



# Journal of Materials and Engineering Structures

## Research Paper

### Investigation on cyclic behaviour of FRC beams incorporating copper slag as sustainable waste

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#### ARTICLE INFO

##### Article history :

Received : 20 March 2020

Revised : 2 June 2020

Accepted : 3 June 2020

##### Keywords:

Cyclic test

Copper slag

Polypropylene fibre

Waste replacement

#### ABSTRACT

Scarcity of the natural sand and large availability of industrial wastes give the way to utilise the industrial by-product in concrete production. This paper showcases the performance of concrete composite containing copper slag and polypropylene fibre under cyclic loading. Fibrillated polypropylene fibre of 0% (P0), 0.2% (P1), 0.4% (P2) & 0.6% (P3) volume fractions and 40% copper slag (C40) are used together. The experimental work was conducted on the reinforced concrete beams of size 100mm x 200mm x 900mm. The criteria considered for discussion are yield power, yield deflection, ultimate strength, ultimate deflection, ductility factors and energy dissipation. It is observed that when subjected to monotonic loading and cyclic loading respectively, the overall load carrying power of C40P2 beam is 5 per cent and 2.71 per cent higher than the reference section. The specimen C40P2 has a ductility factor 25.05 per cent higher than the control beam. Energy absorption capacity of C40P2 is 72.79% more than the normal concrete. It is therefore concluded that, under cyclic loading, the output of 40% copper slag with 0.4% of polypropylene fibres find superior than control concrete.

## 1 Introduction

Utilization of waste is directly linked to sustainability. Waste reduction and waste management require sustainable principles such as reusing, recovering, recycling and remanufacturing. The growing cost of waste disposal, the depletion of natural resources and the need for sustainable growth have all necessitate the reuse of waste materials as a substitute for natural resources [1]. Copper slag is a by-product originating from copper processing industries that have the ability to recycle, produce value-added goods such as abrasive materials, roofing granules, cutting equipment, tiles, glass, railway ballast and paving asphalt [2]. Copper-rich matte (sulphides) and copper slag (oxides) are formed as two separate liquid phases through smelting process. The addition of silica during the smelting process creates active bonded silicate anions in

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combination with the oxides [3]. It contains oxides such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$  and  $\text{MgO}$ , which are either present in the original concentrate or added as a flux. Copper slag has a high density ranges from 3.16 to 3.87 g /  $\text{cm}^3$  based on iron content. Due to its glassy surface attributes low water absorption which allows the surplus amount of free water to remain in concrete for better hydration.

The concrete density increases by 5 per cent as the content of copper slag increases. The absorption of surface water decreased as the copper slag content increased. Hence there is also an improvement in workability. The authors of Ref.[4] found that the highest increase in strength was observed with the replacement of 20 per cent copper slag, the splitting tensile strength increased by up to 80 per cent. The compressive strength of mortars with a 50 percent copper slag replacement has been increased by more than 70 percent compared with the control mixture. It is therefore recommended that up to 40-50 per cent (by sand weight) of copper slag can be used as a replacement for fine aggregates to obtain a concrete with sufficient strength and durability requirements [5].

Ref.[6]-reported that when copper slag was used for longer periods of curing (i.e., 56 and 90 days), most of the samples displayed no adverse strength reversal. The major portion of strength gain takes place at 28-90 days period [7]. One of the study [8] found that gradual increase in compressive strength was observed up to 50% copper slag and increase in tensile strength was observed up to 40% of copper slag replacement. Ref.[9]- investigates the performance of high strength concrete (HSC) at constant workability in which copper slag is replaced for fine aggregate. It is noted that water demand decreased by approximately 22 per cent relative to the control mixture at 100 per cent copper slag replacement. Nevertheless, the absence of the superplasticizer adversely affected the strength and reliability characteristics of HSC. It is recommended that 40 percent of copper slag can be used as a substitute for sand to obtain HPC with good strength and durability [10].

Because of the rise in population, the industrial revolution slowly depletes the nature resources and influences the functioning of the ecological system on earth. On the other side, environmental pollution is the major challenge due to the industrial revolution. Hence, the disposal or dumping of waste requires more energy and cost than the production of parent material. Natural sand formation takes place by the weathering action of bed rocks over hundreds of millions of years. Hence, an alternative material to river sand needs to be sought to address the shortage of river sand. Copper slag produced from the copper industries has grain size equal to sand particles, and no further alteration is needed to be put into use. The use of copper slag in normal concrete, high-resistance concrete, high-performance concrete, and cement mortar applications is studied in past literature.

