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ORIGINAL PAPER

Flexural performance of sustainable concrete beams containing supplementary cementitious materials and glass fiber

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Abstract
After the dawn of the industrial era, pollution across the globe rose at a faster pace. It is essential to use sustainable materials in the construction industry. However, the characteristics of sustainable materials like fly ash, GGBS, and glass fibers may vary when induced and significantly impact the structure's safety and stability. Concrete is a composite matrix that is extremely hard and has high compressive strength but poor tensile strength. Unlike mild steel, concrete's elastic, yield, and plastic regions are difficult to observe and are brittle materials. As a result, concrete failure is impossible to assess. Experiments on three different types of M40 grade concrete with two different reinforcement specifications of 10 mm and 12 mm employed as top and bottom reinforcements have been tested to understand flexural behaviour and failure patterns in the concrete. The sizes of beams 150 mm × 150 mm × 750 mm were employed and tested using 4-point bending. An analytical finite element method (FEM) model compares the results. The flexural strengths of beams cast with a control mix, a proposed mix (50:25:25) of cement, fly ash, GGBS, and adding 0.50% of glass fiber to the optimum mix have been compared. This study shows that the OM and OM-GF mixes can be used for structural purposes in concrete to make it more durable and sustainable.

Keywords Abaqus · Flexural strength · Four point bending test · Glass fiber · Loading frame · Sustainable concrete

1 Introduction

Concrete is the most used manufactured material on the planet. Cement is one of the most important and expensive components of concrete. Because of rising environmental concerns, sustainable materials in concrete have become a popular choice among other best practices. The effect of cement when GGBS and fly ash are partially replaced is essential in the behaviour of concrete. Thermal power plants produce fly ash as a by-product. The iron ore industry produces GGBS as a by-product. In other words, GGBS and fly ash are used in construction as sustainable materials. Furthermore, using GGBS and fly ash instead of cement reduces construction costs. The research studies showed the behaviour of the supplementary constituents has little impact on lower grades of concrete [1–3]. Al-Helfi et al. [1] developed an analytical model in FEM of RHA-supplemented concrete beams and conducted experimental investigations. Karikalan et al. [2] experimented on concrete and replaced cement with GGBS in concrete from 5 to 40%, an increment of 5% each time. They have used steel, hybrid FRP and GFRP bars. Srinivas et al. reviewed the flexural behaviour of geopolymer concrete (GPC) beams been researched and compared to the flexural behaviour of reference concrete beams of the same grade. According to the literature, flexural cracks are developed less in geopolymer RCC beams than in conventional beams. The failure occurs in flexural mode, cracks have generated from the tension zone to the compression zone, and the compressive strength is more significant than before due to decreased porosity as the fineness of fly ash increases [3].

Syed Nasir et al. researched the strength properties of geopolymer concrete with low calcium fly ash replaced by slag in five different percentages. In the end, the mix with 30% GGBS and 70% fly ash yielded the highest compressive and split tensile strength. On the contrary, when the percentage of fly ash grows, the strength diminishes [4]. Kamal et al. [5] experimented with the impact of adding fibers and investigated how they affected the behaviour and strength of reinforced concrete beams. Chandar et al. investigated the mechanical features of partial cement replacement

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with GGBS and Fly-Ash in M40 grade concrete. This study shows that GGBS can replace 10% of cement, and fly ash can replace 15% of cement in concrete, reducing cement consumption and environmental issues [6].

Kamaldeep and Shyam Chamberlin investigated how fly ash and GGBS can be combined to enhance the environmental impact and chemical attacks of concrete. As a result, the flexural strength of a conventional concrete beam is 4.8 kN more than that of a beam blended with 35% fly ash, 45% GGBS, and 20% cement [7].

