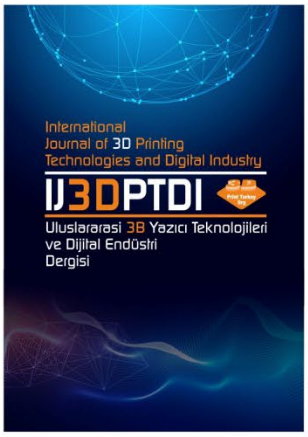

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FLEXURAL PERFORMANCE OF CEMENT MORTARS REINFORCED WITH 3D PRINTED REBARS

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ABSTRACT

This experimental study evaluates the flexural performance of cement mortars reinforced with rebar-type 3D printed polymer reinforcements with rebar geometry directly comparable to conventional steel rebars unlike most existing studies focusing on lattice polymer reinforcements. For this purpose, traditional steel rebar and two types of 3D printed polymer rebars produced from Acrylonitrile Butadiene Styrene and Polyethylene Terephthalate Glycol filaments were used in the experimental studies. The 3D printed rebars were designed with dimensions equivalent to Ø12 traditional steel reinforcement. They produced with 100% infill density using 45º printing orientation to ensure that each printed layer contributes to the strength. Three-point flexural tests were performed on prismatic specimens. The flexural strength, deflection capacity and toughness values were determined using flexural load – mid-span deflection curves and results were discussed, comparatively. Steel reinforced mortars exhibited the highest flexural strength (24.45±2.08 MPa) with a limited deflection capacity (1.25±0.08 mm). PETG reinforced mortars achieved lower flexural strength with an enhanced deflection capacity compared to steel reinforced mortars (19.45±2.00 MPa and 2.17±0.69 mm). 3D printed ABS rebar reinforced mortars provided lower strength but the highest deflection capacity (16.78±2.36 MPa and 2.68±0.48 mm). Toughness analyses revealed that both the 3D printed PETG and ABS rebars remarkably improved the total toughness compared to traditional steel (by 102.12% when the PETG rebar was used and by 982.64% when the ABS rebar was used). In conclusion, this study highlights the potential use of 3D printed rebars as lightweight and corrosion resistant alternative with improved deflection and toughness in cementitious composites.

Keywords: 3D Printed Rebar, Flexural Strength, Mid-Span Deflection, Toughness, Mortar.

1. INTRODUCTION

Traditional steel rebar is the most widely used reinforcement in construction industry. However, steel rebar is sensitive to corrosion when structures exposure to harmful environments including aggressive materials such as chlorides and sulphates [1-2]. The corrosion of steel can lead to cracking of concrete which cause construction element to failure over time due to spalling of concrete and reduction in the cross-sectional area of the steel rebar in the areas such as marine structures, bridge decks or where the de-icing salts are used [1,3-4].

Three dimensional (3D) printing is become widespread in the manufacturing of designed objects last decade [5]. The designed object is sliced into layers via slicer software and printed layer by layer with use of polymer filaments [6]. The commonly used filaments are Poly-lactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS) and Poly-ethylene Terephthalate Glycol (PETG) [6-8].

Recently, there are studies in the literature to reinforce cement based composites with 3D printed reinforcements. Xu and Savija [6] investigated the tensile and flexural behavior of cement based composites reinforced with 3D printed ABS two dimensional meshes. Results indicated that composites with 3D reinforcement exhibited strain hardening and deflection hardening behavior during tensile and flexural tests, respectively. Salazar et al. [9] designed and prepared octet lattice reinforcements using ABS and PLA with two different volume percentages. Ultra-high performance cement composites were prepared in the cubic form for compressive tests and in the prismatic form for flexural tests with using 3D printed octet lattice reinforcements. They reported that composites incorporating 3D printed lattice reinforcements showed high ductility in both flexural and compressive tests. Increasing the lattice volume percentage decreased the compressive strength with higher variability. However, all 3D lattice-reinforced prismatic specimens exhibited deflection hardening behavior under flexural loading. Xu et al. [10] designed functionally graded 3D printed octet lattice structures using ABS and investigated the mechanical performance of cement-based composites reinforced with these structures. Results indicated that the failure mechanism changed from brittle to ductile and both the strength at the failure and work to the rupture were increased. Chen et al. [7] investigated the compressive strength of ultra-high performance concrete reinforced with 3D printed auxetic lattice reinforcements with three different patterns (honeycomb, triangular and octet).

