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Enhancing Structural Performance: Fiber Reinforcement in Sintered Flyash Lightweight Concrete for Impact Resistance and Toughness

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Abstract

Objectives: The goal of this project is to better understand the interaction between fibers and concrete in order to produce Light Weight Aggregate Concrete (LWAC) with improved structural performance that is made from recycled materials, such as sintered flyash aggregate, and LWAC structures that are more resistant to impact loads and other dynamic forces. **Methods:** The sintered flyash aggregates are added as coarse aggregate to the concrete and basalt fiber (0.25% of mix) is used as a secondary reinforcement to improve the energy absorption, impact resistance and toughness behaviour. M30 grade of concrete was arrived after laboratory trials after which the mechanical properties were evaluated. The effect of drop impact load on slabs of size 300mm x 300mm x 50mm reinforced with two layers of bundled wire mesh was studied. The flexural properties of concrete reinforced with fiber prism of size 500mm x 100mm x 100mm were evaluated. **Findings:** With the addition of fiber, flexural toughness index and post-cracking toughness were increased notably on the initial deflections and cracks. The conventional fiber reinforced concrete exhibited a superior peak load capacity compared to normal weight concrete, with a measured increase of 7.5%. Conversely, normal-weight concrete demonstrated a significantly higher deflection under load, exceeding that of fiber reinforced concrete by 47%. LWAC displayed a distinct increase in both peak load (18.7%) and deflection (39.13%) when compared to Normal Weight Aggregate Concrete (NWAC). The incorporation of basalt fiber enhanced the energy absorption by 150% in NWAC and 80% in LWAC. **Novelty:** The incorporation of fiber into lightweight concrete reduces the brittle nature of failure. The post-cracking toughness behaviour was enhanced because of the effect of crack-arresting by fibers. After the first break, it was discovered to retain residual strength, and removing the fibers from the matrix required more force.

Keywords: Sintered flyash aggregate; Light weight concrete; Basalt fiber; Toughness; Impact load; Energy absorption

1 Introduction

The study and optimization of concrete structures under different loading circumstances are still significant challenges in the field of structural engineering. Impact loads provide serious issues that should be considered when designing structures [1]. The behaviour of concrete under impact loads is often inadequately characterized by traditional computational approaches, underscoring the necessity of experimental investigations [2]. Lightweight concrete is a suitable building material where there is a need to reduce dead loads in structures with improved structural performance [3]. The need for lightweight concrete in modern buildings is increasing due to its decreased density, which allows for lighter load-bearing components and reduced foundation dimensions [4]. Further research is required to investigate the possible use of lightweight concrete in structural design, despite efforts to enhance its strength/weight ratio and adaptability. With a lower specific gravity and sufficient performance for structural applications, sintered flyash aggregates have become a viable substitute for conventional aggregates [5].

The purpose of this paper is to investigate the possibility of using fiber reinforcement to improve the mechanical characteristics and impact resistance of sintered flyash LWAC. Fibers are essential for enhancing the post-cracking behaviour of concrete because they bridge cracks and form an interfacial connection between the cement and fiber matrix [6]. Steel fibers have demonstrated potential in enhancing the flexural strength, fracture energy, and compression toughness of concrete, making it ductile under high strain rate loading circumstances [7]. Furthermore, it has been demonstrated that adding natural fibers like basalt improves mechanical characteristics and impact resistance [8], albeit with certain restrictions on compressive strength [9]. The effectiveness of several fibers, such as steel [10], basalt [11], and polypropylene [12], in enhancing the toughness, ductility, and energy absorption capacity of concrete after cracking has been studied. This paper aims to give insights into the best way to include fibers to obtain improved performance of sintered flyash LWAC in structural applications by a thorough study of the literature and experimental results.

Stresses are transferred between cement and aggregate phases in lightweight aggregate concrete. Failure cracks will propagate along the shells of the aggregates, resembling those found in normal weight aggregates. These aggregates can exhibit a distinct failure process, as cracks may propagate directly through them [13]. This research highlights the significance of adding basalt fibre as secondary reinforcement in reducing the inherent drawbacks of sintered flyash LWAC like cracking behavior and failure mode. Engineers can ensure the robustness of lightweight concrete structures against impact loads and other dynamic forces by optimizing their design and performance through greater knowledge of the interaction between fibers and concrete matrix. Improving the structural behaviour of elements while facilitating the use of lightweight aggregate concrete produced from industrial byproducts or waste materials is the thrust of this research.