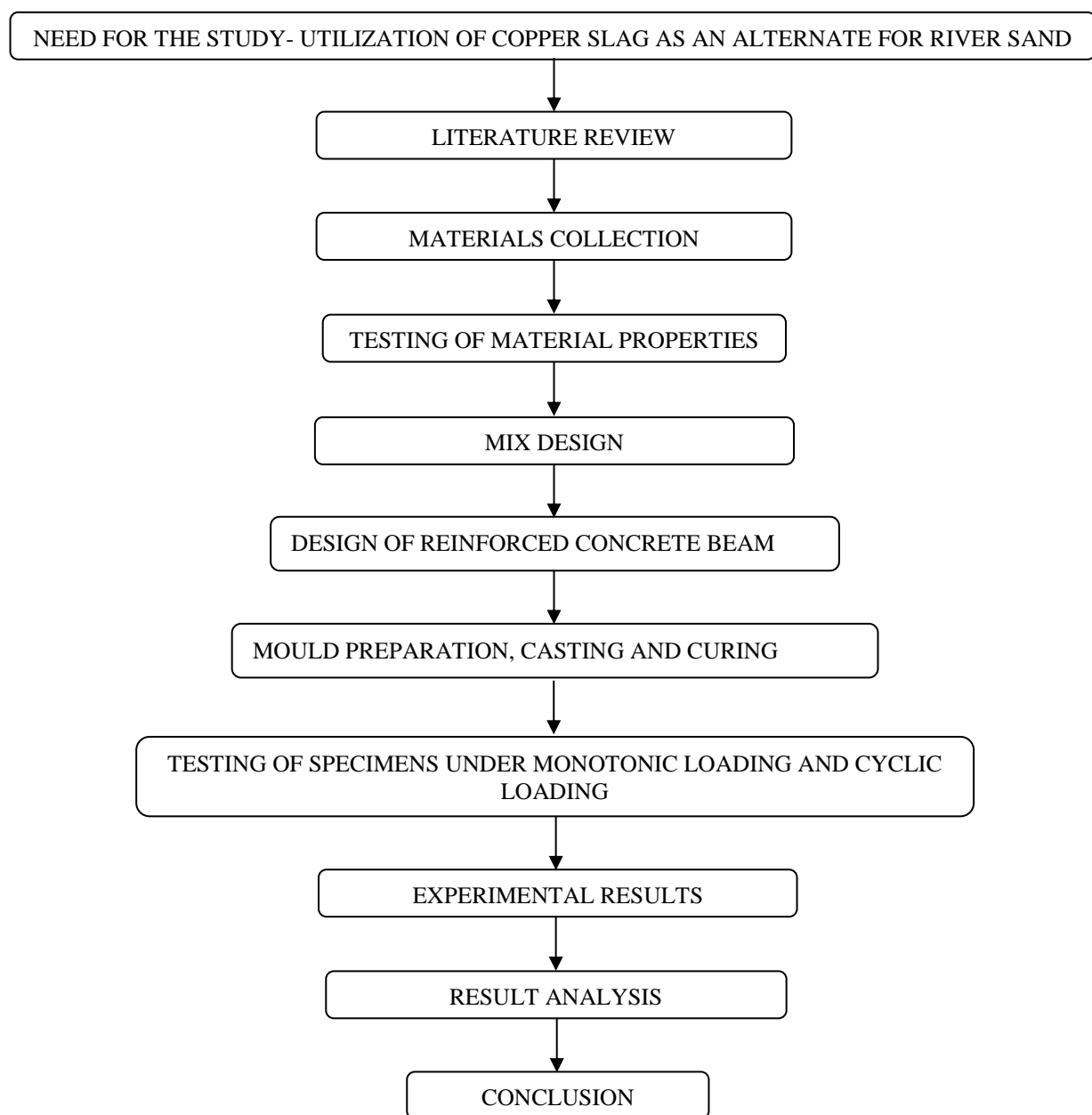
Fibres are widely used in building practices because a plain concrete has a very low tensile strength, minimal ductility and low cracking resistance. The concrete specimen leads to brittle failure due to low tensile strength [11]. The presence of micro-cracks at the mortar – aggregate interface is responsible for the intrinsic weakness of plain concrete. In addition to this, the conventional reinforced concrete does not meet other performance criteria such as im-permeability, resistance to frost, serviceability etc. In concrete, fibres are used to produce tensile stress to arrest micro-cracks and to control crack propagation through the major stressed sections. The use of fibre depends on the fibre geometry and the kind of application it is referred to [12]. This research suggests that 1-2 per cent of the fraction of volume is ideal for a particular use. Polypropylene is a synthetic polymer made from hydrocarbons, which is manufactured using extrusion processes by drawing the material through a die. This offers intrinsic tensile and flexural strength along with substantial plastic shrinkage reduction and minimizes thermal cracking [13]. However, traditional transverse reinforcement can be partially substituted by appropriate fibre material without loss of ductility and strength [14]. It is observed that 11% increase in compressive strength was obtained for 0.5% PPF volume fraction [15]. Owing to its reduced workability, polypropylene fibre has less flow and therefore reduced flowability, so it cannot easily interact with groves without compaction[16].

The researches have centered on evaluating copper slag concrete's mechanical and durability without any admixture. Some of the studies have suggested 20 to 40 percent of copper slag replacement in concrete due to certain drawbacks of copper slag such as minor bleeding and more fluidity in fresh concrete level. In order to resolve the negative attributes of copper slag and examine the effect of copper slag in concrete under cyclic loading, a test was made to incorporate 0.25 to 0.6 percent volume fraction of polypropylene fibre into the concrete.

The beams were tested under positive cyclic loading by one author [17]. The results showed that the presence of polypropylene fibre in the beam increases strength, ductility, energy absorption and rigidity. The effect of incorporating hybrid fibres increases the ductility by 80% and the energy absorption by more than 160%. Instead of adding one fibre, the combination of various types of fibres (hybrid fibres) significantly enhances the potential for energy absorption [18]. Previous study [19] showed that 40% of copper slag and 0.6% of polypropylene fibre is an optimal replacement. Although there is no

detrimental compressive strength compared to concrete control up to 80 percent of the replacement. The same author [20] concluded that up to 60 per cent of copper slag yields good results in studies of durability. It was found that 100% copper slag replacement shows decrement of compressive strength due to excess free water, but 80% copper slag can be used with suitable admixtures[19]. This experimental study aims to use 40% (optimum percentage) of copper slag with 0.2% and 0.4% and 0.6% volume fraction of polypropylene fibre.

The layout of this paper is as follows: Section 2 introduces the experimental programme. This consists of details of materials and mix design, the description of specimens and the test procedure. Section 3 deals with the results and discussions. This section is subdivided further into four categories. First one is to find the load and deflection values at yield stage. The second one elaborates load deflection responses up to the failure stage, the third subdivision discusses ductility factors and the energy absorption capacity is explained in subdivision 3.4. The significance and conclusion of the study are discussed in Section 4 and Section.5. Fig.1 demonstrates the methodology of this research subject, step by step.