This study showed that honeycomb patterned 3D printed auxetic lattice reinforcements increased the compressive strength by 14.6% and 19.4% compared to octet and triangular patterned reinforcements. Qin et al. [11] investigated the effects of different types and shapes of 3D printed polymeric lattice structures on the ductility performance of Cementitious Backfill Composites. The introduction of lattices performed remarkable ductility and toughness, converting the material from brittle to ductile due to the multiple crack formation. The rhombus ordinary resin provided optimal flexural performance. In another study conducted by Hao et al. [12], the mechanical performances of cementitious composites reinforced with six different 3D printed PA6 lattice structures were investigated under compression. This study reported that the use of 3D lattices improved the compressive strength and deformation capacity. The enhanced deformation capacity was associated with the formation of multiple small cracks under vertical compression instead of a single large crack. One another study found that incorporating 3D-printed micro-architected polymeric reinforcement to the mortars increased the average peak load capacity of mortar beams by approximately 20% and the average mid-point deflection before failure by about 2000% compared to non-reinforced samples [13]. Beyond internal architecture, the bond properties between the polymeric reinforcement and the cementitious matrix are vital for composite performance [14]. The interlocking effects due to the 3D printing and inter-layer printing direction are able to enhance bond strength by 56% [14]. In axial compression tests, while the inclusion of polymer lattices may reduce the overall compressive strength and elastic modulus due to the lower elastic modulus of reinforcement material, however, it significantly improves the ductility and post-peak energy absorption capacity of the specimens [15].

As seen in the literature, there are many studies on using 3D printed lattice reinforcements in cement-based composites. Although these studies clearly demonstrate the benefits of lattice type polymer reinforcements in terms of ductility and energy absorption, their complex geometries and non-standardized configurations limit direct comparison with conventional steel rebar used in practice. The primary objective of this study is to experimentally evaluate the flexural behavior of cement mortars reinforced with 3D printed polymer rebars produced from ABS and PETG filaments, designed to replicate the geometry of conventional Ø12 steel reinforcement. Unlike the majority of existing studies focusing on lattice reinforcements, this research directly addresses the performance of rebar-type polymer reinforcements under flexural testing conditions, thereby enabling a clear and practical comparison with traditional steel reinforcement.

2. MATERIALS AND METHODS

Matrix phase of the composites were prepared using CEM I 42.5 R type cement, limestone powder with a diameter below 250 µm, water and superplasticizer (Figure 1). The purpose of using powder aggregate is to increase the physical bonding between the rebar and the matrix phase.

Traditional Ø12 construction steel was used as reference reinforcement to compare the mechanical properties of the reinforced mortars. Additionally, two 3D printed rebars were prepared having the same dimensions with the reference steel based on ABS and PETG. Creality Hyper series ABS and PETG filaments were used in the production of 3D printed rebars. The physical, mechanical and printing properties of ABS and PETG filaments obtained from the manufacturer were given in Table 1.

Figure 1. Materials used in the production of matrix phase.

Table 1. The physical, mechanical and printing properties of filaments.