2 Methodology

This research offers new approaches for improving formulations that use sintered flyash aggregate in place of conventional coarse aggregate so that the failure behaviour between the aggregate and cement interfaces can be improved by adding basalt fiber as secondary reinforcement. In contrast, with conventional approaches, this study provides a thorough comparison of the mechanical characteristics of basalt fiber incorporated in LWAC and NWAC. Some criteria were carefully considered in the setting of research, such as the use of OPC 53 grade cement, conventional river sand for fine aggregate, and manufactured sintered flyash aggregate. Concrete mixes were methodically produced to attain an M30 grade as per IS method of mix design[14], with a coarse aggregate size of 12.5mm for down passage and 0.25% of basalt fibre was added as a secondary reinforcement. Potable water and a superplasticizer based on polycarboxylate ether were added to ensure the best possible mix uniformity. Concrete specimens were cast under standard laboratory conditions and cured for 28 days.

2.1 Impact Test

After 28 days of curing, 12 square slabs measuring 300mm x 300mm x 30mm each with two layers of bundled wire mesh were subjected to an impact test utilizing a drop weight. It was made out of short columns supporting a square-planed, stiff steel frame that had been welded together. In order to give line support along all four corners, the specimen was placed flat and rested on four bars with a 20mm diameter. The specimen was struck with a 3.5 kg hammer that was dropped from a prearranged height. Ideally, the drop's height was set at 1.185 meters. Figure 1 depicts the setup for the Impact test.

Fig 1. Impact Test Set-up

C-clamps were used to secure the panel edges to the supporting frames in order to stop the specimen from rising as a result of impact rebound. A point contact may be created owing to the spherical tip of the plunger that packs the panel. The hammer was physically raised to the required height and repeatedly dropped into the specimen's surface using a rope and pulley system with a pipe guide, which permits a center hit in the vertical direction. To guarantee a smooth descent and to lessen friction, grease was rubbed over the rollers.

The initial energy absorption corresponds to the number of blows corresponding to the first crack and the post-peak impact is calculated from the number of blows corresponding to failure. The energy absorption (Joules) is obtained from the formula:

$$E = N\,x\,w\,x\,h \tag{1}$$

Where,

E=Energy in Joules

w =Weight of hammer (N)

h =Height of hammer (m)

N = No. of Blows

The ductility index is the ratio of energy absorption at the first crack (Ei) and the energy absorption at failure (Ep).

$$Ductility\ Index = E_p/E_i \tag{2}$$

2.2 Toughness Test

The toughness test was conducted on 12 prisms of 500mmx100mmx100mm size. The loading and specimen support system with four-point loading was applied to the specimens without any eccentricity or torque. The test was conducted according to

ASTM: C1018-97 [15]. The toughness test setup is indicated in Figure 2. The toughness or energy absorption is the area under the load-deflection curve according to ASTM C1018-97. The toughness in the study is calculated under specific displacement levels as δ, 1.5 δ, 2 δ, 2.5 δ, 3.5 δ, 5 δ and 10.5 δ based on overall deflection. The toughness calculated at the first deflection ∂ is the toughness at the first crack and the subsequent deflections at1.5 δ, 2 δ, 2.5 δ, 3.5 δ, 5 δ and 10.5 δ are the post-peak toughness. The stiffness is the load per unit deflection of the material. The area under the curve is calculated for each corresponding deflection. The area under the curve of load-deflection up to a limited deflection value divided by the area up to the deflection established at the first crack, as shown in the following formula, is the toughness index.

$$It = (Area\ under\ curve\ (load\ -\ deflection)\ up\ to\ limited\ deflection)/ \\ Area\ under\ curve\ (load\ -\ deflection)\ up\ to\ first\ crack\ deflection \tag{3}$$

The toughness index I_1, I_2, I_3, I_4, I_5 and I_6 were calculated by dividing the total area (the post–peak toughness) up to the deflection of 1.5 δ, 2 δ, 2.5 δ, 3.5 δ, 5 δ and 10.5δ by the area (pre-peak elastic toughness) under the curve up to the deflection at the first crack (δ), respectively.

