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Flexural Characteristics of Mortar Cement Reinforced with 3D-Printed Polymer

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Abstract **-** In this research, reinforcement for cement mortars is printed using polymers-thermoplastics on a Fused Deposition Modeling (FDM) 3D printer and its effect on the strength and response of cementitious mortar samples under bending are studied. Two common thermoplastic polymers; Poly Lactic Acid (PLA) and Polyethylene Terephthalate Glycol-Modified (PETG) are used to reinforce mortar beam samples measuring 200x50x50 mm in flexure. For each thermoplastic type, four bar 150 mm in length and with a plain rectangular cross-section of 10x5 mm were printed and embedded in the specimen and tested under 3-point load flexural load. The samples with PETG reinforcement showed much better flexural behavior than the PLA reinforced samples in terms of ultimate loads and deformations. The average ultimate flexural capacity of the PETG samples is almost double of the PLA samples (11.37 MPa compared to 5.94 MPa), while the deformation of the PETG samples at ultimate loads reached 3 times the deformation of the PLA samples owing to its higher strength and plastic behavior.

***Keywords*:** 3D-printing, FDM process, thermoplastic polymers, reinforcement, mortar, flexure test.

1. Introduction

Recent advancement in additive manufacturing (AM) or 3D printing has increased significantly from using new material and new methods [1], to increase in speed and size of printing. Mainly the price of these printers has reduced significantly allowing for more application in fields like dental, medical, robotics, architecture, arts, manufacturing industry, mechanical and civil engineering [2-3]. Although 3D printing in civil engineering has a lot of potentials and several countries have adopted some level of 3D printing technology in civil structures like in UAE-Dubai in the office of the future which is the first office 3D printed, see ref [4]. And in Italy the D.Shape company by Enrico Dini who designed and fabricated a full scale 3d printer for concrete and he is printing model structures for many countries in Europe see ref [5]. Also, another great 3D printing structures application is by WinSun company in China which is already commercialized 3d printing for homes and up to 3 story houses see ref [6]. And an application in reference [7],is an example of large scale 3d printing of structural elements.

However, currently, there are challenges related to the applications of such technologies in large-scale construction [8-9]. One such challenge is the placement or printing of reinforcement while printing concrete. Nevertheless, the technology exists which allows for different material to be printed using the same nozzle or switching of nozzles for printing a different material. However, this is only available in small-scale applications. Moreover, conventional steel printing technology is highly complicated and expensive [10]. The process of steel printing is powder or weld based while mortar printing usually adopts the Fused Deposition Modelling(FDM) or Fused filament fabrication (FFF) process. These processes are not compatible and therefore their use in printing 3D structural elements is not explored.

Another alternative to conventional steel reinforcement is the use of thermoplastics or polymers to reinforce concrete members [11-12]. Such polymers fibers are currently used in the market to produce fiber reinforced concrete, however, their application to 3D printing in structural elements is very limited. If such 3D printed reinforcement is to be used for structural applications, its properties and the behavior of the composite thus made must be investigated. To this end, this work looks at the use of different 3D printed polymers as reinforcement for OPC mortars. The focus of this paper is to study the flexural response of small-scale prismatic beams reinforced with 3D printed thermoplastic polymers.

2. Experimental Program

2.1. Materials

A mortar mix consisting of cement, fly ash and sand was used. The water to binder ratio was 0.343 sand/binder ratio was 0.714, and fly ash/cement ratio was 0.4. Fly ash was chosen for its workability and its fineness which will improve workability. The mix was tested and the 28day compressive strength and density were 55MPa and 2190 kg/m3, respectively. The thermoplastic polymers that were used as a reinforcement were Poly Lactic Acid (PLA) and Polyethylene Terephthalate Glycol-Modified (PETG). These materials were chosen because they are widely used in Fused Deposition Modelling (FDM) 3D printing process.

2.2. PLA AND PETG Properties

Compression and tensile tests necessary for the study were conducted on these materials. The tensile tests were done for both thermoplastic polymers using coupon test samples. The details of the samples and the test results are presented in *Figure 1* below and the results are tabulated in *Table 1*. The results reveal that both materials have almost the same ultimate strength but the PETG showed a very large elongation and no sudden failure like PLA. This property resulted in huge differences in flexural behavior of both samples as discussed in the Results section.