Properties	ABS	PETG
Density (*gr/cm³*)	1.04	1.27
Tensile Strength (*MPa*)	27	48
Tensile Modulus (*MPa*)	2020	3500
Elongation at break (*%*)	7.63	10
Bending Strength (*MPa*)	48	55
Bending Modulus (*MPa*)	2035	2200
Extruder Temperature (*ºC)*	240-300	220-260
Hot Bed Temperature (*ºC*)	70-90	70-80
Printing Speed (*mm/sn*)	30-300	40-300

Elegoo Neptune 4 Max brand 3D printer was used to prepare the 3D printed rebar with using ABS and PETG filaments (Figure 2). The rebar design was done via TinkerCAD software and designed object sliced into layers via Elegoo Cura software. The printing and bed temperatures were selected as 250 ºC and 80 ºC, respectively. The reason for choosing these temperatures is that they are within the recommended common usage temperature ranges for both filaments used. Infill ratio of the rebar was set 100% to eliminate the effect of internal porosity and focus solely on material behavior. During printing, the printing direction is adjusted to make a 45º with the reinforcement axis in order to ensure that each printed layer contributes to the strength under load.

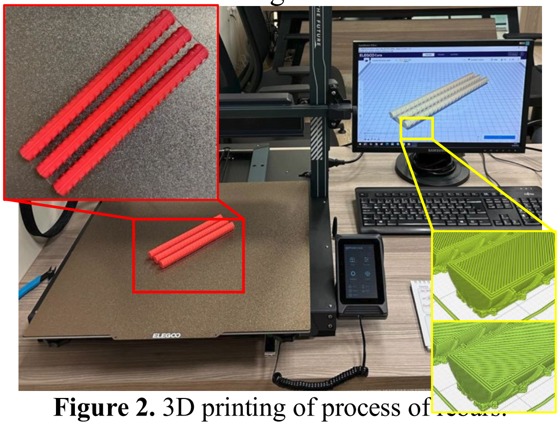


Figure 2. 3D printing of process of rebars.

3D printed rebars were placed into 40x40x160 mm molds. A 3D printed spacer was used to align the rebar in the center of the tension zone (Figure 3). Powder materials were first mixed in a laboratory type mortar mixer for 30 second. Then water and superplasticizer were added to the mixture and mixed for 2 minutes. Matrix phase is manually checked with spoon if there is any agglomeration then mixed for another 2 min in the mixer. Mortar was filled into molds and the surfaces of the specimens were finished with the help of a trowel (Figure 4). Three specimens for each rebar type were prepared for the experimental tests. 1 day after molding process, specimens were demolded and cured in water for 28 days.

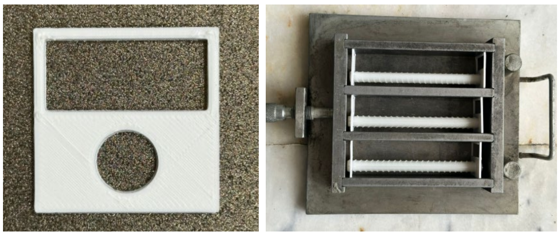


Figure 3. 3D printed spacer and placing of rebar into the tension zone.

Figure 4. Preparation of specimens.

Three point bending tests were performed to the specimens using a ZwickRoell brand hydraulic loading device. Bending tests were performed under deflection controlled loading with a rate of 0.5 mm/min. During the tests deflection values from the mid-span of the specimen were recorded simultaneously with the loads. Load – Mid-span Deflection curves were drawn to determine the mechanical properties of the specimens which figured schematically in Figure 5.

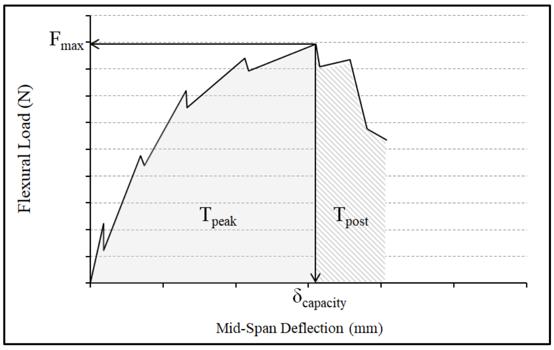


Figure 5. Schematic load – mid-span deflection curve.