As a proportion of the initial fracture strength, the residual strength factor shows how much strength was maintained in the post-cracking stage over a given period of time. The residual strength factor across two variables can be estimated using the following generic formula:

$$R_{1,2} = 100\,x\,(I_2 - I_1) \tag{4}$$

$$R_{2,3} = 100\,x\,(I_3 - I_2) \tag{5}$$

$$R_{3,4} = 50\,x\,(I_4 - I_3) \tag{6}$$

$$R_{4,5} = 25\,x\,(I_5 - I_4) \tag{7}$$

$$R_{5,6} = 12.5\,x\,(I_6 - I_5) \tag{8}$$

The multiplying factor used to find the residual strength depends on the difference in the peak deflection range which is calculated for determining the toughness index.

Fig 2. Test Setup for flexural toughness

3 Results and Discussion

3.1 Impact Test

3.1.1 Energy Absorption

The first crack developed in NWAC at 4th blow whereas the failure occurred at the 6th blow. The first crack appeared at the 2nd blow in LWAC with a punching effect on the surface and the slab failed at the 5th blow. The presence of wire mesh prevented the complete breaking of concrete. The addition of basalt fiber to NWAC and LWAC influenced the failure significantly [16–19]. The first crack appeared in Fiber Reinforced Normal Weight Concrete (FNWAC) at the 5th blow and the slab failed at the 11th blow. The Fiber Reinforced Light Weight Concrete (FLWAC) presented its first crack at the 5th blow but failed at the 9th blow. The sample specimens that failed in the impact test are shown in Figure 3.

Fig 3. Failure pattern of Specimens after Impact Test

The initial energy absorption rate was 10% higher in NWAC when compared to LWAC. The initial energy absorption of FNWAC is 25% higher than that of NWAC whereas, the FLWAC showed a 150% increase when compared to LWAC. The addition of basalt fiber increased the propagation energy absorption in NWAC by 83% and 80% in LWAC. The post-peak energy absorption was 20% higher in NWAC when compared with LWAC. The energy absorption of the concrete mixes is shown in Figure 4.

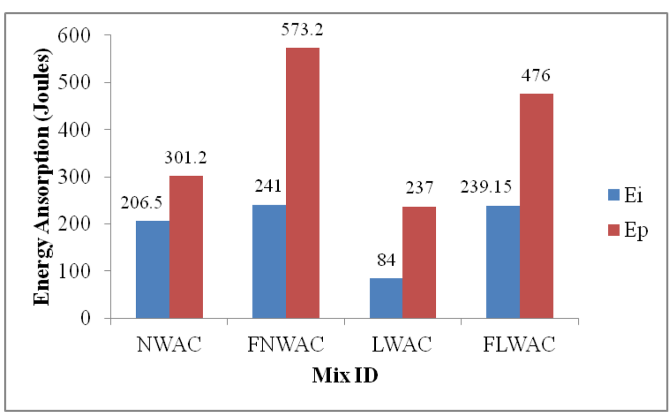

Fig 4. Energy Absorption (Joules) of Concrete Mixes

3.1.2 Ductility Index

The higher the ductility index, better the performance. The ductility index of FNWAC is 47% higher than that of NWAC. The FLWAC showed an improved ductility index of about 38% when compared with LWAC. The difference in ductility index in NWAC and LWAC is 20% where the LWAC showed increased ductility. This is because fibers may span one another and continuously withstand deformation [20]. The LWAC although has lesser tensile strength, the impact test proved that it is no longer inferior to that of NWAC. The ductility index of different concrete mixes is indicated in Figure 5.