Naveena and Kumar explored concrete's maximum weight carrying capacity increases when 30% of the cement has been replaced with GGBS. Replacement of GGBS in place of cement may reduce greenhouse gas emissions in the cement industry. Compared to other specimens, joints with constant fibre proportions have a higher load-carrying capacity than standard concrete [8]. Kumaravel researched Geopolymer concrete and control concrete that have been compared for the flexural behaviour of the beams. GGBS has been added to the fly ash used in GPC at 25% to achieve the desired compressive strength. The load-displacement responses of the GPC and control beams are measured [9]. Kumar and Sarath Chandra Kumar experimented with varying proportions of GGBS replacement and metakaolin addition. The cracking moment was slightly lower when RGPC (Geo Polymer Concrete beams reinforced with GFRP bars) beams were compared to ROPC (Ordinary Portland Concrete beams reinforced with GFRP bars) beams. The number of flexural cracks generated for all beams was about the same. The beams failed due to tensile steel yielding, then concrete crushing in the compression face [10]. Radzi et al. investigated the fire impact on precast concrete beam-to-column connections. The first crack, displacement, joint hardness, and fire protection were all evaluated to determine whether a structure is safe for fire exposure [11]. Varun and Harish examined fresh and hardened properties of M-30 grade control concrete and concrete prepared with fly ash and ground granulated blast furnace slag as partial cement replacements. Blended concrete made using a mixture of Fly ash and GGBS at various percentages of cement yields good results [12].

Gerges et al. studied the influence of construction joints on the bending capacity of single reinforced concrete beams. As the compressive strength of concrete grows, the effect of the construction increases, resulting in a more significant loss in the structural element's bending capacity [13]. Dhivakar et al. discussed on M30 grade concrete containing GGBS, and Fly Ash could be used to replace natural sand partially. 10%, 20%, 30%, 40%, and 50% of the time, quarry sand replaces natural sand [14].

Azad and Samarakoon investigated on utilisation of industrial by-products/waste to manufacture geopolymer cement/concrete. According to a literature review, the technique promises to use industrial wastes and meet the demand for sustainable construction materials [15]. Moazzenchi and Vatani Oskouei experimented on the flexural behaviour of GGBS concrete beam with steel, hybrid FRP, and GFRP bars. The strength of a GGBS concrete beam made with hybrid FRP bars is higher than a GGBS concrete beam made with GFRP bars. The strength of the concrete with hybrid FRP was increased [16]. Vasanth Kumar and Elavenil researched the flexural behaviour of fly ash-based geopolymer concrete using Alccofine. The characteristics of GPC (geopolymer concrete) are enhanced by fly ash and alccofine. To obtain the mechanical and durability properties of various concrete mixes are experimented with concrete cubes, cylinders, and beam specimens [17].

Jamal Khatib et al. investigated the flexural behaviour of reinforced concrete beams containing expanded glass as lightweight aggregates and its applications. The workability of concrete improved when fine aggregates were replaced with expanded glass in the proportion of fifty percent. The decline is greatly diminished above 50%. The compressive strength gradually decreases as a higher percentage of expanded glass is added to the mixture [18]. Mohammed et al. experimented on the mechanical properties, and ductility behaviour of ultra-high performance fiber reinforced concretes (UHPCs). The creation of more undesirable calcium hydroxide particles during the hydration process may be responsible for the loss in strength observed in UHPCs and micro-glass fibers [19]. Heo et al. studied an experimental investigation on the mechanical properties, including strength and flexural toughness of mortar reinforced with steel carbon hybrid fibers. SEM images of the broken FRM surface indicate fiber pullout or debonding. However, numerous carbon fibers became too close when a single FRM was reinforced with carbon fibers, causing fiber balling and clumping [20].

This research aims to address societal issues by incorporating pozzolanic by-products from the coal and iron ore industries into concrete to make it greener, reduce carbon footprint, and be cost-effective without compromising structural stability in higher grades of concrete. That is used for megaprojects and plays a critical role in structural stability and integrity. The flexural tests were conducted on three different types of M40-grade concrete with two different reinforcement specifications. The sizes of beams 150 mm × 150 mm × 750 mm were employed and tested using 4-point bending. An analytical finite element method (FEM) model was used to compare the flexural strengths of beams cast with a control mix, a proposed mix (50:25:25) of cement, fly ash, GGBS, and adding 0.50% of glass fiber to the optimum mix.