On the Load – Mid-span Deflection curves, sudden load drops are occurred due to the formation of the cracks and loads are transferred to the rebars which make the load to rise again. The ultimate load value on the curve is determined and the flexural strengths of the specimens are calculated using Equation 1.

$$\sigma = \frac{3}{2} \cdot \frac{F_{max} \cdot L}{bh^2} \quad (1)$$

Where; σ is the flexural strength, F_{max} is the ultimate load read from the curve, L is the span length (130 mm), b is the width of the specimen and h is the height of the specimen. The deflection capacities of the specimens are determined as the corresponding mid-span deflection value to the ultimate load.

The load – Mid-span Deflection curves were drawn by connecting the data points recorded throughout the experimental process. In this approach, the area between any two successive points corresponds to the area of a trapezoid. To calculate the toughness values, the trapezoidal area between each consecutive pair of points was first calculated. Then, the sum of the areas of multiple successive trapezoids up to the peak load was defined as peak toughness (T_{peak}), while the sum of the areas of successive trapezoids beyond the peak load was defined as post toughness (T_{post}**)**.

To optically characterize the rebar–matrix interfacial bond behavior, the rebar–matrix interfaces were examined following the flexural tests using a handheld optical microscope with a maximum magnification of 250× (Figure 6).

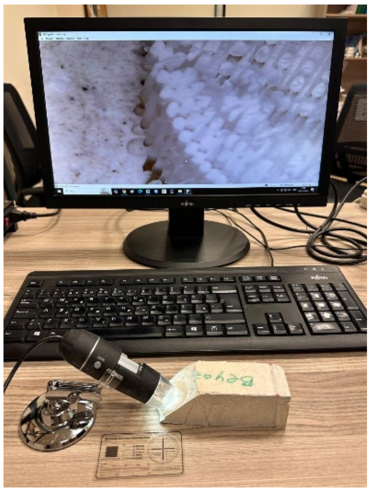


Figure 6. Optical examination of rebar-matrix interface via handheld optical microscope.

3. EXPERIMENTAL RESULTS

3.1. The Load – Mid-span Deflection Curves

The Load – Mid-span Deflection curves of specimens were presented in Figure 7. In the figure, Steel, PETG and ABS rebars were colored as black, red and light grey, respectively.

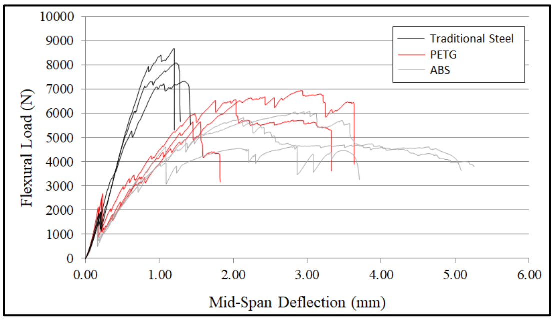


Figure 7. The load – mid-span deflection curves obtained from flexural tests.

The initial slopes of curves for all specimens were found similar up to initiation of first crack. However, after the initiation of the first crack the curves of PETG and ABS reinforced specimens tended to progress more horizontally compared to the samples containing conventional steel. After 1 mm mid-point deflection, it was observed that this horizontal tendency was greater in ABS-reinforced specimens compared to PETG-reinforced specimens. In this case, it is thought that this is due to the fact that the bending modulus and bending strength values of ABS are lower than those of PETG (Table 1).

The steel reinforced specimens exhibited higher load carrying capacity therefore higher flexural strength than PETG and ABS reinforced specimens. The load carrying capacities of the specimens ranged between 7318-8683 N, 5655-6938 N and 4626-6082 N while the corresponding deflection values to these ultimate loads ranged between 1.20-1.33 mm, 1.55-2.92 mm and 2.14-3.03 mm for steel, PETG and ABS reinforced mortars, respectively (Figure 7).

