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Experimental Investigations on the Bond and Flexural Characteristics of PET Reinforced Concrete

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Abstract —— *The safe disposal of non-recyclable plastic material is the most challenging issue for the solid waste management across the globe. Even today, at least 15% of total plastic waste remains untreated. Incorporation of plastic in concrete is an inclining area of research which is one of the ways of utilizing the exponentially increasing plastic waste. Fibres obtained from the food grade Polyethylene Terephthalate (PET) bottles are utilized in an earlier research where satisfactory results were obtained. The present research studies concentrate on resolving the above issues in a beneficial way. In the current study, post-consumer PET bottle is used as reinforcement for concrete and the bond characteristics of PET with concrete and the flexural strength characteristics of concrete reinforced with PET in various forms like hollow bars, strips etc are studied and also compared with those of steel reinforced concrete and the test results are reported with detailed analysis.*

Keywords- *Polyethylene Terephthalate, Bond Strength, Flexural Strength, PET waste concrete, PET Bottle waste,*

I. INTRODUCTION

Polyethylene Terephthalate (PET) is one of the most important and extensively used plastics in the world, especially for manufacturing beverage containers [1]. The production of PET all over the world exceeded 6.7 million tons per year showing a dramatic increase in the Asia due to recent increasing demands in major countries like India and China. Production of PET bottles in Korea has already crossed 130 thousand tons a year. In 2007 the world's annual consumption represented 250,000 million PET bottles (10 million tons of waste) with a growth increase of 15%. In 2016, it was estimated that 56 million tons of PET are produced each year. In the United States 50,000 million bottles are land filled each year. However, most PET bottles used as beverage containers are thrown away after single usage and disposed PET bottles are managed by landfill and incineration, which causes serious environmental problems.

Particular interest is stirring, at present, in the usage of fibers obtained from waste PET bottles. A possible application is to utilize PET fibers as reinforcement for concrete to improve its tensile strength. Concrete is well known for its compressive strength but is low in tensile strength. This reduced tensile strength is partly due to the presence of micro and macro cracks caused by shrinkage of the concrete [4]. Studies have been developed to get the mechanical characteristics of concrete reinforced with PET fibers [2][3].

Work has already been done on the use of plastic waste such as poly vinyl chloride (PVC) pipe, high density polyethylene (HDPE), shredded and recycled plastic waste, polyurethane foam, polypropylene fiber etc. as an aggregate, as filler or as fiber in the preparation of concrete.

The current research work is an extension to the work reported in [12] which is a part of an extensive research in an attempt to develop PET as a reinforcement material in concrete. In the preliminary research work, flexural strength tests were done on Concrete beam specimen reinforced with PET in various forms and the test results were reported. Bond between concrete and PET was found to be one of the important parameters needed for study. So an attempt has been made to study the same along with the flexural characteristics of concrete beams reinforced with PET in other forms other than those reported in [12].

II. ABOUT THE RESEARCH

2.1. Objective of the present research

To study the Bond characteristics between concrete and PET material and the flexural behavior of concrete reinforced with recycled PET bottle in other forms other than those mentioned in [12], in comparison to un-reinforced concrete and concrete reinforced with steel reinforcement.

2.2. Need of the present study

The indiscriminate disposal of PET bottle wastes is posing an enormous threat to the environment. Although only a part of it is recycled, most of the PET waste is being incinerated and resulting in piles of landfills posing potential threat to the ecosystem especially in countries like India. Alternative methods and techniques are being evolved aiming at the safe disposal of these PET wastes but the risk and finances involved are high. Addition of post-consumer PET bottle wastes in concrete is an alternate technique of safe disposal of the same. This present work is an extension to the preliminary research reported in [12] where flexural behavior of post-consumer PET bottles as reinforcement in concrete was studied. The present work aims at studying the bond characteristics between concrete and post-consumer PET material and also the flexural behavior of concrete reinforced with post-consumer PET bottles used in various forms.

