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Structural performance of cinder aggregate lightweight concrete beams with micro-reinforcement

K. Sadhana[1]*, K. Suguna[2] and P. N. Raghunath[3]
[1]Research Scholar, Department of Civil and Structural Engineering, Annamalai University, Chidambaram 608002, India
[2]Professor, Department of Civil and Structural Engineering, Annamalai University, Chidambaram 608002, India
[3]Professor (Retd.), Department of Civil and Structural Engineering, Annamalai University, Chidambaram 608002, India
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*to whom all correspondence should be addressed: e-mail: paaras2612@gmail.com
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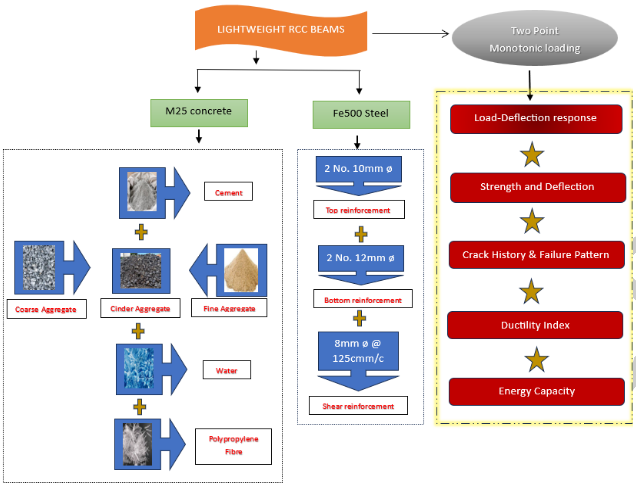
Graphical abstract



Abstract

Incorporating conventional concrete in the construction of structures contributes to more dead load resulting in higher cost of construction, more labour, difficulty in transportation of materials and so on. These impediments can be reduced by using lightweight concrete instead of the conventional concrete. In this study, an attempt has been undertaken to produce a sustainable lightweight concrete beam by utilizing the cinder slag as a substitute material for coarse aggregate. Cinder is a solid waste material which is disposed by the steel and iron industries. Recycling cinder not only helps eliminate the negative impact of its disposal on environment, but also provides a solution for the conservation of non-renewable natural resources. A total of six beams which included the control beam specimen, cinder aggregate based lightweight concrete beam specimen with 0%, 0.1%, 0.2%, 0.3% and 0.4% volume fractions of polypropylene fibre were cast and subjected to monotonic loading until failure occurred. The strength capacities, deformation characteristics, crack spectrum, ductility behaviour and energy capacities of the beam specimens were investigated. The test results demonstrated that by the inclusion of polypropylene fibre enhanced the performance of the lightweight concrete beams in terms of strength and ductility.

Keywords: Cinder aggregate, deformation characteristics, ductility behaviour, lightweight concrete, monotonic loading, and polypropylene fibre

1. Introduction

In addition to economic pressure, there is a rapidly growing social concern over the issues of environmental pollution and unrestricted utilization of natural resources by the concrete industry. As an extensive consumer of limited natural resources and a prominent player in infrastructural development, the concrete industry has an obligation to adopt environment-friendly technologies (Zawawi *et al.* 2020). One such approach is to incorporate cinder aggregates as coarse aggregates in producing lightweight concrete. Cinder is the slag material recovered from steel and iron industries which has a porous structure resulting in lower specific gravity compared to conventional

In lightweight concrete, coarse aggregates are replaced with lightweight aggregates, resulting in a density of 1400 to 2000 kg/m^3 as opposed to the traditional concrete density of 2400 kg/m^3 (Nayır *et al.* 2021). Some of the beneficial properties of lightweight concrete include reduced dead load, excellent thermal insulation, better durability, and improved seismic response (Kumar and Prakash 2015). The addition of fibre to lightweight concrete improves the performance of the concrete in terms of flexural strength, post-crack behaviour, ductility and energy absorption capacity (Alwesabi *et al.* 2022). Some of the commonly preferred fibres are steel, polypropylene, glass, carbon fibre and so on (Saidani *et al.* 2016). Studies revealed that addition of polypropylene fibre has an improvement in flexural toughness and shrinkage cracking resistance (Ahmad *et al.* 2022; Shen *et al.* 2020).