*Fig. 1- Research methodology*

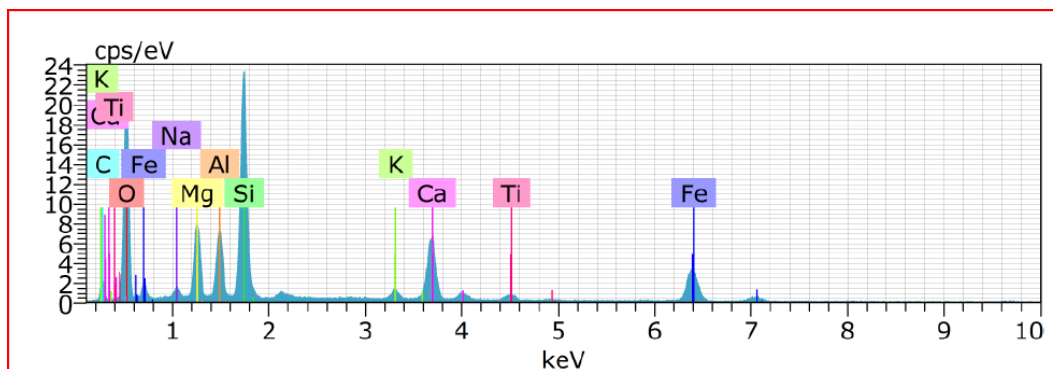
## 2 Experimental program

### 2.1 Materials and mix design

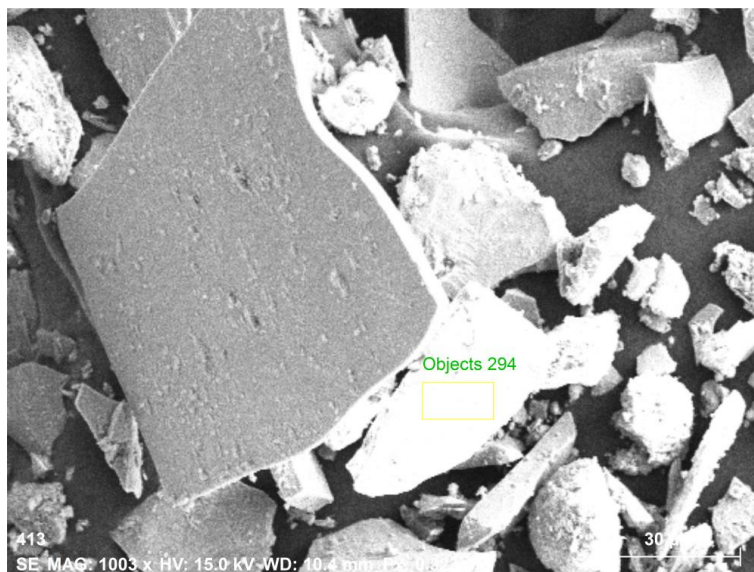
Ordinary Portland Cement of 43 grade confirming to IS 8112:2013 [21] was used. The specific gravity of cement is 3.14. Copper slag, fine aggregate and coarse aggregate were found to have a specific gravity of 3.5, 2.6 and 2.67 respectively. The water absorption of copper slag, fine aggregate and coarse aggregate was 0.15%, 1.25% and 0.92% respectively. Conplast SP- 430 is used as a high-range Naphthalene-based superplasticizer in compliance with IS 9103-1999[22] admixed to avoid segregation, increase flow efficiency and also ensure thorough particle dispersion in the concrete mix. The chemical composition of cement and copper slag is compared in Table 1. A total of 95.35 per cent of SiO<sub>2</sub> , Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> & CaO present in copper slag [23] is found. It is the quantity that meets the minimum requirement of 75% As per ASTM C618-19 [24] as a natural pozzolana. Hence, copper slag can be used in concrete production as a natural pozzolan. The presence of Si, Al, Fe and Ca is well identified through the XRD image of copper slag (Fig.2). Thin, irregular texture in rectangular shape is the copper slag displayed at 1000x magnification in Fig.3.

**Table 1 Chemical composition of Cement and Copper slag**

Components	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>
Cement (%)	20.85	4.78	3.51	63.06	2.32	2.48	0.55	0.24	0.25
Copper slag (%)	33.05	2.79	53.45	6.06	1.56	1.89	0.61	0.28	0



*Fig. 2 - XRD analysis of copper slag*



*Fig. 3 - Microstructure image of copper slag*

The mix was designed for M30 grade as per IS 10262-1982 [25] Indian Standard for Concrete mix proportioning - guidelines. Table 2 and Table 3 represent the mix proportioning of copper slag and polypropylene composite. Naphthalene based superplasticizer of 0.5% dosage was chosen to improve the mobility of concrete. Superplasticizer additions reduce the water-cement ratio to 0.41 from 0.51.

