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Structural performance of reinforced concrete beams containing plastic waste caps

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Abstract. Municipal solid waste contains large amounts of plastic and their utilization has environmental benefits including the reduction of raw materials used and landfill spaces. One of the possible uses of waste plastic is in construction applications such as partial replacement of coarse aggregate in concrete materials. In this paper, the structural capacity of reinforced concrete beams containing waste plastic was investigated. The waste plastic was the cap of a plastic bottle. Four concrete mixes were prepared. The coarse aggregate was replaced with 0, 10 %, 15 %, and 20 % (by volume) waste plastic. All mixes had constant mix proportions and water to cement ratio. All beams were cured for 28 days at 20 °C. The structural performance was assessed by examining the central deflection of the beam at different load increments until failure. In addition, the mode of failure was examined visually. The results indicated that it is possible to use a certain amount of waste plastic in structural applications without affecting the flexural characteristics of reinforced concrete beams.

1. Introduction

Concrete is the second most widely used material in the world after water. Large volumes of virgin materials are required to produce concrete. Any attempts to replace these materials with waste will be greatly advantageous as this will reduce the amounts of quarried materials and reduce the need for landfill spaces [1–5]. Waste materials include solid waste generated from the industry and households including plastic waste. Plastic is one of the most significant innovations of 20th-century material and the amount of plastic waste generated annually has been growing steadily and becoming a serious environmental problem. The estimated annual generation of plastic waste is 4.9 billion tons (reference). For solving the disposal of a large amount of plastic material, the use of recycled plastic in concrete industry may be considered a feasible option. The bulk of the concrete volume consists mainly of aggregates and it plays a substantial role in concrete properties such as workability, strength, dimensional stability, and durability. Using waste materials such as waste plastic in concrete as partial aggregates replacement will affect the structural performance of concrete. Plastic bottle caps are one type of plastic waste that has a designated cylindrical shape that is expected to have an effect on the properties of concrete produced and structural performance of reinforced concrete beams if used as partial replacement of coarse aggregates.

The workability of concrete was found to reduce when Plastic Fibre Reinforced Concrete (PFRC) is incorporated [6]. This was attributed to resistance caused by the fibre, which would hinder the movement of aggregates. The dry density is also reduced in PFRC, which results in the reduction of the self-weight of concrete. This preliminary study has thus shown that the relationships between compressive strength, as used in European standard for plain concrete, can be applied to concrete containing PET-fibres. It was observed during experimentations that normal concrete specimens were suddenly broken into two pieces either cubes or cylinders but PFRC specimens did not suddenly break and failure was ductile.

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Plastic waste can be used in concrete as a replacement of coarse aggregate instead of its disposal. Replacing up to 20 % of coarse aggregate with waste plastic gives an adequate concrete strength specified in the Indian Standard [7]. The density of concrete reduces beyond 20 % replacement of coarse aggregates. Similar findings were reported elsewhere [8]. The compressive strength and splitting tensile strength of concrete containing plastic aggregate are not much different from the reference concrete specimens (i.e. 0 % waste plastic) [8]. However, and beyond 20 % waste plastic replacement, the strength is noticeably decreased. It has been concluded that 20 % of plastic waste aggregate can be incorporated as coarse aggregate replacement in concrete without any long term detrimental effects on the performance of concrete properties [6,7]. In another investigation, the bulk density of cement mortar prepared by replacing 0–100 % (by volume) of sand with two different sizes of polyethylene Terephthalate (PET) aggregates. The results showed that the reduction of bulk density remained small when the volume occupied by aggregates varies between 0 % and 30 %, regardless of their size. However, when this volume exceeded 50 %, the composite bulk densities started to decrease until reaching a value of 1000 kg/m^3. They also found that for the same volumetric percentage of substitution the bulk density decreased with decreasing particle size.