Incorporating the industrial solid waste cinder in producing a structural concrete promotes sustainable development as it minimises the consumption of natural

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resources and curtails the environmental degradation caused by cinder disposal. Further cinder based lightweight concrete is an attractive option in terms of economic aspect.

Tamai (2015) investigated the influence of volcanic pumice aggregate in varying quantity as coarse aggregate on the lightweight concrete. The experimental results showed that the porosity of the concrete increases with the pumice content while the modulus of elasticity value decreases. The use of pumice aggregate led to higher tensile strength and flexural strength in concrete compared to the ACI-318 (American Concrete Institute) code values. It was concluded that during experimental hurdles the equation developed by ACI code can be utilized to quickly determine the modulus of elasticity of lightweight concrete. Miller and Tehrani (2017) investigated the static mechanical property and dynamic property of lightweight concrete with rubberized lightweight aggregate in dosages of 10% to 100%. The static mechanical properties of the tire-derived aggregate lightweight concrete included compressive strength, split-tensile strength, flexural strength, flexural toughness and modulus of elasticity. Additionally, to investigate the dynamic property of the specimens, they were subjected to flexure in an impact test. It was found that rubberized lightweight aggregates reduced the mechanical strength of the concrete but enhanced the toughness and ductility property. The authors suggested that higher rubber content could be adopted when energy absorption is the primary concern. Hameed and Ahmed (2019) conducted an experimental study on concrete which was manufactured using recycled polyethylene terephthalate (PET) aggregate. Five sets of concrete with different PET content of 1%, 3, 5, 7 and 10% by weight of the portland cement were produced. The effect of recycled plastic aggregate on the hardened density, compressive strength, split tensile strength and flexural strength was examined. The experimental results showed that the inclusion of 1% PET leads to an rise in the compressive strength by 58%, rise in the flexural strength by 23.11% and rise in the split tensile strength by 30%. However, the value of density reduced with increase in the PET content. Zawawi *et al*. (2020) examined the mechanical and durability effect of fly ash as fine aggregate in oil palm shell (OPS) lightweight aggregate. Five types of lightweight concrete mixes with fly ash replacing the fine aggregate by 0%, 10%, 20%, 30% and 40% were prepared and subjected to two different types of curing viz. water curing and indoor air curing. The authors observed that OPS lightweight concrete with 10% fly ash as fine aggregate had better Elasticity modulus value, compressive strength, split tensile strength and flexural strength. The water curing method was found to be suitable as it provided adequate water to increase the chemical reaction between cement and pozzolanic material to form the binding material CSH gel. In addition, it was found that 10% fly ash content in OPS lightweight concrete resulted in a denser concrete with high resistance to sulphate attack. Dharan and Lal (2016) carried out a study on the fresh state and hardened state properties of the polypropylene fiber reinforced concrete. The polypropylene fibers of sizes 24mm, 40mm and 55mm were blended together and added to the concrete in volume fractions of 0.5%, 1%, 1.5% and 2% to test its workability, compressive strength, split tensile strength, flexural strength and modulus of elasticity. When 1.5% blended type polypropylene fibres were incorporated into the concrete, a rise in compressive strength of 17% compared to the conventional concrete was noted. The improvement in split tensile strength, flexural strength and modulus of elasticity was at 22%, 24% and 11% respectively when polypropylene fibers were added. Based on the strength results, 1.5% volume fraction of blended type polypropylene fibers was considered as the optimum content. Meesala (2019) assessed the effect of different fibres namely woolen fibres, glass fibres and steel fibres in concrete containing 50% recycled coarse aggregate and 100% conventional coarse aggregate. The concrete was tested for workability, compressive strength, flexural strength, split-tensile strength, modulus of elasticity, density, volume of voids, water absorption and ultrasonic pulse velocity (UPV). The investigation results determined that incorporating fibres in recycled aggregate concrete and normal concrete significantly improved the mechanical properties as the fibres restricts the progress of cracks by bridging mechanism. When compared to the glass fibre and woolen fibre, the higher tensile strength and better grip by the hooks of steel fibre results in increased mechanical properties. However the effect of different fibres on the density, volume of voids, water absorption and UPV was not found to be significant.