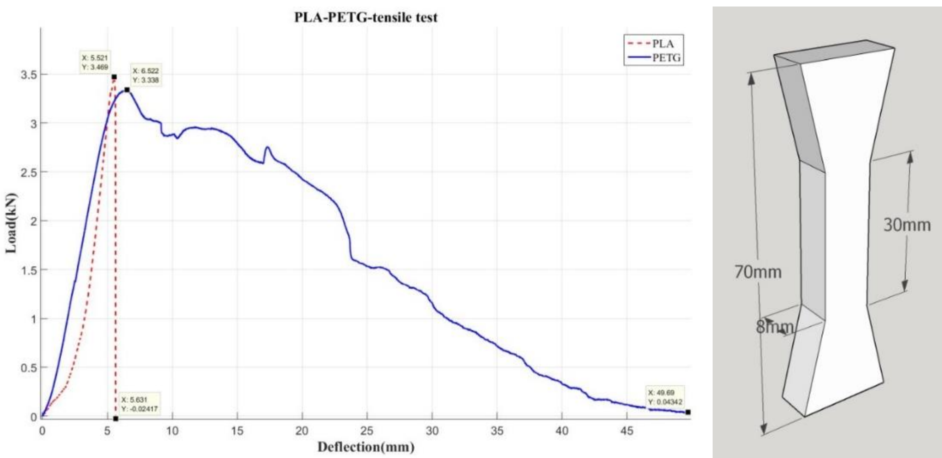

Fig. 1: Tensile test results for thermoplastic polymers(left) and coupon test sample(right).

Table 1: Mechanical properties of PLAand PETG material.

material	Density (kg/m^3)	Tensile strength (MPa)	Elongation%
PLA	1210	43.4	18.5
PETG	1270	41.7	165.5

2.3. Specimens

The Reinforcements were printed using a CAM FDM printer utilizing 3D CAD designed rectangular cross-section of 5mm width by 10mm height and 190mm length. Four bars with a total cross-sectional area of 200mm2 were placed at a clear spacing of 7.4mm between each bar and cover of 5.28mm. As shown in *Figure 2*, the specimen size was 200x50x50mm.

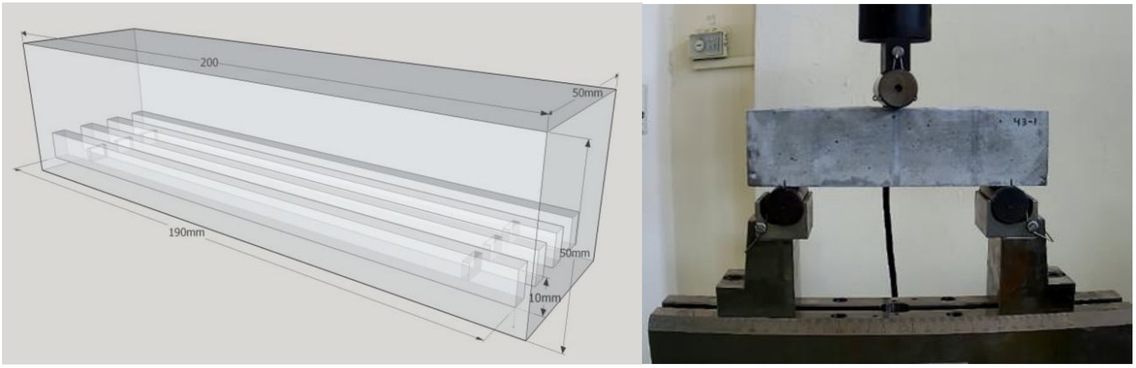

Fig. 2: Schematic of printed reinforcement in mortar prism(left) and center point bending test setup (right).

A total of 6 beams were cast; 3 for each PLA and PETG and tested in flexural in center point bending test. The clear span for each beam was 150mm as shown in *Figure 2* and the loading rate was 0.005mm/sec applied in displacement control using an Instron 8801 material testing machine.