Replacing the fine aggregate with plastic waste containing 80 % polyethylene and 20 % polystyrene was found to cause a reduction in compressive strength [9]. The concrete with 10 % of plastic waste displayed the lowest compressive strength at 28 days of curing, which is about 30 % lower than that of the reference concrete. In addition, the study found a reduction in density of 5 %, 7 %, and 8.7 % for concretes containing 10 %, 15 %, and 20 % plastic aggregates respectively. This is in agreement with results obtained on concretes incorporating lightweight aggregate made with Polyethylene Terephthalate (PET) bottles [10]. The splitting tensile strength of concrete decreased with the increase in plastic waste made from bottles. This decrease was 19 %, 31 %, and 54 % for concrete containing 25 %, 50 %, and 75 % waste plastic respectively. The trend was similar for the modulus of elasticity. Frigione et al [11] replaced the fine aggregate in the concrete with 5 % PET aggregate and concretes had varying w/c ratios were prepared. The splitting tensile strength was reduced in concrete containing PET aggregate and this reduction is more at higher w/c ratio. Moreover, Kou et al [12] reported a decrease in splitting tensile strength when fine aggregate is partially replaced with scraped PVC pipes. The splitting tensile strength at 28 days was 3.06, 2.89, 2.82, 2.58 and 1.83 MPa for concrete incorporating 0 %, 5 %, 15 %, 30 % and 45 % (by volume) respectively PET aggregate. The flexural strength, which is directly related to the splitting tensile strength, was found to increase at 5 % PET replacement at different water to cement ratios [13]. However, at a 15 % replacement, there was a drop in flexural strength compared with the control [13].

The behaviour of reinforced concrete beams containing PET waste [14]. PET particles were shredded and replaced fine aggregate by 5, 10, and 15 %. The beams were lightly reinforced with steel rebar and designed to fail in flexure. The presence of PET waste caused a reduction in compressive strength between 12 and 21 %. The stiffness and mode of failure for recycled PET waste reinforced concrete are almost identical to those of normal beams. There are small reductions in the ultimate load capacity and a slight change in the load-deflection response when using up to 15 % of PET waste. In another investigation, PET waste was used as fibers in reinforced concrete beams [15]. Four different shapes of PET were used in the concrete mixes; ring-shaped, irregularly shaped, synthetic waste wire, and manufactured synthetic macro-fibers. A total of eighteen beams were cast and subjected to four points bending test to study their flexural behaviour. The experiments confirmed that adding ringed shape PET fibers to the reinforced concrete beams did not reduce the deflection. The ductility for reinforced concrete beams was improved with the presence of ring-shaped PET fibers compared with other shapes of fibers.

There has been limited research on the structural assessment of reinforced concrete beams containing waste plastic. Therefore, this paper is concerned with the behaviour of reinforced concrete beams containing waste plastic obtained from bottle caps. This research is part of an ongoing investigation on the use of waste plastic in construction. The specific objectives are to determine the compressive strength and elastic modulus of plain concrete containing plastic bottle caps. In addition, the flexural behaviour and the strain distribution along the depth of the reinforced concrete beams containing waste plastic have been examined. Future work will include the effect of impact and dynamic loads on the behaviours of reinforced concrete beams containing waste plastic [16, 17].

2. Methods

2.1. Mix design

Four concrete mixes were used to examine the structural behavior of reinforced concrete beam containing plastic waste. The control mix (PBC 0) had a proportion of 1 (cement): 3 (fine aggregate): 3 (coarse aggregate) by weight and no waste plastic was used. In mixes PCB10, PCB15 and PBC 20, the coarse aggregate was replaced with 10 %, 15 % and 20 % (by volume) waste plastic bottle caps (PBC) respectively. These caps have a diameter of 25mm and a depth of 12mm. The free water to cement (W/C) ratio for all concrete mixes was kept constant at 0.6. These proportions of materials were selected based on initial trial mixes to achieve adequate workability. The details for all mixes are presented in Table 1.

Table 1. Details of concrete mixes.

Quantities per cubic meter (Kg/m³)						
Sample	R* %	Cement	Water	Sand	Gravel	PBC**
PBC 0	0	314	188.5	942.7	942.7	0.0
PBC10	10	314	188.5	942.7	848.4	30.5
PBC15	15	314	188.5	942.7	801.3	45.7
PBC20	20	314	188.5	942.7	745.1	60.9

* % replacement by volume of coarse aggregate with PBC
** Plastic bottle caps

2.2. Reinforced Concrete Beam Details

Reinforced concrete beams of dimensions 200×300×1200 mm were used. The main reinforcement consists of 3 bars mild steel with 8 mm diameter and this remained the same for all four beams used. Only the content of PBC varied from 0–20 % (by volume of coarse aggregates). The links had a diameter of 6 mm and they were spaced at 200 mm. Figure 1 shows the cross-sectional area of the beam and the reinforcing bars while Figure 2 shows the longitudinal section of the beam with the spaces between stirrups. Three pairs of demec points were located in the upper half of the beam and three in the lower half in order to examine the strain distribution along the cross-section at different loading points as shown in Figure 3.

