deflection, it also varied depending on the flexural strengths. As seen in the graphs, in the cases where the same patterns were used, PA ensured the best results in terms of $T_{1.5}$ compared to both ABS and PETG. In the series of triangular patterns, toughness values were calculated as 542.41 N.mm, 661.42 N.mm, and 932.51 N.mm for PETG, ABS, and PA, respectively. When the honeycomb-patterned reinforcement was used, toughness values were increased in all series between 13.20%-77.66% and calculated as; 963.62 N.mm for PETG, 852.79 N.mm for ABS, 1055.64 N.mm for PA. According to Foti [24], who cuts waste PET bottles in different shapes and uses them to reinforce concrete, "O"-fiber concrete adds much more toughness when compared to short lamellar fiber concrete, and specific forms to helped bind the concrete on either side of a cracked portion. As a result, concrete buildings reinforced with polymers such as PETG, PA, and ABS have been shown to have better durability and reinforcing qualities.

3.5. Cracked Section Analysis

Detailed crack patterns of honeycomb-patterned PA specimens, which were found to the advantageous series in terms of mechanical performance, were given in Figure 8. In the figure, images taken from the front side, bottom, and back side of the specimens were presented. Crack branching was observed through the tensile zone where the reinforcement was placed in all specimens, which was assumed as the main reason for the pseudo strain hardening behavior. During the formation of each crack, the flexural load is lowered, which can be seen in the flexural load – mid-span deflection curves easily.

Since the flexural load is taken on by the reinforcements in the cracked sections and transferred to other sections of the composite, slipping and ruptures begin to occur between the 3D printed reinforcement and matrix and the layers of the 3D printed reinforcement in the cracked sections (Figure 9). Due to these slipping and ruptures, relatively small load drops were also observed in the flexural load mid– span deflection curves.