When the post cracking behaviors of the curves were investigated, the load bearing capacity of specimens reinforced with steel and PETG rebar were exhibited sudden drop. This behavior was explained with the observations during the flexural tests. In the case of the mortars reinforced with steel rebar collapse was occurred on the compression zone of the mortar phase. On the other hand, rebar was ruptured in all specimens reinforced with the PETG which made the load carrying behavior of specimens end, abruptly. When the flexural behavior of ABS reinforced mortars were considered during the experiments, neither rupture nor sudden collapse was observed which made the curves of these specimens prolonged compared to the steel and PETG reinforced specimens. This horizontal progression of the curves indicates sustained load transfer through the polymer rebars after matrix cracking.

3.2. Flexural Strength

The flexural strengths calculated via curves were given in Figure 8. The average flexural strength of specimens were 24.45±2.08 MPa, 19.45±2.00 MPa and 16.78±2.36 MPa for the mortars reinforced with steel, PETG and ABS, respectively. As common, the use of steel rebar provided highest flexural strength. The PETG based rebar achieved approximately 75-80% of the flexural strength of steel reinforced mortars which was also higher compared to ABS reinforced specimens. 3D printed ABS rebar reinforced mortars performed the lowest flexural strength. In a study, it was reported that the hybridization of ABS with PETG increased the tensile strength by 14.24% compared to plain ABS due to the relatively high adherence property of PETG layers which indirectly supports the high flexural strength of 3D printed PETG reinforced mortars than the 3D printed ABS reinforced mortars [16].

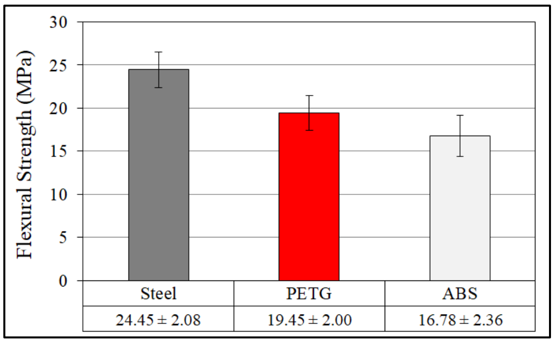


Figure 8. The flexural strengths of mortars considering rebar type.

3.3. Deflection Capacity

The average deflection capacity values obtained from the curves were presented in Figure 9. The deflection capacities of mortars reinforced with steel determined as 1.25±0.08 mm on average. The use of 3D printed reinforcements enhanced the deflection capacity of the specimens. The deflection capacity increased by 76.68% and calculated as 2.17±0.69 mm on average when the PETG rebar were used compared to steel reinforced mortars. This enhancement further increased when the ABS rebar were used and reached up to 114.46% with a deflection capacity of 2.68±0.48 mm on average compared to steel rebar used mortars. Besides, use of ABS rebar increased the deflection capacity of mortars by 23.48% compared to PETG rebar. Note that all specimens performed deflection hardening behavior and this behavior was remarkable when the 3D printed rebars were used. These results were previously mentioned when the 3D printed flat, lattice and truss reinforcements were used in cement mortars and ultra-high performance concrete under flexural loading [6, 9, 17, 18]. The enhanced deflection capacity observed in this study is also consistent with previous findings on 3D printed PLA-based rectangular bar type reinforcements [19].

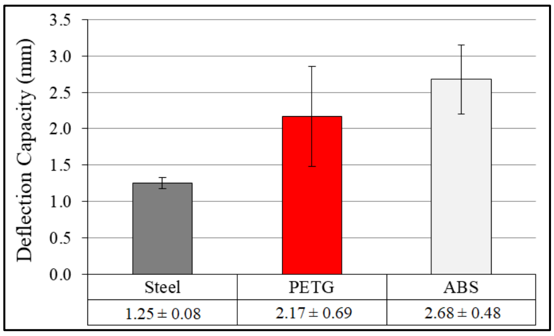


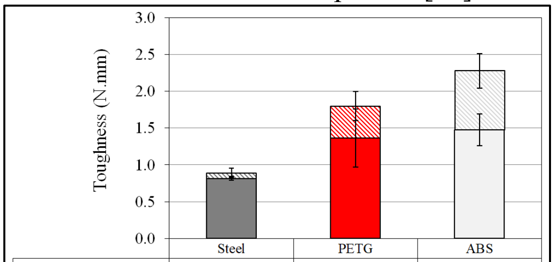
Figure 9. The deflection capacity of mortars considering rebar type.