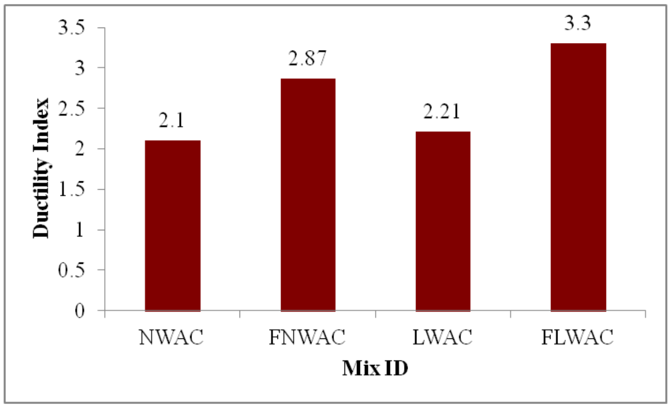

Fig 5. Ductility Index of Concrete Mixes

3.2 Toughness Test

3.2.1 Load Deflection Curves

Figure 8 illustrates the prisms' load-deflection behavior under flexural stress in accordance with ASTM C1018-97. The influence of basalt fiber on NWAC and LWAC beams can be pronounced in terms of its post-peak behavior [21]. Almost all the NWAC and LWAC beams failed in a brittle mode. The failure mode of Fiber reinforced concrete and Conventional concrete are represented in Figures 6 and 7. The failure crack occurred instantaneously on account of the release of the tremendous amount of strain energy with a sudden crack when the peak load is reached. The basalt fiber controlled the strain rate and energy release on account of the bridging effect [22]. Unlike the beams without fiber, the reinforced concrete with basalt fibers had a single peak because it continued to support weight even after the initial break appeared. It can be seen that the deflection is proportional to load up to the 1st crack i.e., the peak load after which the fiber-reinforced concrete showed a remarkable decrease in load when compared to deflection with long descending post-cracking behavior [23].