Several research works have been performed to study the mechanical characteristics of lightweight aggregate concrete and the behaviour of fibre reinforcement in conventional concrete. However, the structural performance of lightweight concrete needs more exploration. Further experimental works on improving the structural performance of the lightweight concrete are a deficit. Therefore, the objective of this work is to study the effect of polypropylene fibre on the strength and deformation characteristics of cinder aggregate lightweight concrete beams.

2. Materials and methods

2.1. Materials

The cube compressive strength of the concrete used for making the beam specimen was 32.44 MPa. The concrete was produced using OPC 53 grade cement, which was obtained from Dalmia cements. The cement had a specific gravity of 3.15. Locally available natural sand conforming to zone III as per IS 383:2016 and M-sand was used as fine aggregate. Based on trial and error, a combination of 55% natural river sand and 45% M-sand, having an average specific gravity of 2.67 was adopted. Well graded crushed granite of maximum size 20 mm conforming to IS 383:2016 and waste cinder aggregate passing through 20mm sieve and retained on 12mm sieve were used as coarse aggregate. The specific gravity of the granite aggregate and cinder aggregate was 2.72 and 2.1 respectively. Polypropylene fibres conforming to ASTM C1116 were used as micro-reinforcement in the concrete specimens. The physical characteristics of the polypropylene fibre are presented in Table 1. Conplast SP430 superplasticizer was used to satisfy the workability requirements. Based on slump test, the dosage of superplasticizer for each mix of concrete was determined.

2.2. Mix proportion

The concrete mix design was done with reference to IS 10262: 2019. The concrete developed was tested for workability and strength. After several trial mixes, the mix ratio was fixed at 1:1.96:3.56 for reference mix and 1:1.96:2.14:1.42 for concrete with 40% cinder as coarse aggregate. The constituent detail of the concrete mixes is presented in Table 2.

Table 1. Properties of Polypropylene Fibre

S No.	Physical Characteristics	Value
1	Length	12mm
2	Diameter	0.01mm
3	Aspect Ratio	1200
4	Specific Gravity	0.91
5	Tensile Strength	4 Gpa
6	Young's Modulus	4000 MPa
7	Elongation	90 %

Table 2. Mix Design Details

Specimen	Cement Kg/m^3	FA Kg/m^3	CA Kg/m^3	Cinder Kg/m^3	Water Kg/m^3	Fibre Kg/m^3
CAB-S	350	686	1246	0	175	0
CAB0-S	350	686	749	497	175	0
CAB1-S	350	686	749	497	175	0.91
CAB2-S	350	686	749	497	175	1.82
CAB3-S	350	686	749	497	175	2.73
CAB4-S	350	686	749	497	175	3.64

2.3. Test beam details

A total of six concrete beam specimens of 3000 mm span and 150mm×250 mm cross-section was cast. Out of six concrete beam specimens, one was the reference specimen with 0% cinder aggregate and 0% polypropylene fibre content. Five other specimens were cast as lightweight aggregate concrete by replacing the conventional coarse aggregate with 40% cinder aggregate. Polypropylene fibre was used as micro-reinforcement at 0%, 0.1%, 0.2%, 0.3% and 0.4% of concrete volume. Steel reinforcements were provided using 2 bars of 10mm at top and 2 bars of 12mm at bottom. To prevent shear failure of beam specimens, shear reinforcements were provided using 2 legged 8mm bars at 125 mm c/c spacing. The details of reinforcement are as shown in Figure 1.