3.4. Toughness

The average toughness values obtained from the curves were considered separately as peak toughness (T_{peak}) with solid-filled bar chart and post toughness (T_{post}) with hatched-filled bar chart in Figure 10. The steel reinforced mortars performed lower toughness compared to the PETG and ABS reinforced mortars. The main energy absorption ability of steel reinforced mortars were obtained up to the peak load with an average T_{peak} value of 0.82±0.03 N·mm while the average T_{post} value was 0.07±0.06 N·mm. This situation reflects the relatively high stiffness but brittle post-cracking response of the steel reinforced mortars, as the inclusion of steel reinforcement typically provides higher post-cracking stiffness but may lead to lower deformability compared to polymer-based reinforcements [20].

The average of the total toughness of steel reinforced mortars was calculated as 0.89±0.05 N·mm. On the other hand, use of 3D printed rebars within the mortars showed a remarkable increase in total toughness. This value was increased by 102.12% on average when the PETG rebar was used and calculated as 1.80±0.52 N·mm. PETG reinforced mortars exhibited higher T_{peak} and T_{post} values compared to steel reinforced mortars. The T_{peak} and T_{post} values obtained from the PETG reinforced mortars were 1.37±0.39 N·mm and 0.43±0.20 N·mm, respectively. ABS reinforced mortars demonstrated slightly higher T_{peak} value (1.48±0.22 N·mm) than the PETG reinforced mortars. Additionally, the T_{post} of the ABS reinforced mortars calculated as 0.80±0.23 N·mm on average which was 982.64% and 83.98% higher than the steel and PETG reinforced mortars, respectively. The average total toughness of ABS reinforced mortars was 2.28±0.19 N·mm.

Both the PETG and ABS reinforced mortars exhibited relatively balanced contribution of T_{peak} and T_{post}, indicating that the specimens not only absorbed more energy before failure but also maintained higher load-carrying capacity after the occurrence of cracks compared to steel reinforced mortars. Additionally, results clearly indicate that 3D printed polymer rebars can alter the failure mode of cement mortars from brittle to damage-tolerant, even when the peak strength is reduced which align with previous studies reporting enhanced damage tolerance and energy dissipation in 3D printed polymer-reinforced cementitious composites [21].

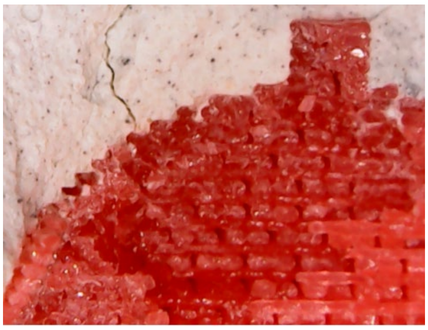


	Steel	PETG	ABS
Post Toughness (Tpost)	0.07 ± 0.06	0.43 ± 0.20	0.80 ± 0.23
Peak Toughness (Tpeak)	0.82 ± 0.03	1.37 ± 0.39	1.48 ± 0.22

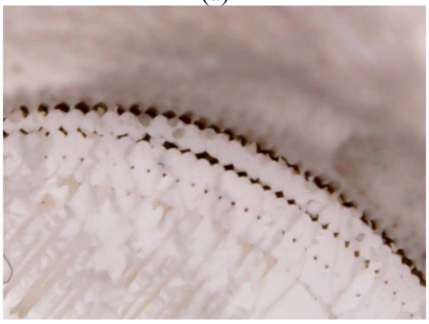
Figure 10. The peak and post toughness of mortars considering rebar type.