3. Results and Discussion

3.1. Material Test Results

As seen from *Figure 1*, PLA is exhibiting brittle behavior and fails suddenly after maximum load. PLA also has a higher elastic modulus seen by the steeper slope than that of PETG. Nevertheless, the behavior of PETG is quite different from the PLA after maximum load (even though PLA has a slightly higher strength) in such that PETG behaves in a ductile fashion shown in the figure by large deflection after the maximum load is reached.

3.2. Flexural Test Results

Test results are plotted in a graph of Load-Deflection as shown in *Figure 3* and a zoomed first crack graph is shown in *Figure 4.*

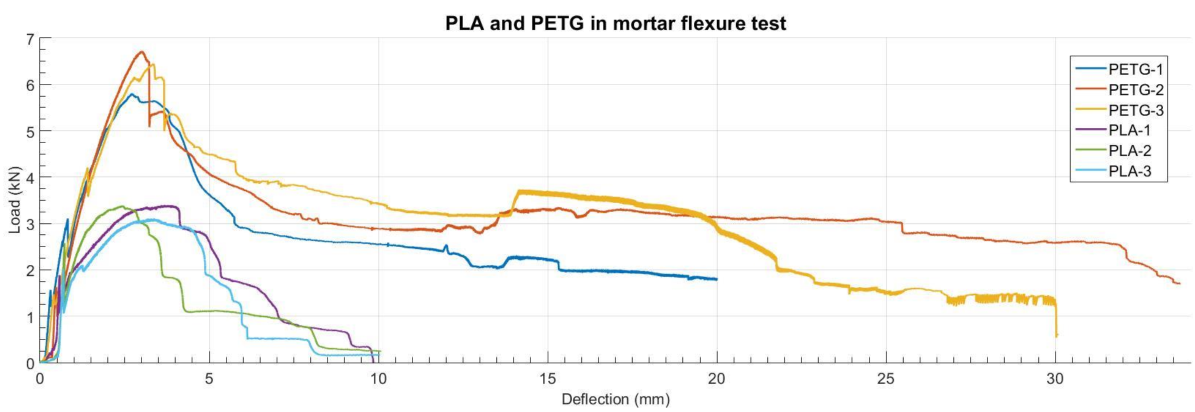

Fig. 3: Load vs deflection curves for all tested specimens.

Looking at the load-deflection results the abrupt change in slope designates the first crack. The graphs of the two materials clearly show the differences in behavior for the materials. The first difference is the load value at first crack as shown in *Figure 4* and tabulated in *Table 2*. PLA-1 to 3 specimens had a higher first crack load with an average value of 2056N compared to PETG-1 to 3 specimens which had an average first crack load value of 1563N. A possible explanation for this behavior may be due firstly to the difference in modulus of elasticity of PLA and PETG. The modulus for PLA as reported by the manufacturer is 3.5GPa while that for PETG is 2.2GPa. This higher modulus of PLA will provide higher stiffness to the flexural system thus delaying the first crack. Secondly according to the material test results PLA has higher tensile strength which will contribute to the higher first crack strength. Thirdly the ductility of PETG will allow the load to be distributed along the sample and reduce the first crack load when compared to the stiff PLA that will resist the load along the sample and provide higher first crack load.

The second difference is in maximum load reached; PETG-1to3 specimens had a much higher maximum load of more than double than that of PLA. As obvious from *Figure 3,* the PLA is much more brittle than the PETG and therefore once the maximum load is reached, the PLA fails abruptly. The PETG, on the other hand, has a ductile response and undergoes large deformations after peak load and this due to the properties of the PETG itself which is more ductile as per *Figure 1* and also the way the 3d printing FDM process works as the outer layers of printed lines strain and rupture due to adhesion with the matrix the inner one takes action and resist force and elongates. This provides some strain hardening characteristics to the composite member which is evident in *Figure 3.*