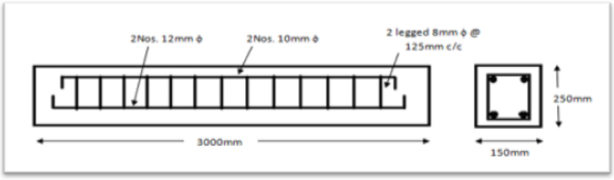

Figure 1. Dimension of Beam Specimens

2.4. Test setup

All six beam specimens were tested under the two-point load in a loading frame having a capacity of 500kN. The specimen was provided with roller support at 100 mm from one end and hinge support at 100mm from another end, such that the effective span of the beam was 2800mm. Three dial gauges of 0.01mm precision were used to measure the displacement, one fixed at the centre below the loading position, one near the right support and one near the left support. The specimen was then subjected to monotonic loading until failure occurred. The crack formation and crack propagation were continuously observed throughout the loading period. The width of the crack that had developed was measured using a crack detection microscope of 0.02mm precision.

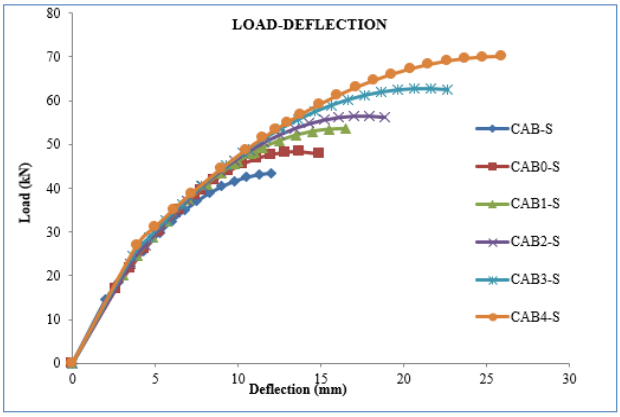

Figure 2. Load-Deflection Curve

3. Results and discussion

3.1. Load-deflection relationship

The load-deflection response of the beam specimens subjected to flexural loading is shown in Figure 2. From the graph, it can be noted that all beam specimens exhibit similar load-deflection behaviour. The initial part of the curve was observed to be linear until the development of first crack. On further application of load, the gradient of the curve reduced slowly along with the formation of a greater number of cracks on the concrete beam. As the loading continued, the longitudinal steel reinforcement started to yield. After the yielding stage, the gradient of the curve reduced significantly, exhibiting large deflections. This behaviour continued till the ultimate load.

3.2. Effect on strength and deflection

The experimental test results of the control beam CAB-S and cinder aggregate lightweight concrete beams without polypropylene fibre (CAB0-S) and cinder aggregate lightweight concrete beams with polypropylene fibre (CAB1-S to CAB4-S) are presented in Table 3. The first crack load was obtained by visual observation. The first crack load increased by 17.23% when cinder aggregate was used as partial replacement to coarse aggregate. The yield load of the beam specimen was obtained from the load deflection graph. When compared to the control concrete CAB-S, lightweight concrete beam CAB0-S showed an increase of 18.48% in the yield load and an increase of 9.77% in the ultimate load value. The deflection in the CAB0-S beam at first crack load, yield load and ultimate load increased by 32.15%, 24% and 24.33% respectively when compared to CAB-S beam.