**Table 2 Mix design for control concrete**

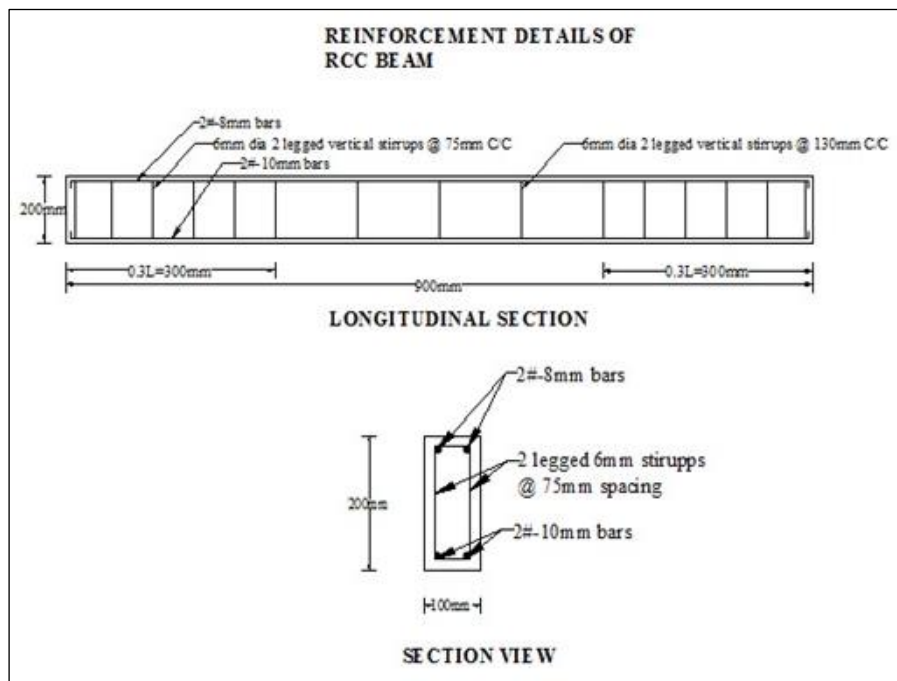
Water	Cement	Sand	Coarse aggregate
148.8 kg/m <sup>3</sup>	363kg/m <sup>3</sup>	620kg/m <sup>3</sup>	1343kg/m <sup>3</sup>
0.41	1	1.71	3.71

**Table 3 Total mix proportions with mix identification**

S.No	Mix ID	Cement	Sand	Copper slag	Coarse aggregate	Water content	Polypropylene fibre
							kg/m <sup>3</sup>
1	C0P0	363	620	0	1343	148.8	0
2	C0P1	363	620	0	1343	148.8	1.82
3	C0P2	363	620	0	1343	148.8	3.64
4	C0P3	363	620	0	1343	148.8	5.46
11	C40P0	363	371	354	1343	148.8	0
12	C40P1	363	371	354	1343	148.8	1.82
13	C40P2	363	371	354	1343	148.8	3.64
14	C40P3	363	370	353	1343	148.8	5.46

**2.2 Specimen details**

The reinforced concrete beam of 100mm wide, 200mm depth and 900mm long is used to test the cyclic behaviour of reinforced concrete specimen. The reinforcement details are given in Fig.4.



**Fig.4 - Reinforcement details**

### 2.3 Testing Procedure

The experimental work was carried out in Servo Hydraulic Universal Testing Machine (Fig.5) which can apply cyclic loading. The cyclic load was given in the increase of 10 percent of the ultimate load, for example when the RC beam’s ultimate load carrying capacity is 100kN under monotonic loading, and then 10 percent of 100kN is applied as cyclic load.



Fig. 5 - Test setup

## 3 Results and discussion

### 3.1 Yield load and yield deflection

Due to the cyclic loading application the yield deflection cannot be observed directly during loading. Drawing the intersection of tangent points determines the yield value. The yield deflection is determined along the deflection axis between the intersection points of the tangents taken from the first and last cycle load-deflection curves [26].

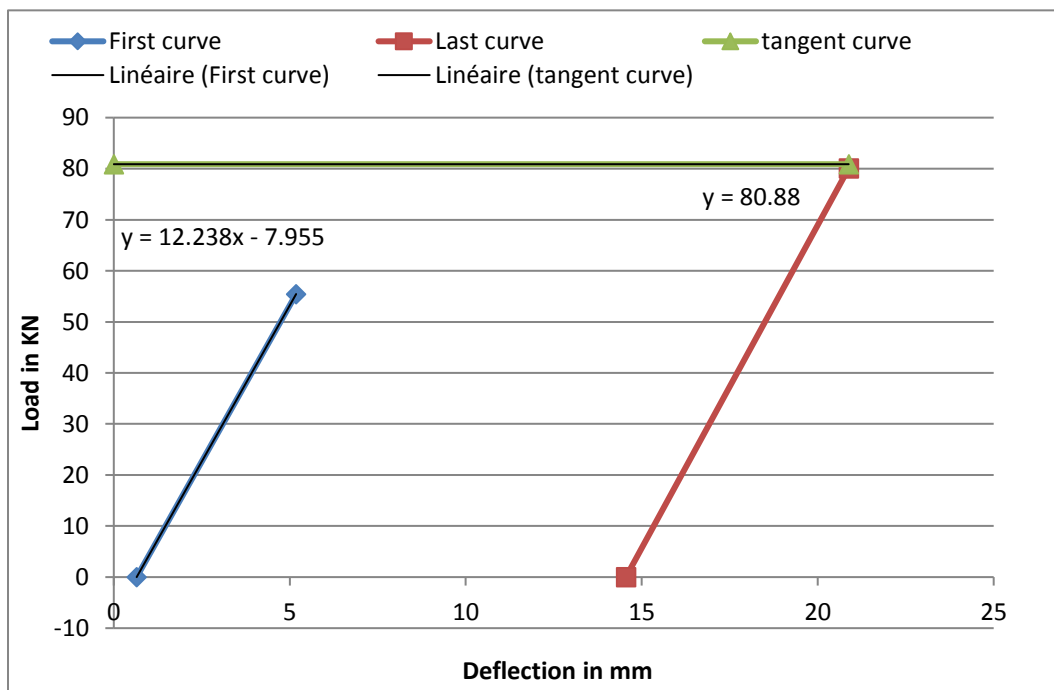


Fig. 6 - Tangents drawn for first curve and last curve

For example, the load-deflection curve of C0P2 beam shown in Fig.5 is considered to determine the yield deflection of that beam. Fig.6 describes the intersection of tangents from first curve to last curve of cyclic response. The tangent of the initial loading curve and the final loading curve is considered. A horizontal line is drawn from the top of the last curve. The trend line equation of first linear curve and horizontal tangent curve of the last cycle are given below.

$$y = 12.238x - 7.95 \tag{1}$$

$$y = 80.88 \tag{2}$$

Solving equation 1 and 2 gives the value of x which is the yield deflection for the respective beam. Similarly the yield deflections are determined for other concrete beams. The findings of cyclic loading on reinforced concrete beam are summarized in Table 4. For the C0P2 specimen, the maximum yield load is 54.07kN, which is 28.8 per cent higher than the control specimen. The yield load of C40P1 and C40P2 is much closer to the control beam indicated that the copper slag replacement does not affect the load carrying capacity.