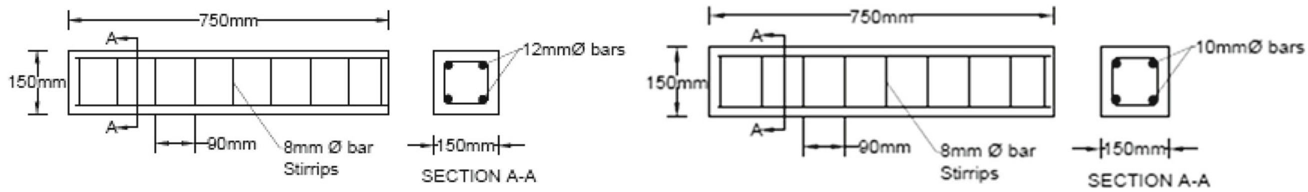

Fig. 1 Details of beam reinforcements

2 Materials and methodology

In this research, we have used three different types of concrete, namely control mix (CM), optimum mix (OM), and glass fiber induced optimum mix (OM-GF). All the concretes are of M40 grade. The optimum proportion is 50:25:25 cement, fly ash and GGBS, respectively. The optimal mix is prepended with Glass fibers to deliver a high impact. A certain proportion of glass fibers can manage concrete cracking, bleeding, shrinkage, and permeability. The strength of the concrete has reduced when additional glass fibers have been added. As a result, we have added the needed quantity of glass fibres to the concrete, resulting in this optimal blend of 0.5 percent glass fibre cementitious material.

In concrete mix design, 53 -grade of Ordinary Portland Cement (OPC) confirmed IS 12269-2013 [21]. 3.15 is the cement's specific gravity. Natural sand, abundant in the Vijayawada area, was also used as fine aggregate. According to IS code 383:2016, the surrounding zone is zone—II. 2.65 is the specific gravity of the Fine Aggregate. Crushed stone coarse aggregate was used, which was readily available in the Vijayawada area. 20 mm and 10 mm aggregates have employed in the experiment. Specific gravity values of 20 mm and 10 mm are 2.71 and 2.72, and the coarse aggregate.

Fly Ash was received from the Vijayawada Thermal Power Station (VTPS) in Vijayawada, Andhra Pradesh, and it meets IS:3812 part 1 requirements. Fly ash has a specific gravity of 2.3, and GGBS has been utilised to preserve its durability and ductility. The fineness of the GGBS is 3500 cm^2/gm. We acquired the GGBS and its specifications from JSW in accordance with IS 16714:2018. GGBS has a specific gravity of 2.86. Glass fibres are extremely lightweight. It is 12 mm in length and 12 microns in diameter. Superplasticiser Master Ease 3708, which is used to improve the rheological behaviour and mechanical properties of concrete. The amount of admixture used is specified in IS 456. Reinforcement of 8 mm, 10 mm, and 12 mm was employed. The details of beam reinforcements are shown in Fig. 1.

In Fig. 2, the flowchart demonstrates the methodology of flexural performance of sustainable concrete beams containing supplementary cementitious materials and glass fiber. The reinforcing cages were placed in the centre and double-checked. It was made sure that no oil was accidentally spilt