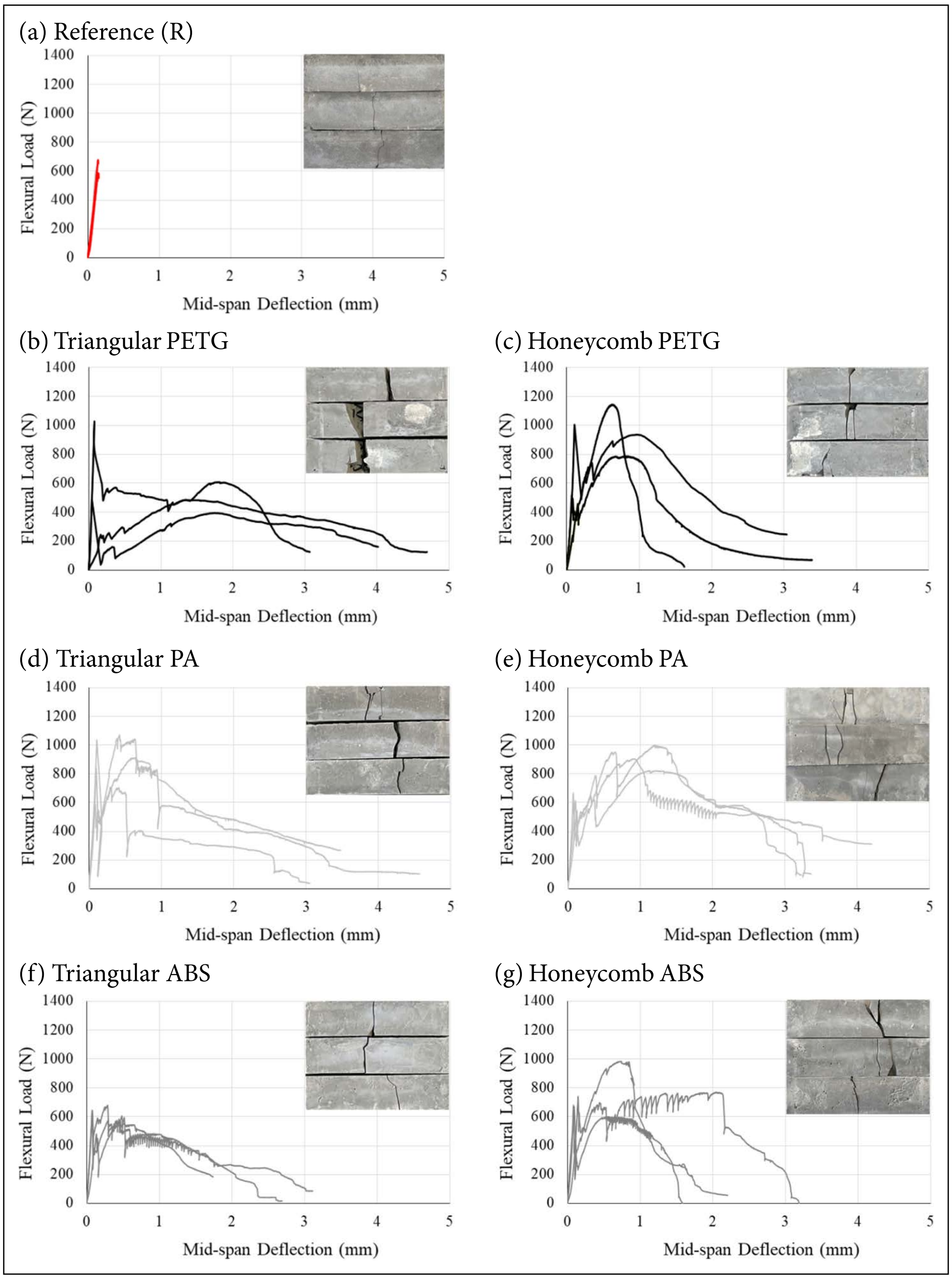

Figure 4. Flexural load – mid-span deflection curves of specimens.

4. CONCLUSIONS

Today, polymer wastes are one of the leading causes of environmental pollution. For this reason, studies on re-evaluating recyclable polymers (thermoplastics) in different areas of use are increasing daily. The concrete 3D printing technique, which has the potential to revolutionize traditional building and construction methods by providing benefits in terms of low cost, high efficiency in automated construction, design freedom, and downsizing [25], can be combined with the 3D printing technique using filaments such as ABS, PA, and PET-G filaments, which are recyclable thermoplastic polymers. This study evaluated the potential use of 3D-printed polymers as an alternative reinforcement in cement-based composites. Within the case, three different 3D-printed polymers (PETG, PA, and ABS) with different geometries (triangular and honeycomb) were prepared, and their mechanical performances under three-point flexural tests were compared.

- The use of the honeycomb pattern further increased flexural strengths compared to the triangular pattern in the case of PETG and ABS. In the PA series, similar val-

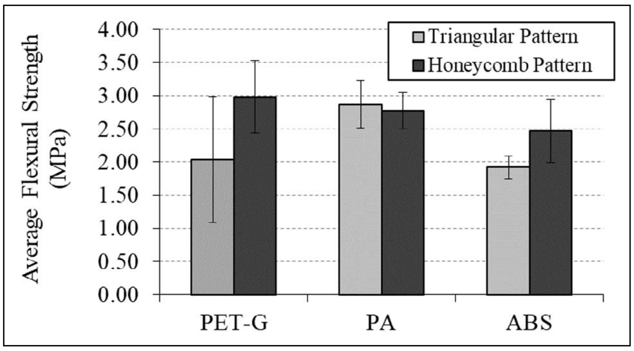

Figure 5. Flexural strengths of composites.

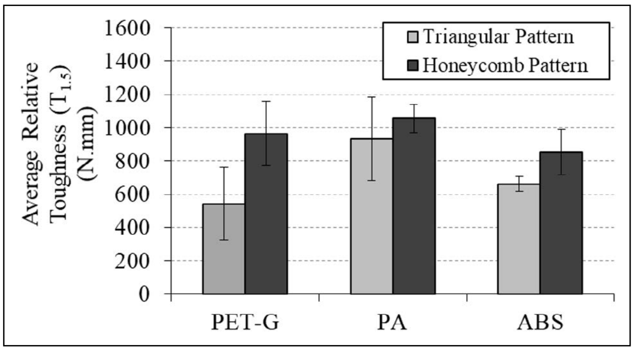

Figure 7. Relative toughness of composites.

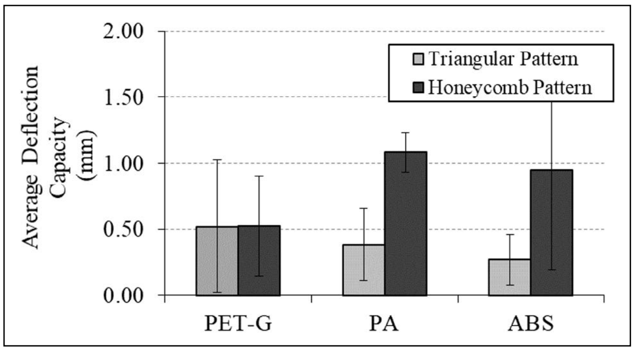

Figure 6. Deflection capacity of composites.