**Table 4 Summary of results in load deflection response**

Mix ID	Deflection (mm)		Yield load (kN)	First crack load (kN)	Number of cycles at first crack load	Ultimate load (kN)		No of cycles for failure	Max crack width(mm)
	Yield	Ultimate				Monotonic Loading	Cyclic loading		
C0P0	5.81	25.94	41.944	30.8	5	134.96	67.76	11	7
C0P1	5.51	19.45	37.46	24.64	4	105.08	55.44	9	4
C0P2	5.95	20.88	54.07	36.96	6	92.63	80.08	13	6
C0P3	5.5	25.38	51.77	30.8	5	108.4	67.76	11	9
C40P0	5.5	14.39	37.7	24.64	4	134.96	67.76	11	5
C40P1	6.8	25.43	41.37	36.96	6	123.9	67.76	11	7
C40P2	5.14	29.19	42.01	43.12	7	141.9	69.6	10	13
C40P3	8.97	22.48	38.06	24.64	4	138.28	67.6	11	4

### 3.2 Load deflection responses

Owing to the introduction of polypropylene fibres (Fig. 7 & Fig.8), peak loading increased. With the increase in fibre content the slope of the softening branch was reduced. The total load carrying capacity of the C40P2 beam, when loaded monotonically and cyclically, is 5 percent and 2.71 percent higher compared to the reference concrete. Fig.9 displays the microstructure picture of C40P2 showing a denser particle packing as comparison to the control concrete [27]. C40P2 beam experiences a typical crack width of 13 mm. Total C40P2 beam deflection is 29.19 mm which is greater than control concrete deflection (25.94 mm). The composite matrix therefore helps the beam to deflect more than the control beam ensuring serviceability. At the same time, C0P3 provides an ultimate 25.38 mm deflection that is less than the control beam.

The number of cycles in copper slag concrete does not change substantially [28]. While observing the crack pattern, cracks are started at the interface of reinforcement and concrete. Fig.10 to Fig 13 illustrates the crack pattern of all specimens. Fibre-reinforced concrete restrains the cracks from the systematic development of cracks on the concrete surface. The cracks created during loading are closed during unloading, because of the application of PPF. Fibre anchoring in the mass matrix leads to increased concrete stiffness. Crack formation, propagation, and development in fibre-reinforced concrete are slower and more stable than conventional concrete. It can also withstand reversed cyclic loading [29]. Because of the crack bridging effect, fibres boosted the post-peak response under bending. The post-cracking behavior was extreme for higher volume fraction resulting in increased strain capacity and deformation capacity in the pre-failure zone [30]. The same was checked with C0P3 's greater load carrying ability.

Control concrete exhibits spalling of cover concrete in reverse cyclic loading where there is no spalling of concrete as polypropylene fibre reinforced concrete beam with copper slag. This is due to the bridging effect of polypropylene fibre and copper slag concrete matrix [31].