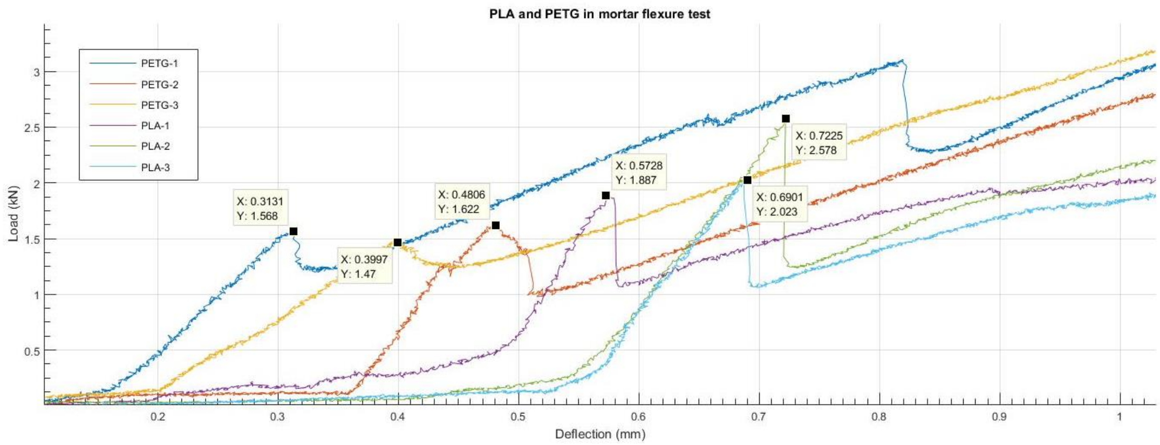

Fig. 4*:* Close up view of Load-deflection curve showing first crack for all specimens.

Looking at the deformation results, the PLA samples reached around 10mm mid-span deflection, while PETG reached above 30mm and still has a load carrying capacity more than the first crack load and not all bars were broken. This again can be explained by the material properties. As evident, the PETG is much more ductile than the PLA and therefore offers larger deflections before failure. This behavior is also evident when the thermoplastic is used in a composite.

Figure 5 below shows the samples after testing. It is noted that most samples failed in flexure but for the PETG-1 and 3, some shear crack were also observed. This, of course, is due to large deformations which redistribute the stresses caused by loading. However, the failure for all tested samples was flexural. Also, all samples experienced large cracks that started at first cracking load and grew as the load was increased up to failure.

Table 2: First crack, maximum load, and flexural strength values.

	PLA				**PETG**			
Sample	First crack load(N)	Max load (N)	Modulus of rupture (MPa)	Max strength (MPa)	First crack load(N)	Maximum load (N)	modulus of rupture (MPa)	Max strength (MPa)
1	1887	3392	3.4	6.1	1568	5799	2.8	10.4
2	2578	3389	4.6	6.1	1622	6722	2.9	12.1
3	2023	3108	3.6	5.6	1470	6443	2.6	11.6
Average	2056	3296	3.7	5.9	1553	6321	2.8	11.4

Fig. 5: Failure modes of the tested samples; left PLA right PETG.

The summary of results is tabulated in *Table 2* below shows the load at first crack and the maximum load and average values.

The toughness and residual strength parameter were also examined, and area under the load-deflection graph or energy absorbed were calculated for each sample as shown in *Figure 6* below and tabulated in *Table 3.* The area under the curve for PETG deflections was taken only to the 30mm mark to be able to compare the results between all the PETG samples. From the calculated areas, it is concluded that PETG has an average toughness value of 91.6J and PLA 16.3J. Thus, PETG is absorbing 5 times the energy absorbed by PLA which gives it a distinct advantage for structural applications.

Table 3: Area under the curve -Absorbed energy for the tested specimens.

	PLA	**PETG**
Sample	Energy (J)	Energy (J)
1	18.9	75.8
2	14.8	101.9
3	15.2	97.1
Average	16.3	91.6