Table 3. Results of Tested Beams

Beam Specimen	First Crack Stage		Yield Load Stage		Ultimate Load Stage	
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
CAB-S	14.50	2.00	29.75	5.24	43.50	12.00
CAB0-S	17.00	2.64	35.25	6.50	47.75	14.92
CAB1-S	20.25	3.03	37.25	7.01	53.50	16.51
CAB2-S	22.75	3.49	40.50	7.83	56.25	18.82
CAB3-S	24.50	3.62	45.25	9.28	62.50	22.60
CAB4-S	27.00	3.9	48.75	10.50	70.00	25.90

When compared to the lightweight concrete beam without fibre reinforcement, the first crack load of the lightweight concrete increased to 58.82% when 0.4% volume fraction of polypropylene fibre was incorporated. The load capacity of the CAB4-S beam increased by 38.32% and 46.6% in yield load and ultimate load respectively compared to the CAB0-S beam. This increase in flexural strength of the lightweight concrete beam was due to the higher tensile strength and stitching mechanism exhibited by the polypropylene fibre. The CAB4-S beam showed an increase of 47.56% in deflection at first crack load compared to CAB0-S. The deflections of the CAB4-S beam at yield load and ultimate load increased by 61.54% and 73.59% respectively when compared to the beam CAB0-S. This deflection behaviour was due to enhanced bond provided by the polypropylene fibre between the cinder aggregates and the cement paste.

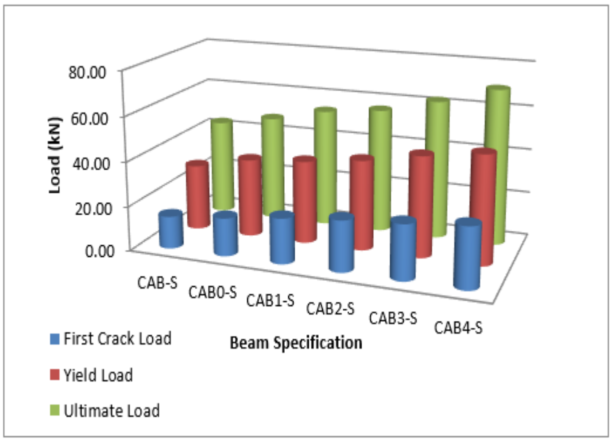

Figure 3. Effect on Load Capacity

The load values and deflection values of all the lightweight concrete beam specimens tested for the study are represented in Figures 3 and 4.