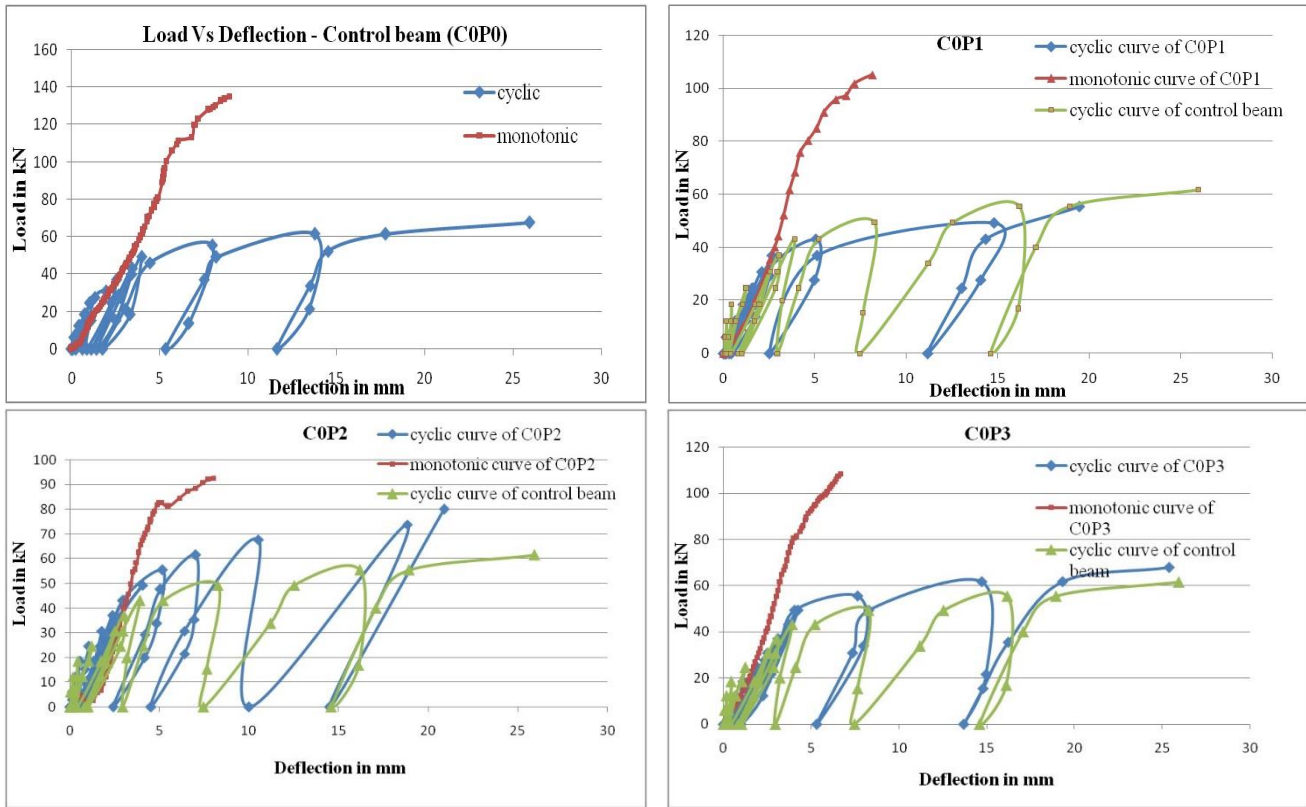


Fig. 7 - Load deflection behavior of concrete with PPF and without copper slag

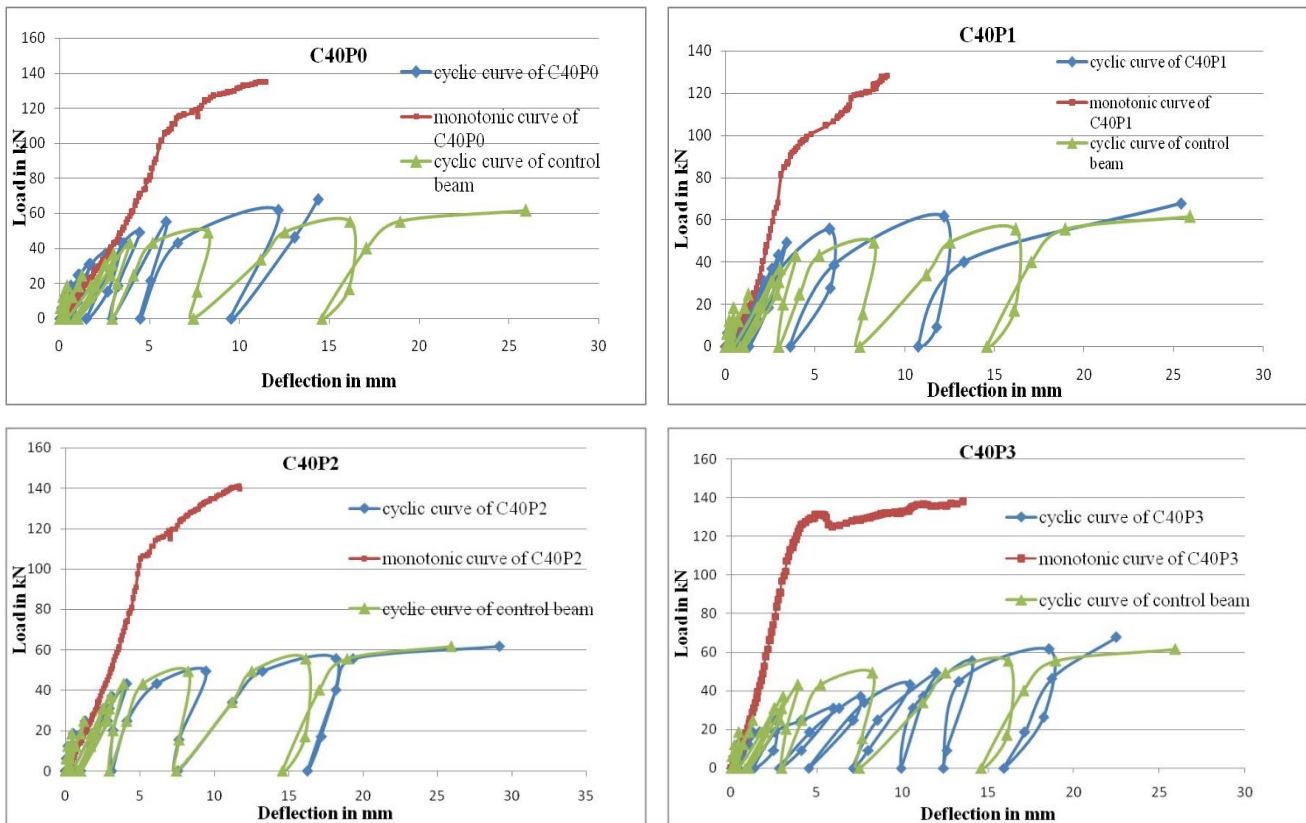


Fig. 8 - Load deflection behavior of 40% copper slag replacement





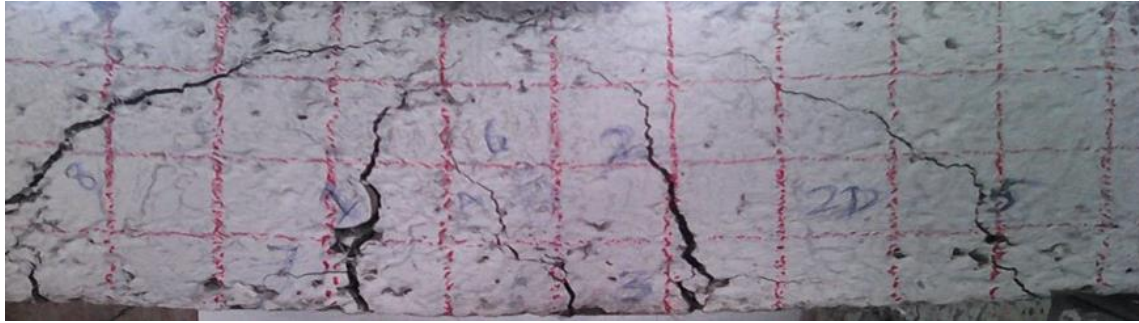


Fig. 13 - Deflection pattern of C40P3

After yielding, the most stressed part of the concrete develops rapid debonding between reinforcement and concrete that also allows the crack expansion that is available at unload. If loaded increased further the cracks spread to the nearest parts.