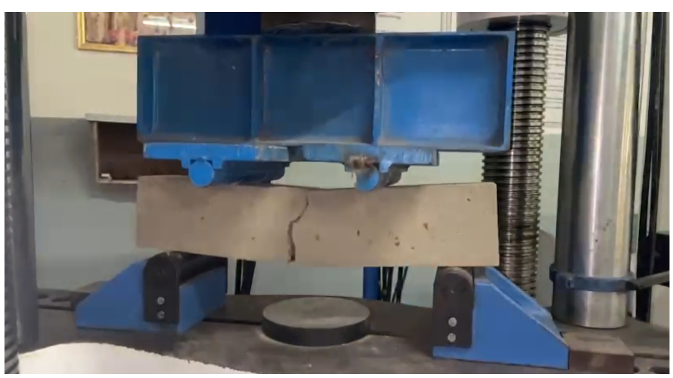

Fig 6. Failure mode of Fiber reinforced concrete

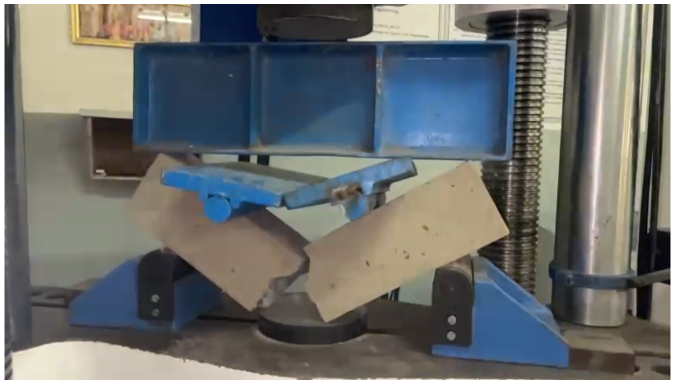

Fig 7. Failure mode of Conventional concrete

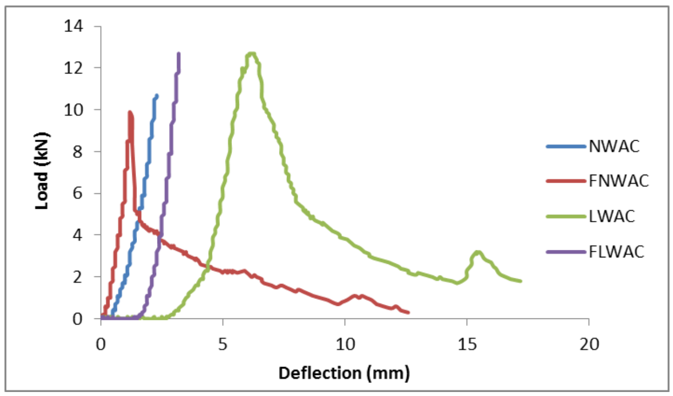

Fig 8. Load-deflection Curves of Concrete Mixes

3.2.2 Toughness and Energy Absorption Behaviour

The addition of fiber to NWAC increased the stiffness to about 2 times whereas the addition of fiber to LWAC decreased the stiffness to 0.5 times. The impact of the fiber orientation in the concrete matrix is the cause of these variations in the outcomes [24]. The better the orientation of fibers, the better will be the stiffness and vice-versa [25]. The area under the curve is the measure of toughness and with each increasing subsequent deflection, the toughness is found to be increasing [26]. However, the difference in the area of energy absorption between the FNWAC and FLWAC is found to be marginal. The toughness index under each loading is calculated based on the area under the curve corresponding to the loading at the first crack. The FNWAC showed a better toughness index when compared to the FLWAC. The average strength retained under each specific deflection after the first crack is expressed in terms of residual strength. An entirely flexible post-cracking behavior can be seen as a residual strength factor of 100, and a drop in strength factor denotes a reduction in residual strength. The toughness characteristic of different concrete mixes is tabulated in Table 1. The observed improvements in impact resistance for fiber-reinforced concrete with sintered flyash aggregates (SFA) can be attributed to the fiber bridging effect. These fibers bridge cracks that initiate within the cementitious matrix, effectively transferring stress and preventing crack propagation. This mechanism contrasts with the typical failure mode of SFA concrete, which involves crushing of aggregates and debonding at the interface between the aggregate and mortar matrix. This debonding significantly reduces the concrete's ability to resist impact loads. Previous research suggests [4] good tensile behavior in SFA, potentially contributing to improved performance. However, the inclusion of fibers becomes crucial. Fibers effectively bridge the matrix, mitigating the detrimental effects of debonding observed in plain SFA concrete. This synergistic effect between SFA and fibers leads to a more controlled failure pattern under impact loading. The inclusion of fibers enhances the concrete's ability to transfer load throughout the entire matrix. This improved load transfer mechanism prevents localized stresses from concentrating at the aggregate-mortar interface, thereby reducing the likelihood of debonding and subsequent failure under impact.

Table 1. Toughness Characteristics of Different Concrete Mix

Mix ID	NWAC	FNWAC	LWAC	FLWAC
Peak load (kN)	10.7	9.9	12.7	13.4
Deflection (mm)	2.3	1.2	3.2	6.3
Stiffness (kN/mm)	4.65	8.25	3.97	2.12
Area under the curve (kN.mm)				
δ	10.45	10.396	11.4	13.338
1.5 δ	-	27.405	-	20.955
2δ	-	36.945	-	34.136
2.5δ	-	47.175	-	45.657
3.5δ	-	62.954	-	59.738
5.5δ	-	87.759	-	80.807
10.5 δ	-	115.63	-	110.3
Toughness index				
I_1	-	2.636	-	1.571
I_2	-	3.554	-	2.559
I_3	-	4.538	-	3.423
I_4	-	6.053	-	4.478
I_5	-	8.441	-	6.058
I_6	-	8.951	-	7.138
Residual strength %				
$R_{1,2}$	-	91.8	-	98.8
$R_{2,3}$	-	98.4	-	86.4
$R_{3,4}$	-	75.8	-	52.8
$R_{4,5}$	-	59.7	-	39.5
$R_{5,6}$	-	46.8	-	33.2

4 Conclusion

This study demonstrates that basalt fiber reinforcement offers a promising approach to enhance the energy absorption, toughness, and ductility of both NWAC and LWAC. The observed improvements in impact resistance, durability, and overall material performance pave the way for the development of more robust and sustainable concrete structures. Enhanced energy absorption: Basalt fiber reinforcement significantly increased energy absorption capacity in both NWAC (150%) and LWAC (80%), indicating improved impact resistance and durability. Fiber addition led to a notable increase in flexural and post-cracking toughness indices, especially for FNWAC compared to FLWAC. This highlights the efficacy of fiber reinforcement in enhancing material toughness. It is observed that the Fiber reinforcement increased toughness (flexural & post-cracking) and peak load (7.5% for normal weight, 25.2% for lightweight). However, normal weight concrete deflected more (47%) than fiber-reinforced concrete. The study establishes a correlation between increasing deflection and escalating energy absorption and toughness. However, significant deflections also resulted in reduced residual strength, necessitating further investigation for practical applications. The research focused on specific fibre type (basalt) and concrete compositions. Further studies with different fibers and mix designs are warranted. The investigation identified a trade-off between deflection and residual strength, requiring optimization strategies for real-world implementation.

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