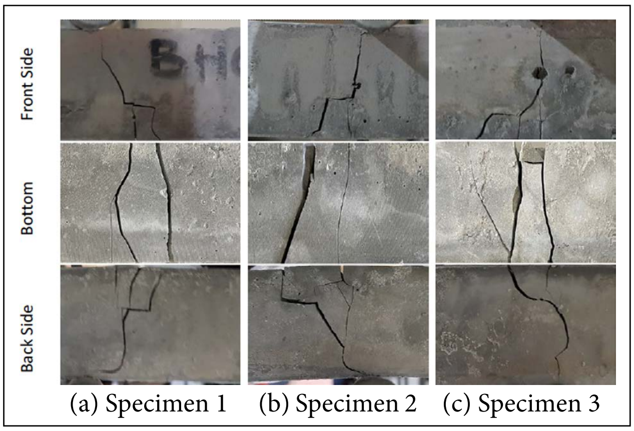

Figure 8. Crack patterns of honeycomb-patterned PA specimens.

ues were obtained regarding flexural strengths by using either triangular or honeycomb patterns.

- When 3D triangular-patterned reinforcements were applied, PA demonstrated flexural strengths that were 41.38% and 49.48% greater than those of PETG and ABS. The flexural strength of PETG and ABS rose by 46.80% and 28.65%, respectively, with the addition of honeycomb-patterned 3D reinforcements.
- When the reinforcement product was altered from a triangle to a honeycomb pattern, PETG's deflection capacity was preserved. However, PA's deflection capacity grew by 176.92% to 1.08 mm, and ABS's deflection capacity increased by 251.85% to 0.95 mm.
- With the application of the honeycomb-patterned reinforcement, relative toughness values improved in all series by 13.20–77.66% and were found as follows: 963.62 N.mm for PETG, 852.79 N.mm for ABS, and 1055.64 N.mm for PA. The use of the honeycomb pattern also exhibited higher results than the triangular pattern in relative toughness repetitively.
- PA gave higher flexural toughness values than PETG and ABS within the same patterns.

In conclusion, this study clearly showed that 3D-printed PA-type filament in a honeycomb pattern is more effective by taking preserved flexural strength, enhanced deflection capacity, and highest flexural toughness into consideration and has the opportunity to be used as reinforcement for ob-

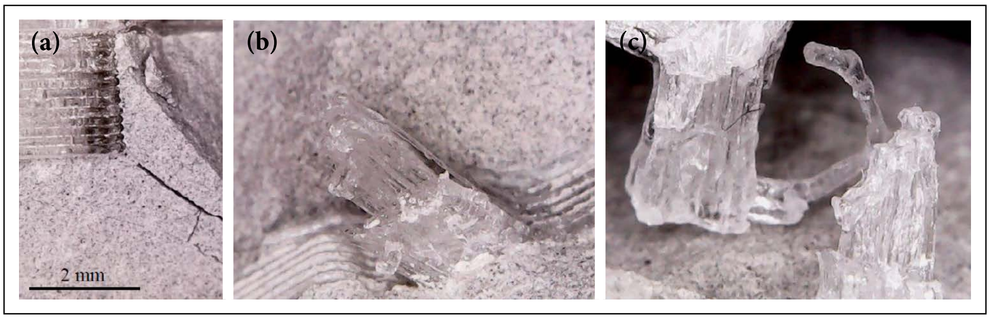

Figure 9. **(a)** Micro-cracking of the matrix, **(b)** Slipping of layers, **(c)** Rupture of the reinforcement.

taining cement-based composites with pseudo deflection hardening behavior. Both novel materials (like those used in this work) and recyclable polymers can be examined for usage in many applications to promote a sustainable future.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

REFERENCES

[1] American Society for Testing and Materials. (2012). *Standard terminology for additive manufacturing technologies* (ASTM Standard No. F2792-12). https://www.astm.org/f2792-12.html

[2] Hull, C. W. (1984). Apparatus for production of three-dimensional objects by stereolithography. *U.S. Patent No. 4,575,330*. Washington, DC: U.S. Patent and Trademark Office.

[3] Crump, S. S. (1989). Apparatus and method for creating three-dimensional objects. *U.S. Patent No.* CA2027731C. Washington, DC: U.S. Patent and Trademark Office.

[4] Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2016). Structural performance of reinforced geopolymer concrete members: A review. *Construction and Building Materials, 120*, 251–264. [CrossRef]

[5] Bassurucu, M., Fenerli, C., Kına C., & Akbas, S. D. (2022). Effect of fiber type, shape, and volume fraction on mechanical and flexural properties of concrete. *Journal of Sustainable Construction Materials and Technologies, 7*(3), 158–171. [CrossRef]

[6] Farina, I., Fabbrocino, F., Carpentieri, G., Modano, M., Amendola, A., Goodall, R., Feo L., & Fraternali, F. (2016). On the reinforcement of cement mortars through 3D printed polymeric and metallic fibers. *Composites Part B: Engineering, 90*, 76–85. [CrossRef]