2.3. Significance of research

DoraFoti reported that addition of a very small amount of fibers from recycled and shredded PET bottles can have a large influence on the post-cracking behavior of plain concrete elements [4]. Batayneh et al. reported a decreasing trend of flexural strength with increasing plastic waste aggregate content in the concrete[7]. Saikia and de Brito[13] also found lower flexural strength values for concrete containing PET aggregate than for concrete containing natural aggregate only. Marzouk et al.[8] mentioned that a 50 vol.% replacement of aggregates by PET wastes leads to a reduction of the thermal conductivity by 46% and reported that the modulus of elasticity of PET based composites decrease slightly with increasing waste content upto 20% (just 5%). Anoop et al. reported a significant increase in the flexural strength of concrete reinforced with PET and also in case of combination of both steel and PET in concrete and also suggested that better bonding between PET and concrete could significantly enhance the mechanical properties of PET reinforced concrete [12].

In the present paper, the bond characteristics and the flexural behavior of concrete reinforced with recycled post consumer PET bottles were examined in comparison with un-reinforced and steel-reinforced concrete and the test results were reported.

2.4. Methodology

In the present research work, experimental investigations were conducted for assessing the bond strength of PET reinforcement in concrete and the flexural strength of concrete provided with PET reinforcement in various forms like hollow bars and strips. Concrete cylinder specimens embedded with PET bars or steel were adopted for carrying out Pull out test for assessing the Bond strength as per IS 2770 (Part 1): 1967 and ACI procedures and 100x100x500mm sized beam specimens were adopted for carrying out the Flexural strength tests and the test results obtained were reported.

For the Bond strength tests, 3 types of cylinders were cast with hollow PET bars embedded in the cylinder concentrically to depths of 150mm, 130mm and 100mm from the top and the rest of the length of the PET bars is left over the top of cylinder for gripping during the test.

A Hollow PET bar is prepared by cutting post-consumer PET bottles discarding the top and bottom portions of the bottle. It is rolled as a hollow bar and tied with PET strings helically with varying pitches and some specimens are prepared by tying with PET strings along the length of the PET bar at regular intervals to form a bar of dimensions about 30cm long hollow bar, with outer diameter of 20 mm and thickness of 0.9 mm and inner diameter of 18.2 mm. In the above mentioned PET bars, one set of PET bars were prepared by tying with PET thread helically with a pitch of 1.5cm designated as HP1.5, another set with a pitch of 4 cm which are designated as HP4 in the work and the other set of bars are prepared by tying the threads across the bar lengthwise at a pitch of around 2.5 cm and are designated as AT4. These are shown in ***Figure 1***.

Each set of the above mentioned PET hollow bars are embedded into concrete cylinders as shown in ***Figure 4*** and the cylinders were subjected to 28days and 7 days curing prior to testing. Also, a set of cylinders were embedded with 8mm diameter steel bars into the cylinder concentrically to depths of 150mm and 110mmm and cured for 7 and 28 days before testing for the purpose of comparison with that of the PET bar embedded cylinder specimens.

Pull out tests were conducted on all the above mentioned specimens where, the embedded PET hollow bars and 8mm diameter steel bars were pulled out of the cylindrical specimen keeping it in the UTM, as per the standard procedures laid in IS 2770-part 1:1967 and ACI methods.

For determining the flexural strength of PET reinforced concrete, 8 types of concrete beam specimens having size 500 x 100 x 100 mm were used in this research work. Beams without any reinforcement made of plain concrete are Control beams, the first type, designated as CB. Concrete beams reinforced with one steel bar of 8mm diameter and 48cm long were the second type of specimens designated as RS. Those reinforced with two steel bars are of third type, designated as RS-2. Concrete Beams reinforced with PET hollow bars which are helically wound with PET strings are the fourth type, designated as RPHW. Concrete beams reinforced with PET hollow bars that are tied with PET strings at regular intervals along the length are designated as RPAW. Concrete beams reinforced with hollow PET bars that are coated with sand on the outer surface are designated as RPHSC. The beams reinforced with PET bars which were filled with sand in the internal hollow space are designated as RPHSF. The concrete beam reinforced with 2 bunches of PET strips of 2cm wide each are designated as RBS-2(2).

Figure 1. Hollow PET bars

Figure 2. Bunch of strips of 2cm width each

In the preliminary research mentioned in [12] concrete beams reinforced with PET long strips which are placed along with steel reinforcement in the tension zone exhibited interestingly high flexural strength. So an attempt was made by incorporating bunch of PET strips having width of each strip being 2cm into the concrete beams as shown in Figure 2. The flexural strength test results of these specimens were reported.