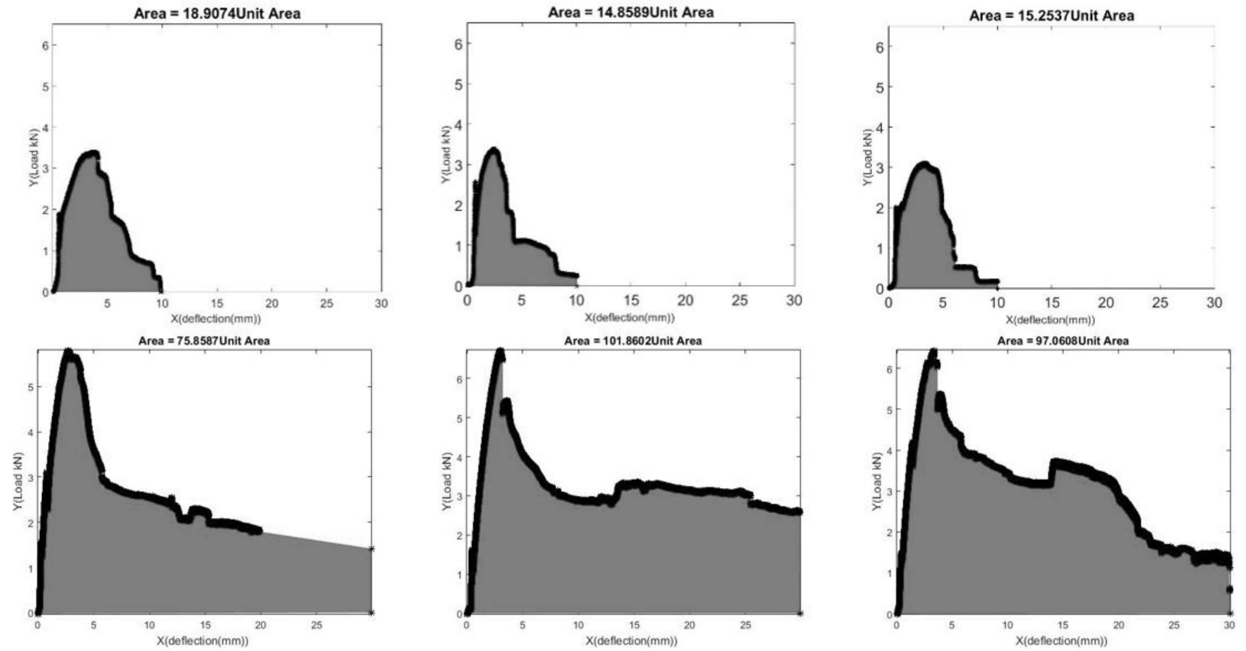

Fig. 6: Area under the curve for each Specimen.

4. Conclusion.

The effects of printed reinforcement using polymers-thermoplastics by Fused Deposition Modeling (FDM) 3D printer on the strength and deformation of cementitious mortar samples under bending are studied. Two common thermoplastic polymers; Poly Lactic Acid (PLA) and Polyethylene Terephthalate Glycol-Modified (PETG) are used to reinforce six mortar beam samples measuring 200x50x50 mm tested under 3-point flexural test. For each thermoplastic type, four bar 150 mm in length and with a plain rectangular cross-section of 10x5 mm were printed and embedded in the specimen. The following conclusions can be drawn from the test results:

1- The samples with PETG reinforcement showed much better flexural behavior than the PLA reinforced samples in terms of ultimate loads and deformations. This was as expected since the PETG material itself exhibits higher ductility than PLA. This ductility is also evident in the composite beams.
2- The average ultimate flexural capacity of the PETG samples is almost double that of the PLA samples while the deformation of the PETG samples at ultimate loads reached 3 times the deformation of the PLA samples.
3- The PETG's high ductility property gave the reinforced mortar a high flexural strength with higher strain hardening properties after the fracture of the mortar. PLA reinforced samples behaved in a brittle manner and provided higher first crack load compared to PETG reinforced samples but failed at lower deflection and load values than PETG reinforced samples.
4- The energy absorbed by the PETG samples was on average 5 times more than the PLA samples also due the properties of PETG and its behavior with concrete. Using 3D printed polymers as reinforcement in mortar can improve the energy absorption significantly.

Given the adaptability of such reinforcement to be printed on site and the enhanced flexural behavior of such cement composites as evident from this initial study is encouraging and requires a more intensive investigation of the adaptableness of such methods in large scale construction. Further tests to be conducted is using different polymer material with higher strength such as Polyester and Polypropylene and Nylon, also the use of fiber reinforced polymers, also Further study to compare the same and different materials with higher and lower strength mortar should be done.

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