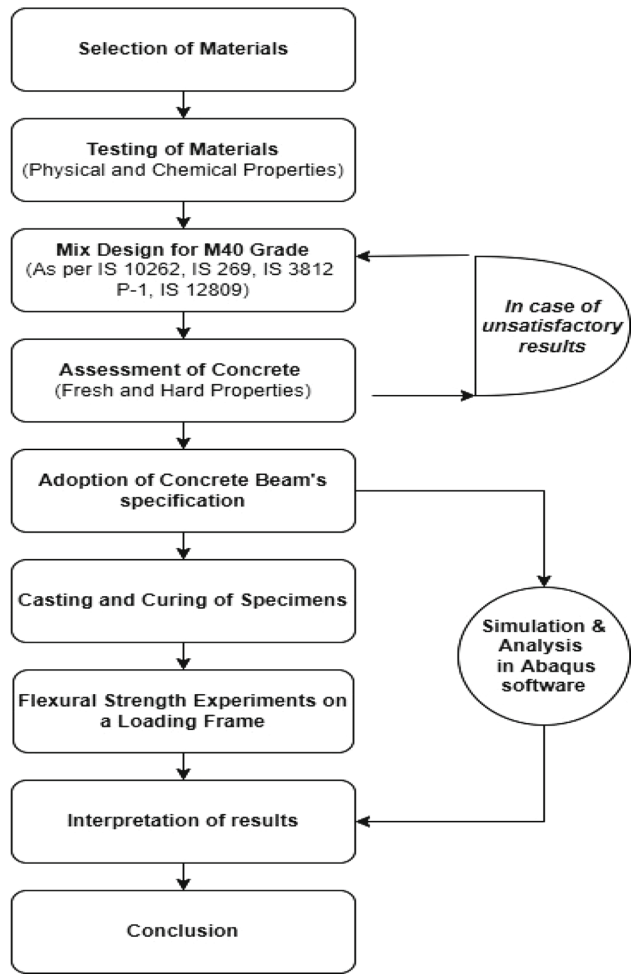

Fig. 2 Methodology

or caught on the reinforcing cage. Concrete must be mixed to have a homogenous concrete quality (Table 1).

Mixing the concrete was done with the help of a machine. The coarse aggregate was first placed in the mixing drum, followed by the fine aggregate, and finally, the cement was added to the mixing drum. The components were vigorously combined until a color-uniform combination was achieved. The water, which already contains admixture, is slowly added to the dry mix. The concrete is then placed on a damp surface (used for mixing), hand-mixed once, and then poured into beam moulds. A needle vibrator has been used to compact the concrete to achieve satisfactory compactions for all

Table 1 Reinforcement details

Specimen ID	Length (MM)	Width (mm)	Depth (mm)	Compression reinforcement (mm)	Tensile reinforcement (mm)	Shear reinforcement (mm)	Spacing of shear reinforcement (mm)	Clear cover (mm)
CM 12	750	150	150	12	12	8	90	25
OM 12	750	150	150	12	12	8	90	25
OM-GF 12	750	150	150	12	12	8	90	25
CM 10	750	150	150	10	10	8	90	25
OM 10	750	150	150	10	10	8	90	25
OM-GF 10	750	150	150	10	10	8	90	25

Fig. 3 Testing of concrete beams on a loading frame

six beam specimens. The reinforcement cage has been given special attention to avoid displacement. A metal trowel has used to smooth and finish the concrete's surface. Because the hydration of concrete necessitates a particular amount of water, which is lost or evaporated due to temperature conditions, curing has been performed to prevent or restore the water content. Water has commonly used to cure concrete. All six beams were immersed in a curing tank for 28 days. The beams were tested using four-point bending on the loading frame, which is shown in Fig. 3.

The materials values like Cement, GGBS, and fly ash are represented in Table 2. Where 1 is the volume of cement, 1.33 is the volume of fine aggregate, and 2.78 is the volume of coarse aggregate, the water-binder ratio used is 0.40.

In the same way, Abaqus software has been used to create and test an analytical FEM model [22]. Select a three-dimensional solid part edge, including geometry and orphan mesh elements. The steel-reinforced beam has a concrete core with four cylindrical extrusions. This steel stringer provides the necessary rigidity and durability of the beam, making it structurally sound. A solid part representing the beam and four stringer reinforcements representing the steel reinforcements can be created. The Mesh module assigns solid elements to concrete and line elements to stringers.

Six beams are experimented with using three different types of concrete mix. These specimens are categorized into two sets based on the primary reinforcement used. 10 mm and 12 mm HYSD Fe 500 steel bars have been used as primary reinforcement, as shown in Fig. 1. These beams were tested on the loading frame using 4-point bending. For the 4-point test, a load rating-controlled system was used and the load shall be applied at a rate of loading of 400 kg/min. An LVDT at the mid-center of beams and reinforcement details are in Table 1.