The details of various types of concrete beam specimen used are listed in ***Table 1***.

2.5 Materials used

The materials used in the current research are:

- 43-Grade Portland Pozzolana Cement (PPC)
- Coarse Aggregate
- Sand confirming to Zone II
- Water
- Recycled PET
- Steel bars of 8mm diameter

The material properties of PET were reported in [12]. The PET material obtained from various sources of post-consumer beverage bottles was tested for tension and their modulus of elasticity is presented in ***Table 2***.

Table 1. Details of beams specimen used

S.No.	Type of Concrete Beam	Designation
1.	Control specimens	CB
2.	Concrete beam reinforced with one Steel bar	RS
3.	Concrete Beam reinforced with two steel bars	RS-2
4.	Concrete Beam reinforced with helically wound PET hollow bar	RPHW
5.	Concrete Beam reinforced with across tied PET hollow bar	RPAW
6.	Concrete Beam reinforced with sand coated PET hollow bar	RPHSC
7.	Concrete Beam with sand filled PET hollow bar	RPHSF
8	Concrete Beam reinforced with 2 bunches of PET strips - 2cm wide	RBS-2(2)

Table 2. Modulus of elasticity of PET material

S.NO	Source of PET Material (bottles)	Modulus of elasticity (GPa)
1	Sprite	4.72
2	Coca cola	4.35
3	7 up	4.01
4	Kinley	2.56

PET material obtained from post-consumer Sprite & Coca cola bottles were widely used in this study which are having higher modulus of Elasticity. The following types of PET reinforcement were used for the purpose of investigation.

1. Helically wound Hollow PET Bars : A hollow PET bar is prepared by cutting post-consumer PET bottles discarding the top and bottom portions, and the central portion is cut longitudinally, folded round with outer diameter of 24mm, the inner diameter of 22.8mm and thickness of 0.6mm, and it is helically wound with PET strings with pitch 2cm. For increasing the length of the reinforcing bar to 48cm, the individual bars are overlapped to a length of 12cm to obtain full required length of 48cm.

2. Across tied PET Hollow Bars: The PET hollow bars mentioned above are tied with PET strings around the bars at a pitch of 4cm as shown in ***Figure 3***.

3. Bunch of Strips-2cm wide: The Bunch of strips (2cm width) is prepared by cutting the PET Bottles longitudinally into strips of each 2 cm width. The length of each strip is around 15cm. Overlapping was done with similar strips by pinning, with an overlap length of 6cm to obtain a total length of 48cm. These individual strips of 2cm width each are bunched together for required thickness by tying them with PET strings. The bunches of PET strips are shown in ***Figure 2.***

Concrete used is of M_{25} grade obtained by IS method of mix design as per IS 10262:1993 and the proportions of mix are given in ***Table 3***.

Table 3. Concrete mix proportions

Material	Content(Kg/m^3)
Cement	370
Sand	662.47
Coarse Aggregate	1195.1
Water	166.5

Figure 3. Across tied hollow PET bar

2.6 Test programme

Bond strength is the measure of the effectiveness of the grip between concrete and the reinforcement used. The setup of the concrete samples for the bond strength is shown in ***Figure 5***. The test to determine the level of adhesion or bond strength between concrete and hollow PET bars was determined by the Pull out test and the bond strength was calculated using the equation mentioned below.
Calculation of bond stress,

$$\tau = P/\pi.\ \phi.\ l$$

Where
τ = Bond Stress (N/mm^2)
Ø = The average diameter of the test bar (mm)
l = Development length or embedded length (mm)
P = Load at failure

The Cylinder specimens are mounted in the Universal testing machine in such a manner that the bar is pulled axially from the cylinder as shown in ***Figure 5***. The load is applied to the reinforcing bar at a rate not greater than 2.250 kg/mm, or at no load speed of the testing machine head of not greater than 1.25 mm/min. Dial gauge is fixed to measure the slip of the bar. The movement between the reinforcing bar and the concrete cylinder, as indicated by the dial micrometers are read at a sufficient number of intervals throughout the test to provide at least 15 readings by the time a slip of 0.25 mm has occurred at the loaded end of the bar. The loading is continued and readings of movements recorded at appropriate intervals until a minimum slippage of 2.5 mm has occurred at the loaded end.