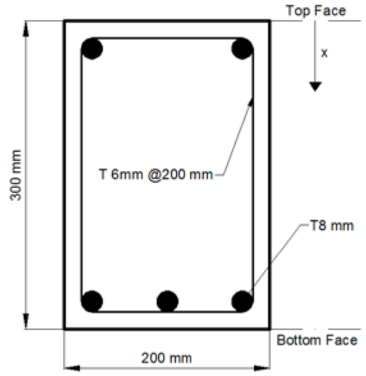

Figure 1. Cross-section of the beam and reinforcement.

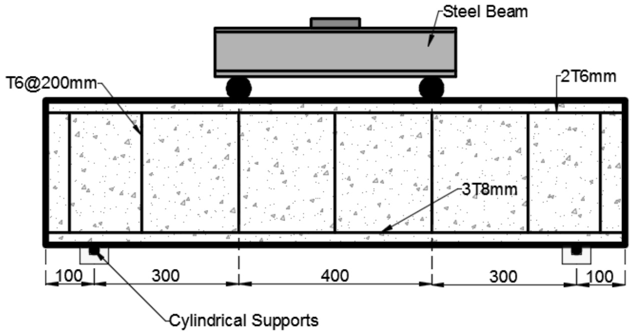

Figure 2. Longitudinal section of the beam with supports and loads (dimensions in mm).

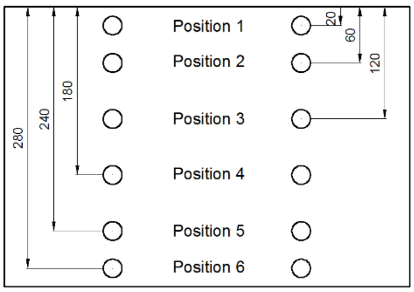

Figure 3. Position of strain measurements (dimensions in mm).

2.3. Casting

After calculating the quantity of materials required for the mix (i.e. cement, aggregate, sand, bottle caps, and water), the materials were weighed. Timber molds were used to cast the concrete specimens (i.e. cubes and beams). The molds were cleaned and oiled before casting. For the compressive strength test, cubes of 100 mm in size were used. These cubes were also used to measure the ultrasonic pulse velocity and to determine the density of concrete. For the Modulus of Elasticity (E) cylinders of 100 mm diameter and 200 mm length were cast. For the structural performance, beams of 200×300×1200 mm were used. The coarse aggregates were placed first in the mixer, followed by the fine aggregate and cement. The dry materials were mixed for two minutes, then water was added slowly and mixing continued until a homogenous mix was obtained as shown in Figure 4. This usually took between 3–4 minutes. Before casting the slump for each mix was measured as shown in Figure 5. The casting of cubes and beams was carried out in two and three layers respectively. Each layer is compacted in order to remove entrapped air as shown in Figure 6. Then specimens of the mixes underwent a slump test. The slump for the control mix was 12.5 mm and 0 mm for those with PBC replacements due to the bond between PBC and fresh concrete. For each mix, 8 cubes, two cylinders, and one beam were cast. After casting the cubes and cylinders were placed in a water tank, while the beam is covered with wet burlap and remained in the lab until testing.

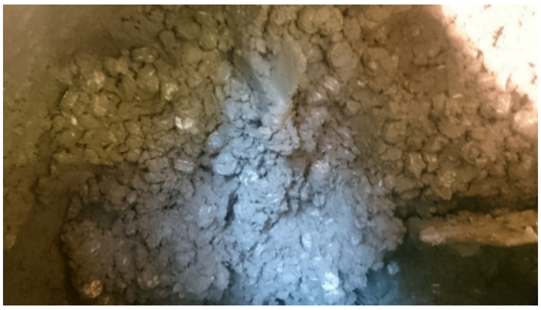

Figure 4. Mixing of concrete.

Figure 5. Control mix slump.

Figure 6. Casting and compaction.