3.5. Optical Characterization of Rebar–Matrix Interface

The images taken during the optical observations were presented in Figure 11. The examinations showed that PETG rebar–matrix interface was comparatively denser and had more continuous contact region with fewer visible voids. This bonding enhanced the physical adhesion and improved the mechanical interlocking between the rebar and the cementitious matrix. This efficient bonding is consistent with the higher flexural strength achieved by PETG rebar reinforced mortars (Figure 11a). In contrast, the ABS-matrix interface exhibited more pronounced layer markings and localized micro-gaps along the interface zone and between the printed layers, indicating weaker adhesion and explaining the decreased flexural strength of ABS rebar reinforced mortars (Figure 11b). However, despite its more flawed interface, ABS rebar reinforced mortars showed no sudden fracture during bending. This resulted in continuous crack bridging behavior and prolonged post-crack load transfer that contributed to achieve the highest deflection capacity and overall toughness through all rebar types. As a result of this, it can be assumed that the polymer ductility partially compensates for the reduced interface bond strength.



(a)



(b)

Figure 11. Optical examination of rebar–matrix interface: a) PETG rebar – matrix, b) ABS rebar – matrix

4. CONCLUSION

This study evaluated the flexural performance of cement mortars reinforced with traditional steel rebar and two types of 3D printed polymer rebars produced from ABS and PETG filaments. The results showed that while steel reinforcement provided the highest flexural strength, the use of 3D printed polymer rebar significantly improved the deflection capacity and toughness of the mortars. PETG reinforced mortars achieved a substantial proportion of the flexural strength of steel-reinforced specimens. Additionally, optical microscopy observations showed a denser and more continuous rebar–matrix interface with fewer interfacial gaps within the PETG rebar reinforced mortars which enabled more effective stress transfer prior to cracking, therefore, higher flexural strength than the ABS rebar reinforced mortars.

On the other hand, ABS reinforced mortars achieved the greatest deflection capacity and total toughness due to their stable non-rupturing deformation behavior and sustained crack-bridging capability after matrix cracking. The use of 3D printed polymer rebars mitigated the brittle failure typically observed in steel reinforced specimens, enabling a more gradual and energy absorbing response under flexural loading conditions. These findings suggest that 3D printed polymer reinforcements offer a promising alternative particularly for applications where deflection capacity, crack control, and corrosion resistance are prioritized over peak strength.

On the other hand, the mechanical trends observed for 3D printed PETG and ABS rebars can also be discussed within the broader context of fiber-reinforced polymer (FRP) reinforcement systems, such as FRP rebars, which have been widely proposed as corrosion-resistant alternatives to conventional steel. FRP rebars generally exhibit high tensile strength but relatively low elastic modulus compared to steel, resulting in reduced peak stiffness and lower flexural strength, yet improved durability in aggressive environments [1]. The enhanced post-cracking ductility and energy absorption achieved by ABS rebars in this study can represent an advantage over conventional FRP systems, as many FRP rebars provide limited deformation capacity after cracking due to their brittle behavior [22]. While both FRP rebars and 3D printed polymer rebars share key benefits such as lightweight construction and corrosion resistance, additive-manufactured rebars may offer an additional design space for tailoring ductility and crack-bridging behavior through controlled geometry and polymer deformation mechanisms.

Based on these discussions, future research should focus on evaluating the long-term durability of 3D printed polymer rebar, particularly their resistance to environmental influences such as moisture, temperature fluctuations, and chemical exposure. Optimization of rebar geometry, printing orientation, and infill patterns is recommended to enhance mechanical performance and improve the interaction between the rebar and the mortar. Large scale structural testing is also essential to validate the applicability of these reinforcements in real construction scenarios. Finally, comprehensive assessments of the economic and environmental impacts of polymer based 3D printed rebar will support their potential integration into practical and sustainable construction applications.

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