3.3 Displacement ductility factor

Displacement ductility factor is the ratio of dividing maximum load to the yield load at each step. Fig.14 illustrates the displacement ductility for all proportions and the cumulative variation in ductility. The specimen C40P2 has a factor of ductility 25.05 per cent higher than the control beam. The C40P3 beam shows very low ductile compared to any other proportion. Because of the high dimensional stability [32] and increased compressibility, copper slag is very effective in enhancing stress concentration. Poor water absorption and glassy structure of copper slag influences fibre dispersion, resulting in a low ductility in 0.6 percent volume fraction fibre [33]. Cumulative ductility is useful for determining the strength reduction factor at the end of cyclic charge. There is a smooth slope to the average ductility slope for all proportions. Relative to all other proportions, C40P2 has the highest cumulative ductility factor as it undergoes major deflections between yield and failure.

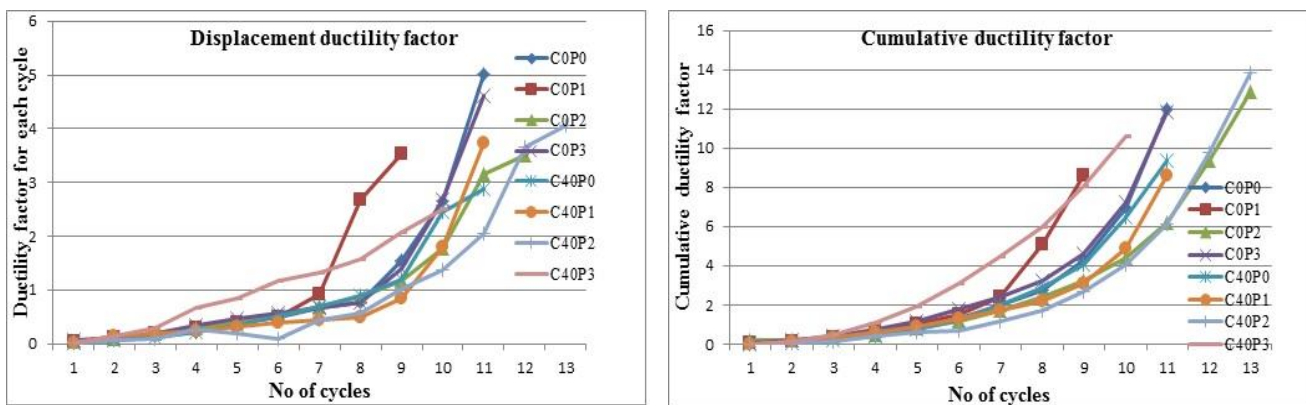


Fig.14 - Ductility factors

3.4 Energy absorption capacity

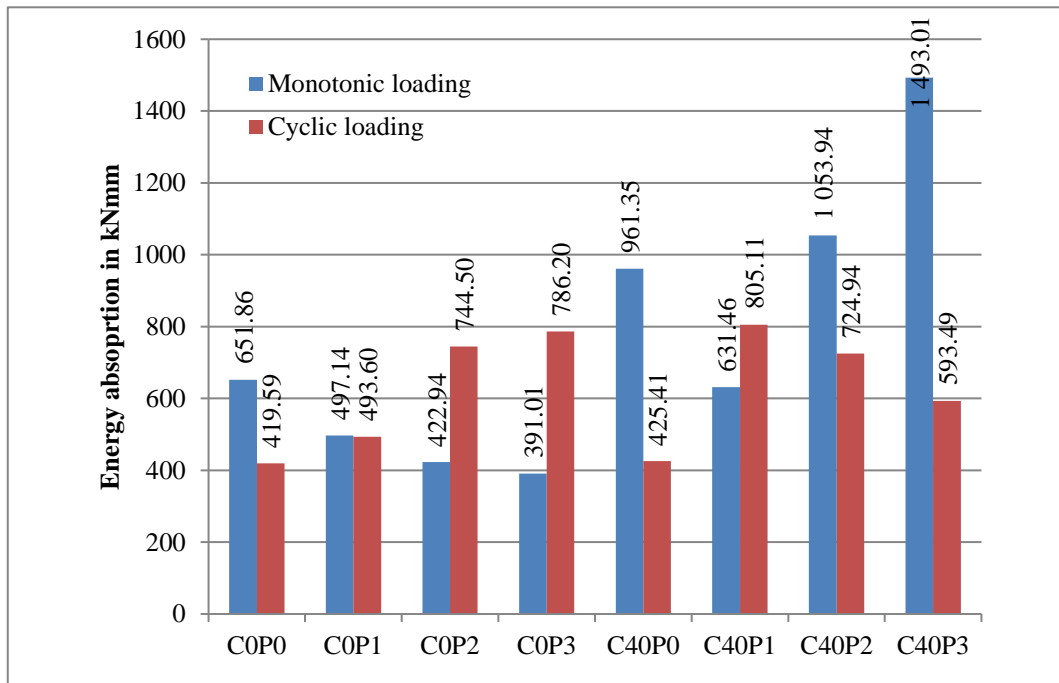
The area under the load-deflection curve is the energy dissipation during loading. Using Trapezoidal rule the area under the load-deflection curve is calculated in excel. The energy in monotonic and cyclic loading is measured and compared in Table 5 and its variation is shown in Fig.15. It is clearly known from the table values that the fibre-reinforced concrete displays more energy absorption. Energy absorption capacity of C40P2 is 72.79% more than the control concrete. Control concrete has the lowest energy absorption of 419.58Nm under cyclic loading.