3 Results and discussion

This section comprises two sections. First, an overview of the fundamental properties of the considered mixes, followed by details of the beams with different reinforcement detailing, as shown in Fig. 2. Some fundamental properties like workability, bleeding, segregation, and plastic shrinkage come under the fresh properties category, and compressive strength, split tensile strength, and flexure strength represents the mechanical properties. All these properties are evaluated based on the standard test procedures confirming the IS codes. According to IS 1199–1959, the control and optimum mix workability are assessed within the normal ranges. It has also been observed that there is no bleeding, segregation, or plastic shrinkage [23]. Both flexure and compressive strength test was carried out according to IS:516-1959, [24] and the split tensile strength test was carried out according to IS 5816. [25] Compressive, split tensile, and Flexural strengths of three different types of the concrete mix have been tested after 28 days at a temperature of 27 °C and represented in Table 3.

It has been observed that the control mix has peak values. The results conclude that no apparent advantage exists in utilizing the supplementary materials. Even though the reduction of cement quantity has much less impact on the

Table 2 Mix design details

Type of concrete	Cement (kg/m^3)	W/B Ratio	Water (kg/m^3)	Fly ash (kg/m^3)	GGBS (kg/m^3)	Glass Fiber (kg/m^3)	FA (kg/m^3)	CA 20 mm (kg/m^3)	CA 10 mm (kg/m^3)	Admixture (kg/m^3)
CM	415.1	0.40	157.75	–	–	–	751.15	691.33	462.57	2.1
OM	207.53	0.40	157.75	103.78	103.78	–	729.70	671.60	449.4	2.1
OM-GF	207.53	0.40	157.75	103.78	103.78	20.70	729.70	671.60	449.4	2.1

Table 3 Effect of cement replacement on the fresh and hardened properties of various concrete mixes

Type of concrete	CM	OM	OM-GF
Workability	Good	Good	Moderate
Bleeding	No	No	No
Segregation	No	No	No
Plastic Shrinkage	No	No	Negligible
Temperature	27	27	27
Compressive strength @ 28 days	48.5	44.75	42.7
Split tensile strength @ 28 days	3.35	3.3	3.2
Flexural strength @ 28 days	7.3	6.92	6.4

Table 4 The deflection values obtained in the Abaqus FEM model and the experimental values of beams

Beam	Experimental deflection (mm)	Analytical model deflection (mm)
CM 12	6.32	5.06
OM 12	6.27	5.22
OM-GF 12	6.66	5.98
CM 10	5.9	4.83
OM 10	6.75	5.05
OM-GF 10	7.2	5.89

variation in strength. Thus, all three mixes are considered for casting the beams. The specific dimensions of the beams are 750*150*150 mm, were cast and tested to resist flexure failure. Beams are designed and reinforcement percentage varies by providing the 10 mm and 12 mm diameter bars. Simultaneously, the analytical model was simulated by using Abaqus software. Comparison of deflection values of CM, OM, and OM-GF beams both experimental and analytical, are represented in Table 4. Furthermore, the deflection values are represented for all six beams with varied reinforcement. The combined effects of GGBS and fly ash on the compressive strength of concrete were that the hydrate gels of GGBS helped to reduce the detrimental effects caused by the neat fly ash, and at the same time, the GGBS could increase the binding between the GGBS and fly ash phases and the binding between cement matrix and aggregates due to compactness of microstructure.

The material properties, beam size, reinforcing details, and testing conditions are all as realistic. The basic assumptions are, the internal forces, such as bending moments, shear forces, and normal and shear stresses, at any section of a member balance the external loads at that section. Secondly, sections perpendicular to the axis of bending keep their plane after being bent. A perfect bond between concrete and steel at the interface prevents slippage. Thus, both must deform. Modern deformed bars have high mechanical interlocking and natural surface adhesion, so this assumption is close. Since the tensile strength of concrete is only a small fraction of its compressive strength, the concrete in the tensioned portion of a member is typically fractured. Microcracks in well-designed members make the cracked concrete unable to resist tension stress. Thus, concrete cannot withstand any tension stress. The results obtained from the analytical model are represented in Fig. 4.