The bond strength test results are reported in ***Table 4.***

Figure 4. Cylinders with PET bar of helical pitch

Figure 5. Bond strength test setup

Flexural strength is a measure of the tensile strength of concrete. It is a measure of resistance to failure in bending. The beams were tested for flexural strength after curing for 28 days in a Digitalized universal testing machine. The deflection in the beam is noted at regular intervals from the deflection dial gauge and the load at the point of failure is noted. The Concrete beam specimens are placed in the machine in such a manner that the load is applied to the uppermost surface as cast in the mould, along two lines spaced 20.0 or 13.3 cm apart. The axis of the specimen is carefully aligned with the axis of the loading device. The load is applied without shock and increasing continuously at a rate such that the extreme fibre stress increases at approximately 0.7 kg/sq.cm/min that is, at a rate of loading of 180 kg/min for the 10.0 cm specimens. The load is increased until the specimen fails, and the maximum load applied to the specimen during the test is recorded. The appearance of the fractured faces of concrete and any unusual features in the type of failure is noted.

The flexural strength of the specimen is expressed as the modulus of rupture f_b which if 'a' equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of the specimen, in cm, is calculated to the nearest 0.05 MPa as follows:

$$f_b = \frac{PL}{bxdxd}$$

When 'a' is greater than 13.3 cm. or

$$f_b = \frac{3Pa}{bxdxd}$$

when 'a' is less than 13.3 cm but greater than 11.0 cm.
where
b = measured width in cm of the specimen,
d = measured depth in cm of the specimen at the point of failure,
L = length in cm of the span on which the specimen is supported
P = maximum load in kN applied to the specimen.

The test setup is shown in ***Figure 6.*** The Flexural strength of each type of beam was obtained and the load-deflection characteristics of the beam up to the point of failure are reported in this paper.

Figure 6. Flexural strength test setup

III. TEST RESULTS AND DISCUSSION

3.1 Bond strength test results

Before commencing the Bond strength tests, the development length or embedded length of both the PET hollow bar and the steel bar was assumed as 150mm. But while testing after 28 days of curing, it was observed that PET hollow bars as well as steel bars, initially deformed elastically with gradual increase of load and the PET hollow bar failed at 7 cm from top of bar which is provided for gripping, while the steel bar failed in cup and cone fracture. This is due to the excess embedded length provided in both the cases which is preventing the bars from slipping away from the concrete. So No Slip was observed. Then in the next trial, both PET hollow bars and steel bars were tested with 150mm embedded length at 7days curing. Similar behavior was observed in this case also, even though the expected strength of concrete is lesser at seven days curing.

As a third trail, embedded length was reduced to 110mm for steel bars and 130mm for PET hollow bars and checked for 7days curing, where it was observed that both the PET hollow bars and the steel bars exhibited significant slip failure and the reinforced bars completely slipped away from concrete. While the former started slipping from concrete at a load of 4061N and came out of concrete completely at a load of 4345 N, the later started slipping at a load of 4237N and completely came out of concrete at a load of 22759 N. This behaviour of large variation of load at final slip may be attributed to the greater surface roughness of the steel bar compared to the smoother surface of the PET hollow bar.

Table 4. Bond strength test results

S.No.	Type of Specimen	Load at 0.25mm slip (N)	Ultimate Load of Pull Out Specimens (N)	Bond stress at 0.25 mm slip(MPa)	Bond stress at failure(MPa)
Ld=130mm			Curing period = 7 days		
1	HP1.5	414	444	0.497	0.758
Ld=110mm			Curing period = 7 days		
2	HYSDS	431	2320	1.532	3.366
Ld=100mm			Curing period = 7 days		
3	HP1.5	398	422	0.426	0.452

As a fourth trail pull out tests were also conducted by reducing the embedded length of hollow PET bar to 100mm at 7 days curing. But the bar started slipping from concrete at a load of 399N and came out completely at a load of 422N. This shows that the bond strength developed at 100mm embedded length is less than that of 130mm embedded length. So 130mm embedded length is considered to be optimum case for PET hollow bar and 110 mm for steel bar. The Bond strength test results are presented in ***Table 4*** in which Ld denotes the development length provided or the embedded length.