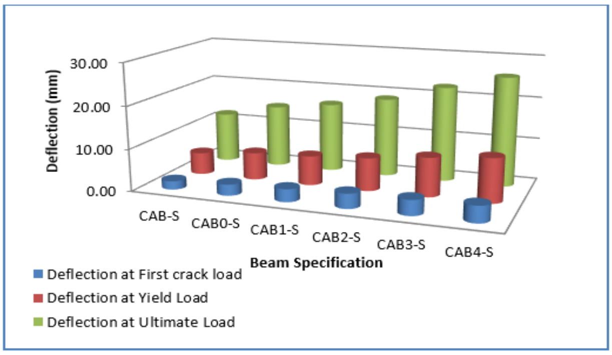

Figure 4. Effect on Deflection

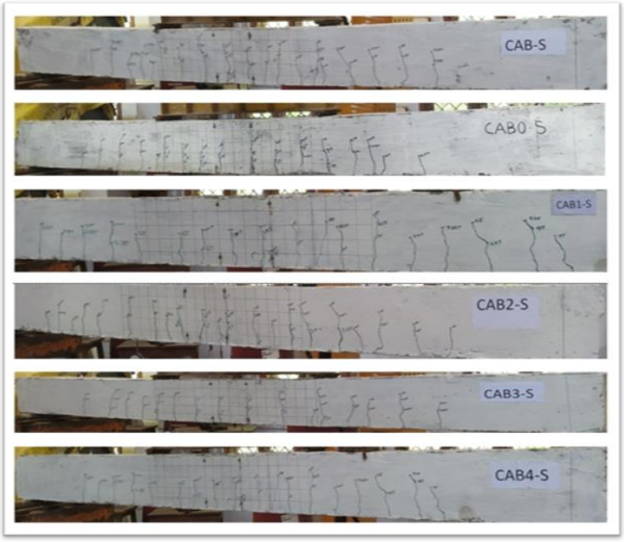

Figure 5. Crack Pattern and Failure Mode

3.3. Crack History and Failure Pattern

The crack pattern of the lightweight concrete beam with polypropylene fibre at ultimate load is presented in Figure 5. During the initial application of load, fine cracks oriented in the vertical direction were developed in flexural zone. On load increments, these flexural cracks propagated further, and additional cracks were initiated in the flexural zone. As the loading continued, the cracks formed in the centre extended towards the point of loading in a diagonal pattern. The maximum width of the crack, number of cracks and the mean spacing between the cracks at ultimate loading stage are shown in Figure 6 to Figure 8.

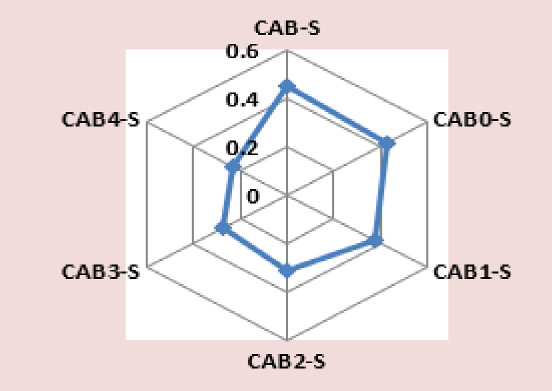

Figure 6. Crack Width

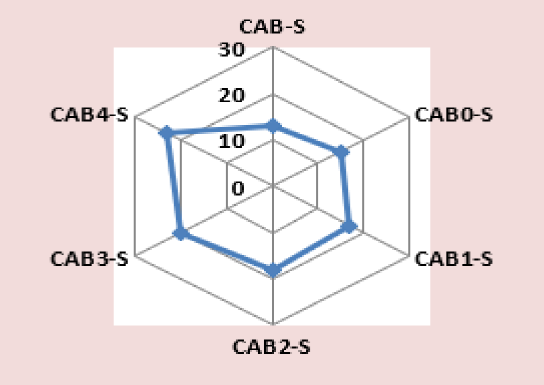

Figure 7. Number of Crack

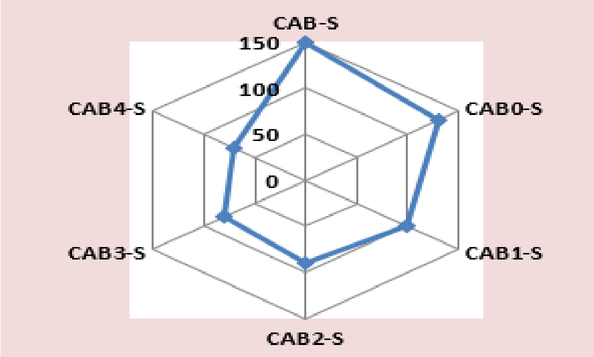

Figure 8. Crack Spacing

The crack width of lightweight concrete beam with fibre reinforced was increased by 46.51% at ultimate load stage when compared to the beam CAB-S and CAB0-S. The maximum number of cracks formed in the CAB4-S beam during the ultimate loading increased by 53.33% and the average spacing between the cracks decreased by 46.15% compared to the CAB-S and CAB0-S beams. It was observed that addition of polypropylene fibre resulted in large number of smaller cracks while the concrete without fibre reinforcement resulted in bigger cracks. This could be due to the bridging action provided by polypropylene fibre, which restrained the formation and propagation of cracks in concrete.

3.4. Ductility index

Ductility is defined as the ability of a material to undergo large deformation prior to failure. The ductility index is expressed in terms of deflection and energy. The deflection ductility is the ratio of deflection at ultimate load to the deflection at yield load, while the energy ductility is the ratio of area under load-deflection curve up to ultimate load to the area under load-deflection curve up to the yield load. The deflection indices of the control beam, lightweight concrete beam specimens with and without fibre reinforcement are presented in Figure 9.