Dissipation of hysteretic energy at a given amplitude distinguishes the energies of consecutive periods. Once the first cracking occurs, and more energy is dissipated up to the peak load. Cracking is lesser and distributed in the beams reinforced with fibre than control beam. Cracks are smaller in thickness than those formed in the reference beams up to the peak load and before collapse progresses.

**Table 5 Energy dissipation, initial stiffness and displacement ductility factor**

S.No	Beam ID	Energy dissipation (Nm)		Initial stiffness (kN/mm)	Displacement ductility factor
		Monotonic Loading	Cyclic Loading		
1	C0P0	651.86	419.58	5.81	4.55
2	C0P1	497.14	493.60	5.51	3.02
3	C0P2	422.93	744.49	5.95	3.36
4	C0P3	391.00	786.20	5.5	4.61
5	C40P0	961.34	425.40	5.5	2.87
6	C40P1	631.45	805.11	6.80	3.73
7	C40P2	1053.94	724.93	5.14	5.69
8	C40P3	1493.01	593.48	8.97	2.5

Bridging effect of the cracks is known as crack sewing. This phenomenon results in enhancement of ultimate load carrying capacity of the concrete structures which in turn leads to increase in energy absorption capacity. Due to the increase in ductility the fracture of concrete does not occur abruptly. Hence, the area under load displacement curve is found to be increased [34]. The energy absorption value of copper slag concrete with fibre under monotonic loading is 2.23 times more than the control concrete. Meanwhile, the rate of increase is decreased in the case of cyclic loading in which the composite mix gives 1.73 times more than the control concrete.



*Fig. 15 - Energy dissipation*

#### 4 Research significance

Nowadays, all waste is transformed to energy-efficient material that contributes to the society's creation of a sustainable environment. It is possible to explore concrete with copper slag as an alternative to natural sand as a valuable, environmentally friendly and sustainable material that produces superior mechanical and durability characteristics. Sterlite Industries (India) Ltd, Tuticorin produces 3.5 million tons of copper slag every year as waste. A large area of land is occupied due to the

dumping of these wastes. Copper slag has no concentrated hazardous chemicals other than metal oxides. It has further benefits, such as pozolonic behaviour, low water absorption, higher density, dimensional stability, high rigidity, strong mechanical properties and no adverse effects on durability. The integration of polypropylene fibre will resolve some of the negative attributes including high fluidity, poor bonding due to glassy copper slag particles. Polypropylene fibre increases tensile strength, improves bonding capacity, improves microstructural characteristics, increases ductility and increased energy absorption, etc. Incorporating copper slag instead of sand and adding polypropylene fibre as an admixture in concrete results in an eco friendly concrete with good strength and serviceability.

## 5 Conclusion

The proposed study focused on investigating the cyclic behaviour of fibre-reinforced concrete that uses copper slag as a replacement for river sand. The research aims at counteracting the impact of excess fluidity in concrete due to low water absorption of copper slag and improving ductile behaviour through the use of polypropylene fibres in concrete. Subsequent conclusions are drawn:

Adding polypropylene fibre reduces the amount of free water in concrete. It improves the bonding of fibre and copper slag between the aggregate cement matrix by bridging and ball bearing effect, respectively.

With respect to C0P2, the average yield load is 28.8 percent greater than the control specimen. The yield load of C40P1 and C40P2 is much closer to the control beam indicated that the copper slag replacement does not affect the load carrying capacity.

The number of cycles in the copper slag concrete mixes is not substantially altered. The ultimate load carrying capacity of C40P2 beam is 5% and 2.71% higher when subjected to monotonic loading and cyclic loading respectively.

It is observed that the energy released at a given displacement increases abruptly or sharply when major cracks emerge or extend. Cracks in the fibre-reinforced beams are smaller and more dispersed than control beams. Cracks are smaller in thickness than those formed in the reference beams.

The specimen C40P2 has a factor of ductility 25.05 percent higher than the proportions of the control beam because it undergoes significant deflections between yield and failure state.

Control concrete has the lowest energy absorption of 419.58Nm under cyclic processing. C40P2's energy absorption efficiency is 72.79 per cent higher than the control concrete.

Under monotonic loading copper slag concrete with fibre is 2.23 times more energy absorption value than the concrete control. Meanwhile, the rate of increase in cyclic loading is reduced where the composite mix gives 1.73 times more than the control concrete.

Therefore, replacing the fine aggregate with 40% copper slag and 0.4% polypropylene fibre is the best combination to perform well under cyclic loading.

## Notation

M30	Mix of characteristic compressive strength equals to 30N/mm <sup>2</sup>
CS	Copper Slag
PPF	Polypropylene Fibre
C0P0	Copper slag 0% and Polypropylene fibre 0% (Control concrete)
C0P1	Copper slag 0% and Polypropylene fibre 0.2% volume fraction
C0P2	Copper slag 0% and Polypropylene fibre 0.4% volume fraction
C0P3	Copper slag 0% and Polypropylene fibre 0.6% volume fraction
C40P0	Copper slag 40% and Polypropylene fibre 0.0% volume fraction
C40P1	Copper slag 40% and Polypropylene fibre 0.2% volume fraction

C40P2	Copper slag 40% and Polypropylene fibre 0.4% volume fraction
C40P3	Copper slag 40% and Polypropylene fibre 0.6% volume fraction
x	Yield deflection in mm
y	Yield load in kN

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