2.4. Testing

The compressive strength and the modulus of elasticity tests were conducted according to BS EN 12350-1:2000 [18] and BS EN 12390-13:2013 [19] respectively. The four-point test was used to determine the flexure behaviour of reinforced concrete beams. Figure 2 shows the location of the supports and point loads. The beam was tested at 5kN increment until yielding started. At each load, the machine was stopped in order to measure the central deflection and the strain at different levels as shown in Figure 3. The load at first crack was recorded. Then, the loading continued until failure and the central deflection was measured. The propagation of cracks was observed throughout the duration of the test.

3. Results and Discussion

Figure 7 shows the average density of each concrete sample. The density of the reference sample (PBC0) was 2.49 t/m^3, whereas when PBC was used, a noticeable reduction in density occurred. The reduction was about 9 % for concrete with 20 % PBC. This is partly due to the low-density PBC and the voids created by the empty space of PBC.

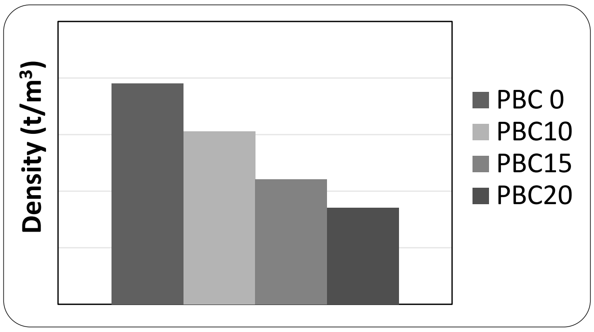

Figure 7. Average Density for concrete samples.

Figures 8 and 9 show the compressive strength and modulus of elasticity at 28 days for all concrete mixtures respectively. The compressive strength for the control mix is slightly less than concretes with PBC. The same trend was observed for the modulus of elasticity. This could be due to the better bond between plastic caps and the mortar, and the geometrical shape of bottle caps. This may be due partly to the rough surface of the curved side and the empty space of the PBC.

Figure 10 shows the load-deflection curve for all concrete beams. In general, the control beam shows more ductility than beams with PBC. The ductility factor that relates the yield displacement (Δy) to the maximum displacement just before failure (Δm) was calculated and presented in Table 2. It can be clearly noticed that the ductility factor for the control beam (0 % PCB) is more than twice that of the beam with 20 % PCB. However, the maximum load for PBC beams is slightly higher than that of the control. This may be due to the higher compressive strength and modulus of elasticity (E) obtained in the mix with 20 % PCB. Khatib et al 2017 [20] reported similar results.

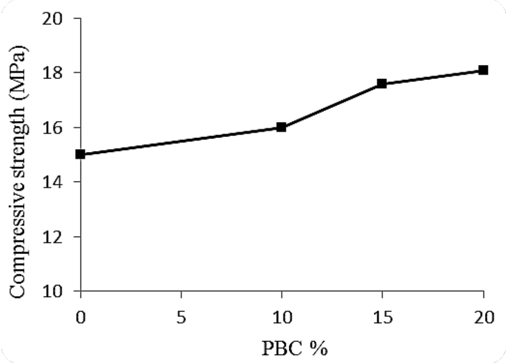

Figure 8. Compressive Strength (28 days).

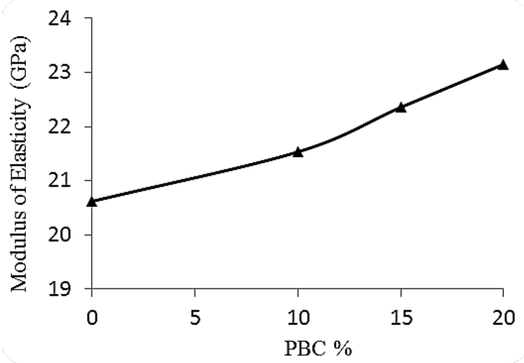

Figure 9. Modulus of Elasticity.