[7] Zhang, Y., Zhang, S., & Deng, M. (2022). Four-point bending tests of ECC: Mechanical response and toughness evaluation. *Case Studies in Construction Materials, 17*, Article e01573. [CrossRef]

[8] Dogan, F., Dehghanpour, H., Subaşı, S., & Maraslı, M. (2022). Characterization of carbon fiber reinforced conductive mortars filled with recycled ferrochrome slag aggregates. *Journal of Sustainable Construction Materials and Technologies, 7*(3), 145–157. [CrossRef]

[9] Rosewitz, J. A., Choshali, H. A., & Rahbar, N. (2019). Bioinspired design of architected cement-polymer composites. *Cement and Concrete Composites, 96*, 252–265. [CrossRef]

[10] Hamidi, F., & Aslani, F. (2019). Additive manufacturing of cementitious composites: Materials, methods, potentials, and challenges. *Construction and Building Materials, 218*, 582–609. [CrossRef]

[11] Xu, Y., & Šavija, B. (2019). Development of strain hardening cementitious composite (SHCC) reinforced with 3D printed polymeric reinforcement: Mechanical properties. *Composites Part B: Engineering, 174*, Article 107011. [CrossRef]

[12] Shweiki, A., Junaid, MT., & Barakat, S. (2019). *Flexural characteristics of mortar cement reinforced with 3D-printed polymer*. In Proceeding 4th World Congress on Civil, Structural, and Environmental Engineering (CSEE'19), Rome, Italy, Paper No. ICSECT 154. [CrossRef]

[13] Katzer, J., & Szatkiewicz, T. (2019). Properties of concrete elements with 3-D printed formworks which substitute steel reinforcement. *Construction and Building Materials, 210*, 157–161. [CrossRef]

[14] Katzer, J., & Szatkiewicz, T. (2020). Effect of 3D printed spatial reinforcement on flexural characteristics of conventional mortar. *Materials, 13*(14), Article 3133. [CrossRef]

[15] Salazar, B., Aghdasi, P., Williams, I. D., Ostertag, C. P., & Taylor, H. K. (2020). Polymer lattice-reinforcement for enhancing ductility of concrete. *Materials and Design, 196*, Article 109184. [CrossRef]

[16] Xu, Y., Zhang, H., Gan, Y., & Šavija, B. (2021). Cementitious composites reinforced with 3D printed functionally graded polymeric lattice structures: Experiments and modelling. *Additive Manufacturing, 39*, Article 101887. [CrossRef]

[17] Gödek, E., Şevik, S., & Özdilli, Ö. (2020). *A study on flexural behavior of cement paste reinforced by using 3D-printed polylactic acid-based reinforcement*. In Proceeding 2nd International Icontech Symposium on Innovative Surveys in Positive Sciences, pp. 270–277, Budapest, Hungary.

[18] Santana, H. A., Amorim Júnior, N. S., Ribeiro, D. V., Cilla, M. S., & Dias, C. M. R. (2021). 3D printed mesh reinforced geopolymer: Notched prism bending. *Cement and Concrete Composites, 116*, Article 103892. [CrossRef]

[19] Hofler, R., & Renyi, S. (1914). GB157429A. https://patents.google.com/patent/GB157429A/en?oq=GB157429A.

[20] Abuşka, M., Şevik, S., & Kayapunar, A. (2019). Experimental analysis of solar air collector with PCM-honeycomb combination under the natural convection. *Solar Energy Materials and Solar Cells, 195*, 299–308. [CrossRef]

[21] Habib, F. N., Iovenitti, P., Masood, S. H., & Nikzad, M. (2018). Cell geometry effect on in-plane energy absorption of periodic honeycomb structures. *The International Journal of Advanced Manufacturing Technology, 94,* 2369–2380. [CrossRef]

[22] Turkish Standardization Institute. (2016). *Methods of testing cement - Part 1: Determination of strength* (TS EN Standard No. 196-1). https://intweb.tse.org.tr/Standard/Standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073088066113082087078107067083069056.

[23] Blok, L. G., Longana, M. L., Woods, B. K. S. (2020). Fabrication and characterisation of aligned discontinuous carbon fibre reinforced thermoplastics as feedstock material for fused filament fabrication. *Materials, 13*(20), Article 4671. [CrossRef]

[24] Foti, D. (2011). Preliminary analysis of concrete reinforced with waste bottles PET fibers. *Construction and Building Materials, 25*(4), 1906–1915. [CrossRef]

[25] Shahzad, Q., Umair, M., Waqar, S. (2022). Bibliographic analysis on 3D printing in the building and construction industry: Printing systems, material properties, challenges, and future trends. *Journal of Sustainable Construction Materials and Technologies, 7*(3), 198–220. [CrossRef]