From ***Table 4***, it can be inferred that maximum bond can be achieved for PET hollow bars when they are provided with an embedded length of 130mm into concrete where maximum bond stress is developed. Bond strength of hollow PET bar in concrete is 32.44% of that developed using steel bars and this decrease is due to smooth surface of PET hollow bar.

3.2 Flexural Strength Test Results

During the testing of concrete beams in the UTM, the deformations of beams are noted at corresponding load intervals and these values are shown in the graphs below and the flexural strengths obtained are presented in ***Table 5***, and the variation of flexural strength among different types of beams is clearly presented in the bar chart in ***Figure 11***.

Table 5. Flexural strength test results

S.No.	Designation of test beam	Equivalent area in mm^2	Flexural strength (28days) in MPa
1.	CB	-	5.84
2.	RS	50	17.01
3.	RS-2	101	19.59
4.	RPHW	51	4.52
5.	RPAW	51	4.49
6.	RPHSC	51	2.92
7.	RPHSF	51	6.93
8.	RBS-2(2)	108	8.84

3.2.1. Comparing CB, RS & RS-2

The flexural strength of concrete beam reinforced with steel bars is far greater than that of control beams and also the ductility of the concrete beam reinforced with steel bars is greatly increased due to the tensile force borne by the steel bars in RS & RS-2 as seen in ***Figure 7***. While the control beam exhibited brittle failure, the steel reinforced concrete beams performed ductile behaviour before failure.

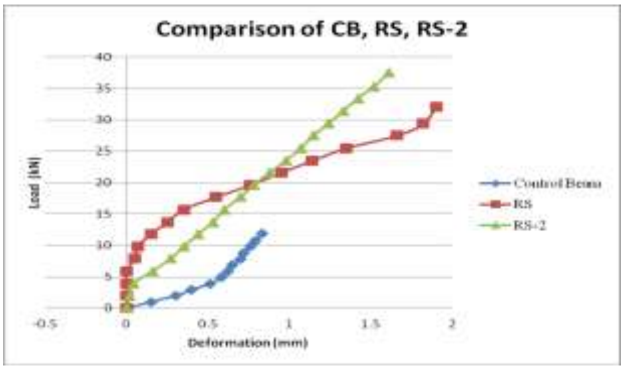

Figure 7. Load vs Deformation curves for CB, RS& RS-2

3.2.2. Comparing CB, RS, RS-2 & RPHW

By providing helically wound PET bars, the ductility of the beam increased but the flexural strength decreased than that of control beams. Flexural strength is 22.6% lesser compared to control beams. Also 75.3% & 76.9% lesser than that of RS & RS-2. But, even after the initiation of failure also, it performed well retaining its original position due to ductility provided by the PET bars, unlike the brittle failure in case of control beams. Even after the failure of beam, the beam is not entirely collapsed, it sustained and took more load till complete failure during the entire test. This behaviour can be clearly seen for ***Figure 8*** where the beam took large deformation before failure compared to Control beams.

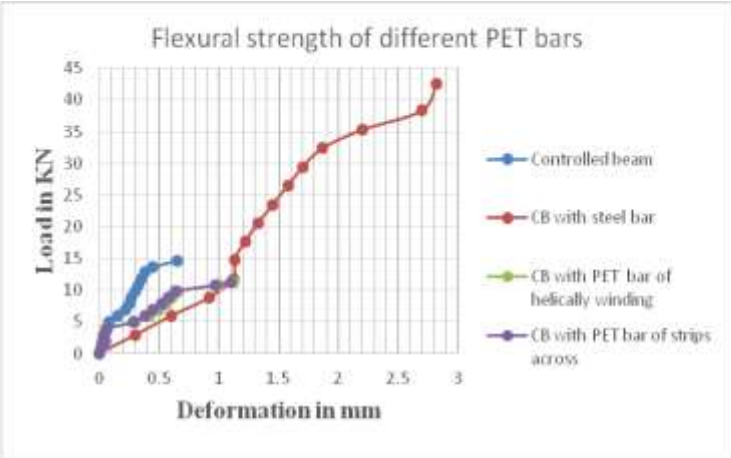

Figure 8. Load vs Deformation curves for CB, RS, RPHW & RPAW

3.2.3. Comparing CB, RS, RS-2 & RPAW

From ***Figure 8,*** it can be observed that RPAW has similar behaviour as that of RPHW. The RPAW beam has shown less flexural strength than RPHW by 0.66% and is also lesser than 23.12% that of control beams. Even though variation of pitch is provided there is no significant variation in flexural strength. The PET bars bent completely at the collapse load of the beam. This may be attributed to the hollow PET bar and also it slips more from concrete due to lesser bonding with concrete. So the RPHW has less flexural strength than that of control beam.