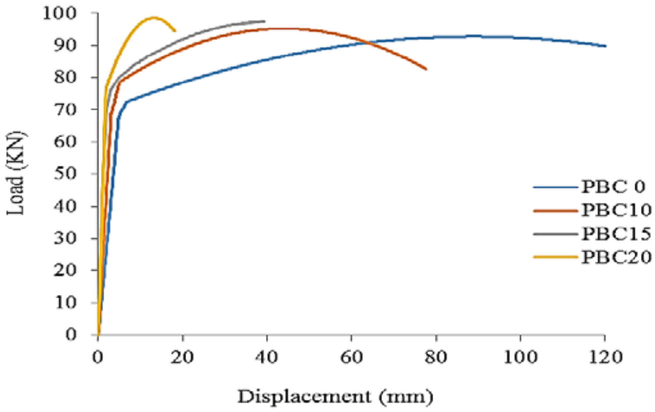

Figure 10. Load-Displacement Curve for all samples.

Table 2. Load-Displacement results.

Sample	Δ_y (mm)	Δ_m (mm)	Δ_m / Δ_y	P_{max} (KN)	P_{max}/P_{ref}
PBC 0	5	120	24	92	–
PBC10	3.4	77.5	22.8	96	1.04
PBC15	2	39.2	19.6	97	1.05
PBC20	1.7	18.1	10.6	98	1.07

The mode of failure for beams with and without PBC is illustrated in Figures 11 and 12. The crack pattern and the mode of failure are similar, and both reflect the flexural failure mode. The cracks started from the bottom face of beams and then propagated vertically through the sides till forming U-shape cracks covering both sides. As for the first crack appearance, Table 3 presents the first crack load and ultimate load reached by each sample. It can be noticed that the reference beam (PBC0) start cracking at a lower load than the samples with PBC. The maximum load for the beams is higher for those with PCB. However, the maximum load was similar to all beams containing PCB.

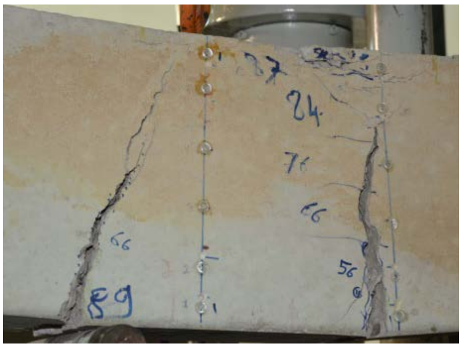

Figure 11. Flexural cracks for 0 % PBC beam.

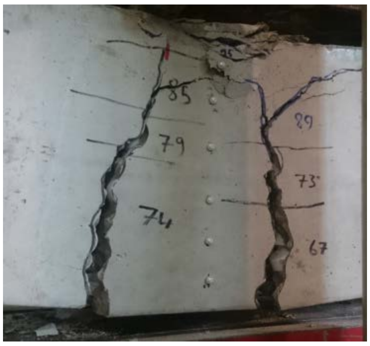

Figure 12. Flexural cracks for 10 % PBC beam.

Table 3 Load at first and final crack.

Sample	First Crack Load (KN)	Ultimate Load (KN)
PBC 0	56	92
PBC10	58	96
PBC15	63	97
PBC20	66	98

The strain distribution along the depth of the beam at different load increments is shown in Figure 13 to 16 for mixes with 0, 10, 15 and 20 % PBC respectively. The strain values for the control beams are larger than those for beams with PCB for the same load. This correlates with the larger central displacement for the control beam as compared with the beam consisting of PBC for the same load. This does not seem to agree with the results on the lightweight aggregate reported by Khatib [20]. This can be due to the amount of recycled aggregate used in each case and the type of lightweight aggregates used. The neutral axis shifts upwards as the load increases. This is better illustrated in Table 4, where the distance (x) of the neutral axis (Figure 1) from the top face is presented. The depth of neutral axis in beams with PBC is higher than that for control (PBC0) at the same loading condition.

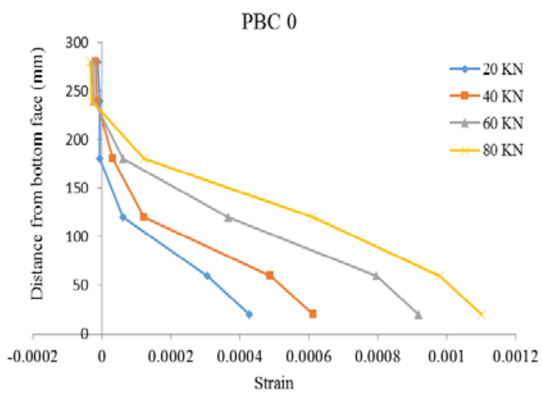

Figure 13. Strain Distribution for PBC0.