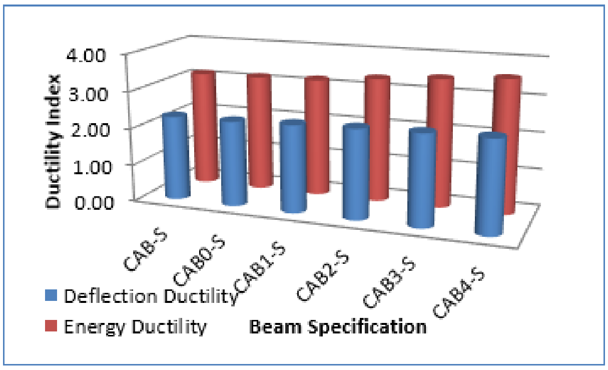

Figure 9. Effect on Ductility

It can be observed that the ductility indices of the lightweight concrete beam specimens increased with increase in the fibre content. The deflection ductility and energy ductility of the CAB4-S beam increased by 7.46% and 13.18% when compared to CAB0-S beam. Also, ductility indices of the lightweight concrete beam were found to be higher than the CAB-S beam. Higher ductility ratio represents the ability to sustain large deformation before failure occurs, thus providing ample warning prior to the occurrence of failure.

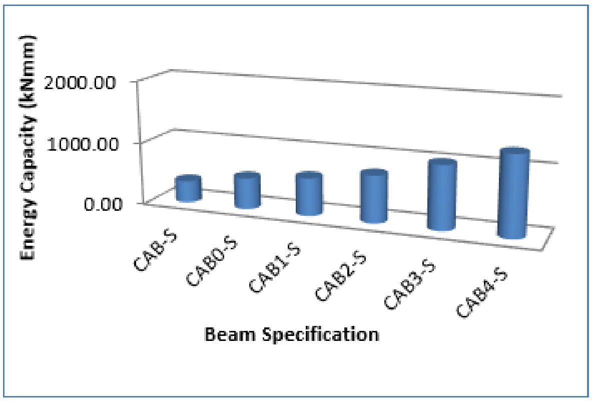

Figure 10. Effect on Energy Capacity

3.5. Energy capacity

Energy capacity is defined as the ability of a material to absorb and store energy. The energy capacity of the concrete beams is obtained as the area under the load-deflection curve. The energy capacity of the concrete beam specimens that were tested in this study is shown in Figure 10. The inclusion of polypropylene fibre in the lightweight concrete has resulted in higher energy capacity than the lightweight concrete without fibre content. The CAB4-S beam showed an increase of 154.29% in the energy capacity compared to the CAB-S beam. Higher ductility in a concrete structural member result in improvement in the energy capacity.

4. Conclusions

Based on the experimental study the following conclusions are drawn:

The inclusion of polypropylene fibre increased the ultimate load carrying capacity of the cinder aggregate lightweight concrete beams to a maximum value of 46.6%. The deflection of the lightweight concrete beams with fibre reinforcement was reduced significantly at all stages of loading. The deformation capacity of the fibre reinforced beam specimens was increased up to 73.59%.

All the fibre reinforced lightweight concrete beam specimens exhibited flexural failure. At ultimate loading stage, the lightweight concrete beams with 0.4% polypropylene fibre showed a reduction in crack width by 46.51%.

The ductility property of the lightweight concrete beam improved when polypropylene fibre content was increased. The deflection ductility value increased to 7.46%, energy ductility value increased to 13.18% and energy capacity value increased to 154.29% when 0.4% polypropylene fibre was added.

The experimental results show that incorporation of polypropylene fibre enhanced the flexural behaviour of the cinder based lightweight concrete, making it appropriate for use as a structural concrete material. Further the fibre reinforced lightweight concrete can be used for structural members like beam and column, load bearing walls, roof elements, noise barriers etc.

Conflicts of interest

The authors have no conflicts of interest to declare.

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