The CM 10 and CM 12 have 1.4 and 2% of the steel-to-beam area, respectively. In comparison, there is a 0.6% reduction in the steel area. The beam CM 10 failed at 89.3 kN, with a 5.9 mm deflection detected at mid-span. The beam CM 12 failed at 112.1 kN, and 6.32 mm deflection has observed at mid-span. The findings showed a 0.6% increase in steel area, a 25.53% rise in load-carrying capacity, and a 7.11% increase in deflection value in Fig. 5.

The OM 10 and OM 12 have 1.4% and 2% of the area of steel to beam area, respectively. There is a reduction of 0.6% of the area of steel comparatively. The beam OM 10 failed at 81.3 kN, and 6.75 mm deflection has observed at mid-span. The beam OM 12 failed at 108.3kN, and 6.27 mm deflection has observed at mid-span. Based on the results, we can conclude that a 0.6% increase in steel area enhanced the load-carrying capacity of the beam by 33.21% while decreasing the deflection value by 7.65%. The steel area-to-beam area ratio in the OM 10 and OM 12 is 1.4% and 2%, respectively, shown in Fig. 6.

In comparison, the steel area is reduced by 0.6%. The OM 10 beam failed at 81.3 kN, resulting in a 6.75 mm deflection at mid-span. The OM 12 beam failed at 108.3 kN, resulting in a 6.27 mm deviation at mid-span. The results show that a 0.6%