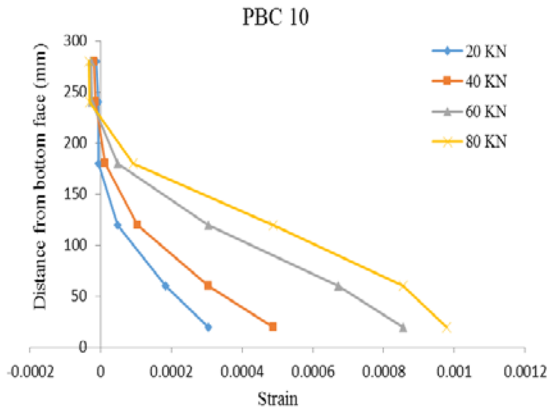

Figure 14. Strain Distribution for PBC10.

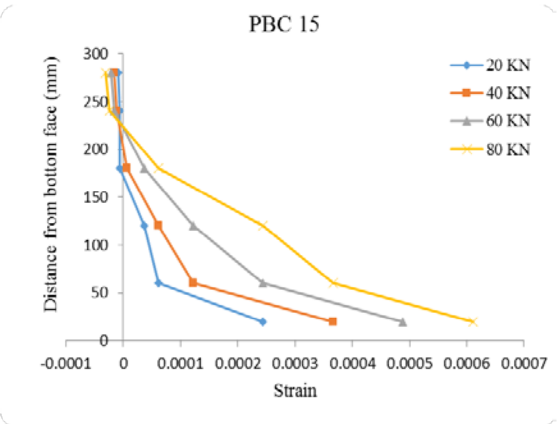

Figure 15. Strain Distribution for PBC15.

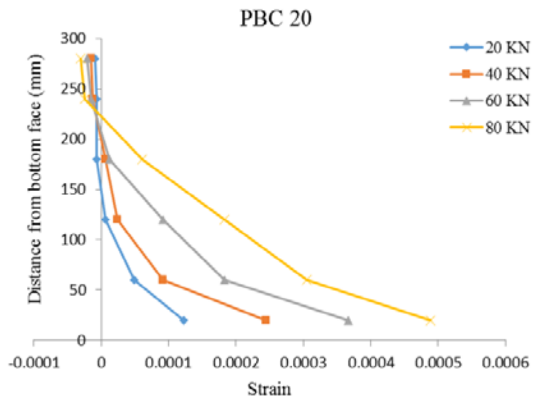

Figure 16. Strain Distribution for PBC20.

Table 4. Neutral axis depth (x) at different loads.

PBC0		PBC10		PBC15		PBC20	
Load (kN)	x (mm)	Load (kN)	x (mm)	Load (kN)	x (mm)	Load (kN)	x (mm)
20	45	20	46.3	20	51.3	20	53.6
40	41.5	40	43.2	40	49.3	40	52
60	36.2	60	37.6	60	42.3	60	45.1
80	32.8	80	34.3	80	39.4	80	39.9

4. Conclusion

The following conclusions are based on the results of this study:

• Replacing coarse aggregates with PBC reduces the concrete density. At 20 % PCB replacement, the concrete density is reduced by about 10. The workability of concrete is reduced when PCB is present in the mix.

• There was an increase in compressive strength and modulus of elasticity when PBC is incorporated in the concrete mix. The load at failure was also higher when PBC is present. This could be due to the better bond between plastic caps and the mortar, and the geometrical shape of bottle caps.

• The ductility of concrete containing PBC is reduced. For example, the control mix had a ductility factor of 24 while the mix with 20 % PBC the ductility factor was 10.

• The failure mode for both beams was flexural mode. That occurred as expected since all samples were designed to fail in flexural. The first crack appeared on the control beam (PBC0) was at a load of 56KN, and it gradually increased with the increase in PBC content reaching 66KN at 20 % PBC replacement. This is a good indication of delaying crack appearance when using PBC in concrete.

• As for strain distribution, it was found that for the same load the tensile strain in the control beam was higher than those with PBC. This can be justified by the larger central deflection for the control beam. The depth of the neutral axis decreased as the load increased for all beams. The presence of PBC increased the depth of the neutral axis at similar loads.

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