3.2.4. Comparing CB, RS, RS-2 & RPHSC

RPHSC performed with similar behaviour as that of RPAW. Flexural strength is the least in this case compared to all other types resulting in 34.9% less than that of RPHW and 50% less than that of control beams. The sand coated on the PET got removed with the application of load on the beam due to shear action between PET bar and concrete. Also bar slipped away more from concrete. The PET bar bent at the collapse load of the beam completely and was completely unstable as it was hollow and slipped away more from concrete. So, RPHSC beam showed very less flexural strength compared to control beams.

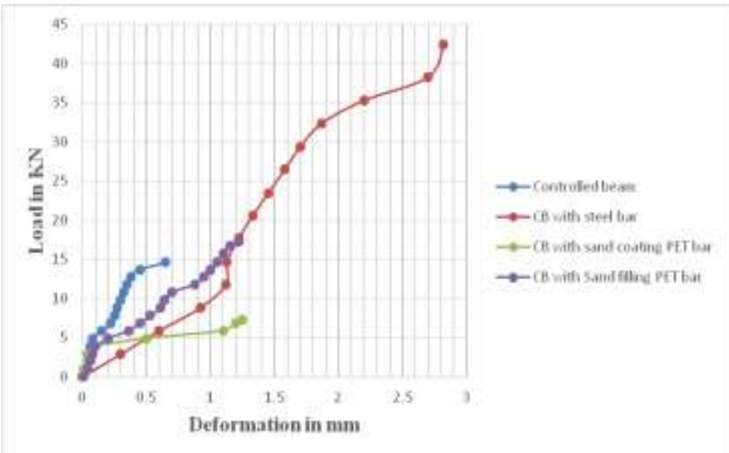

Figure.9 Load vs Deformation curves for CB, RS, RPHSC & RPHSF

3.2.5. Comparing CB, RS, RS-2 & RPHSF

From ***Figure 9,*** it can be clearly seen that RPHSF performed much better than the control beams, though it is not as good as steel reinforced beams. RPHSF showed much better ductile behaviour taking more loads and deformations much better than the control beams. RPHSF has flexural strength, 18.66% more than that of control beams and 53.32% higher than that of RPHW. The bar did not bend and performed well at the collapse load of the beam, because the PET bar is filled with sand and also its slippage from concrete is lesser resulting in more flexural strength than that of control beams.

3.2.6. Comparing CB, RS, RS-2 & RBS-2(2)

The concrete beam RBS-2(2) performed very well among the PET reinforced concrete beams. The RBS-2(2) has flexural strength 51.36% more than that of control beam. Since the final deformation before failure in this case is much more before collapse of the beam, the ductility is more than that of all other types of PET reinforced concrete beams examined in the present study. At a load of 15990N the first crack developed and at a load of 17756N the second crack developed for the RBS-2(2) beam, this behaviour is similar to Concrete beams reinforced with steel. On further application of load, the beam failed at 20306N. RBS-2(2) beam performed very large deformation before failure as can be seen from ***Figure 10***, which is even better than that of steel reinforced concrete beams, giving sufficient warning before failure. Also the beam was taking more additional load even after multiple cracks unlike the control beams which failed suddenly causing brittle failure. The ductile nature of RBS-2(2) beam can be clearly seen from ***Figure 10***.

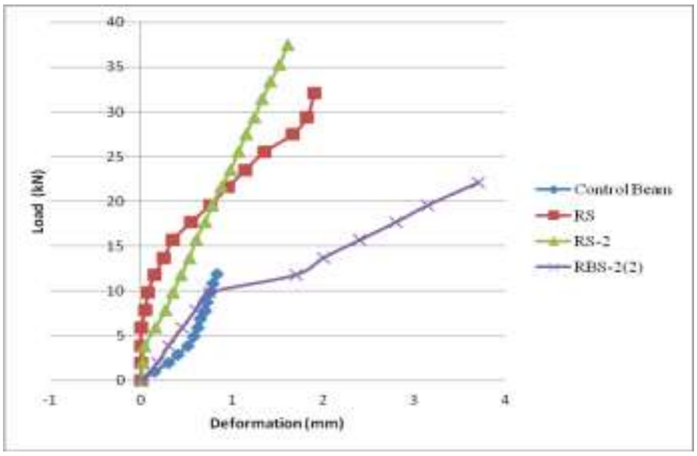

Figure 10. Load vs Deformation curves for CB, RS, RS-2 & RBS-2(2)

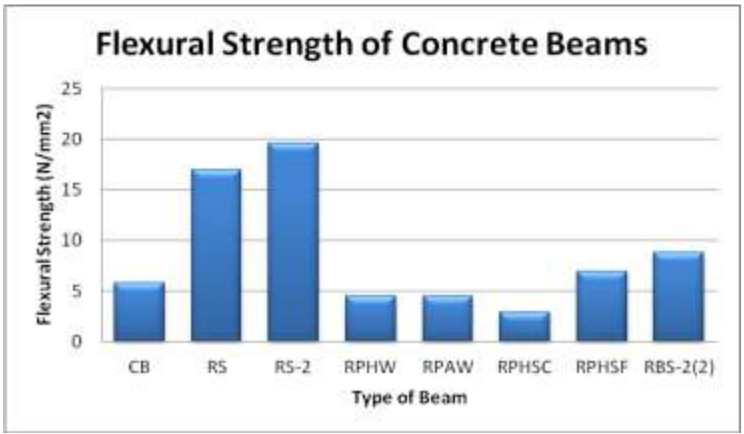

Figure 11. Bar chart showing variation of flexural strength

IV. CONCLUSION

Based on the experimental results the following conclusions were drawn in the present study:

From bond strength test results, it was observed that for a development length or embedded length of 130mm, hollow PET bar exhibited only slip failure and no other mode of failures such as split or crack failure of concrete was observed. So, more bond strength can be obtained at this embedded length. Bond strength of hollow PET bar in concrete is 32.44%

of that in HYSD steel bar and is at a decreasing trend. This is due to smoother surface of PET hollow bar compared to hard and ribbed surface of the steel bar which is showing more bond with concrete. No significant variation of bond strength was observed among PET hollow bars of types HP1.5, HP4 & AT. Bond strength depends on the strength of concrete and the age of concrete.

From flexural strength test results, it was observed that among the hollow PET bar type reinforcement, the one with sand filled performed well and was stable while testing and showed significant increase of 18.66% in flexural strength than the control beams.

No significant difference was observed in RPHW and RPAW in the flexural strength results. So the type of PET bars whether wound with strings helically or across tied PET bars, don't have much influence on variation of flexural strength.

Sand coated PET hollow bar exhibited poor performance among all. This is because with the increase of loading, shear between concrete and poor adhesion of sand with the PET bars caused erosion of the sand coating causing failure much earlier.

Concrete beams provided with two bunch of PET strips as reinforcement, RBS-2(2), performed very well among all the types of PET reinforcement. Increase of flexural strength by 51.36% is very significant compared to the control specimens. Also ductility performance of the beam is very significant compared to all other types of the beams as it exhibited large deformation before failure giving sufficient warning before complete collapse.

Much more investigations are required on PET Strips and bunch of strips with respect to bond and flexural properties.

PET reinforcement with sand filling and bunch of strips is a better alternative in situations where there is a problem of corrosion. By providing PET reinforcement in concrete, the self-weight of concrete and cost of construction can be reduced and it could be an environment friendly method of disposal of solid waste in the country.

In days to come, the usage of plastic may increase exponentially, so usage of plastic in concrete is essential rather than disposal. Hence utilizing PET effectively in the construction industry.

V. FUTURE SCOPE

The flexural strength behavior can be studied using bunch of PET strips as reinforcement on full scale beam specimens and slabs. Toughness and impact strengths are the other aspects to study with respect to PET reinforced structures. Bond strength may be increased by suitable measures that in turn increase the flexural strength of concrete. If PET bars or strip type reinforcement can be manufactured then they may certainly give more flexural strength compared with manually made bunch of strips.

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