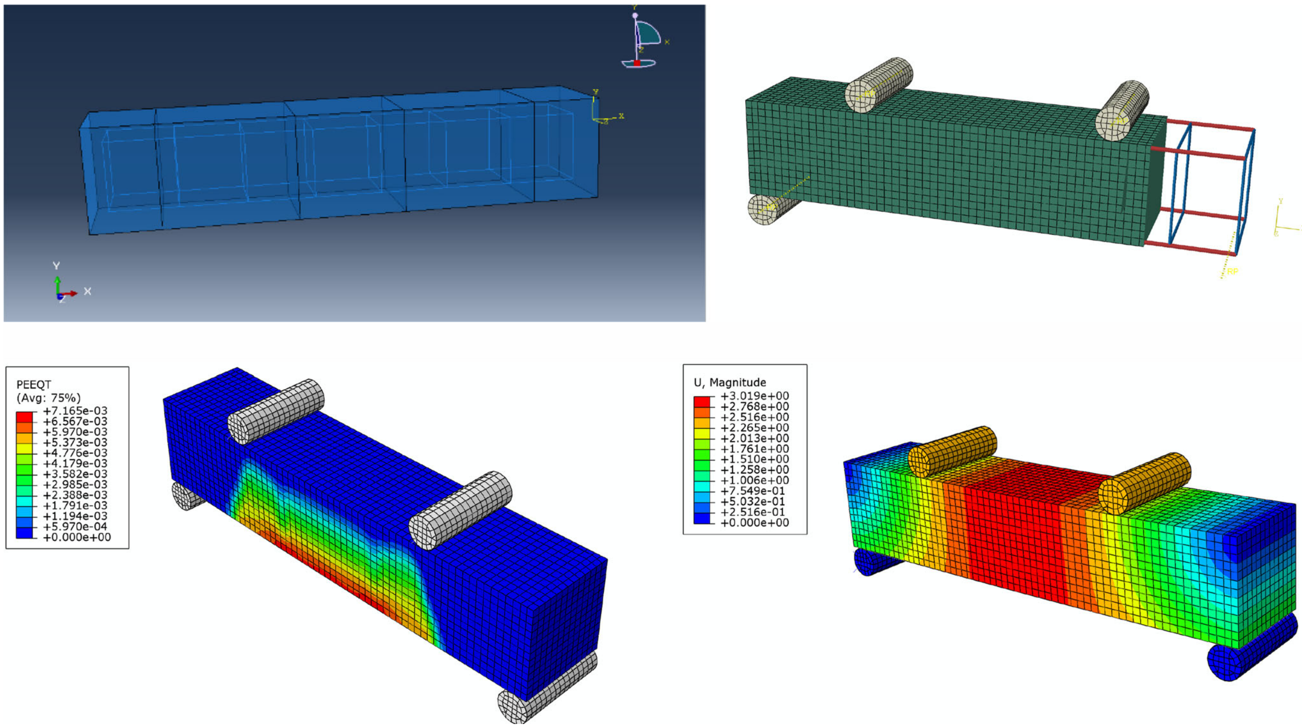

Fig. 4 Beam diagram in an analytical model

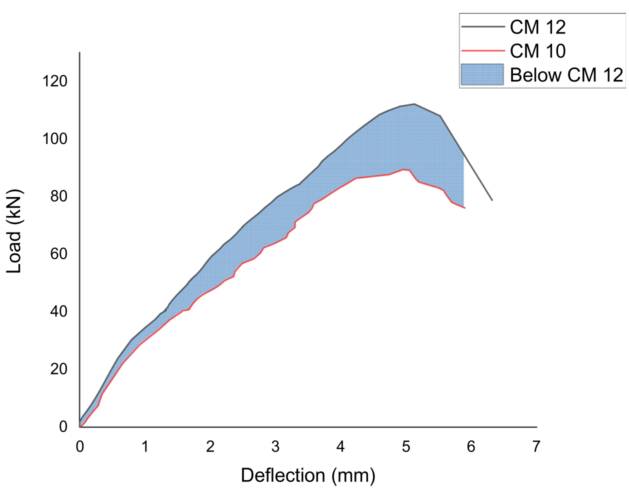

Fig. 5 Load and deflection graph of CM 10 and CM 12 Dia

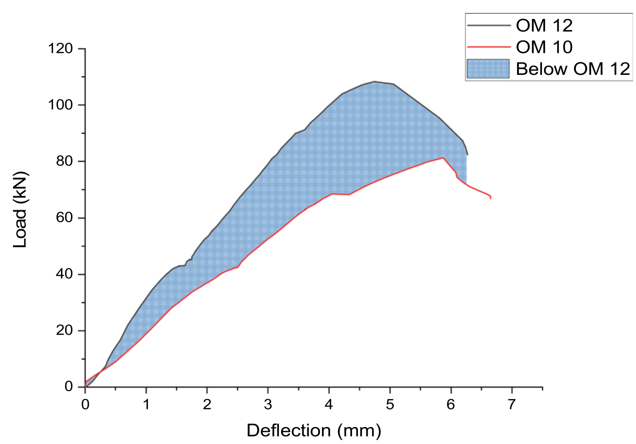

Fig. 6 Load and deflection graph of OM 10 and OM 12 Dia

increase in steel area enhanced the load-bearing capacity of the beam by 33.21%, while the deflection value has reduced by 7.65%.

The OM-GF 10 and OM-GF 12 have 1.4% and 2% of the area of steel to beam area, respectively shown I Fig. 7. In comparison, the area of steel is reduced by 0.6%. The beam OM 10-GF failed at 75.4 kN with a 7.2 mm deflection at mid-span. The OM-GF 12 beam failed at 96.8 kN, with a 6.6 mm deflection reported at mid-span. According to the results, the beam's load-carrying capacity increased by 28.38%, and the deflection value decreased by 9.09% due to a 0.6% increase in steel area. The steel area to beam area ratio of the OM-GF 10 and OM-GF 12 is 1.4% and 2%, respectively. In comparison, there is a 0.6% reduction in steel area. At 75.4 kN, the OM 10-GF beam failed, resulting in a 7.2 mm deflection at mid-span. At 96.8 kN, the OM-GF 12 beam failed, resulting in a 6.6 mm deflection at mid-span. The results show that a 0.6% increase in steel area enhanced the load-bearing capability of the beam by 28.38%, while the deflection value dropped by 9.09%.

Figure 8 shows the behaviour of beams containing 12 mm steel bars as primary reinforcement. CM 12, OM 12, and

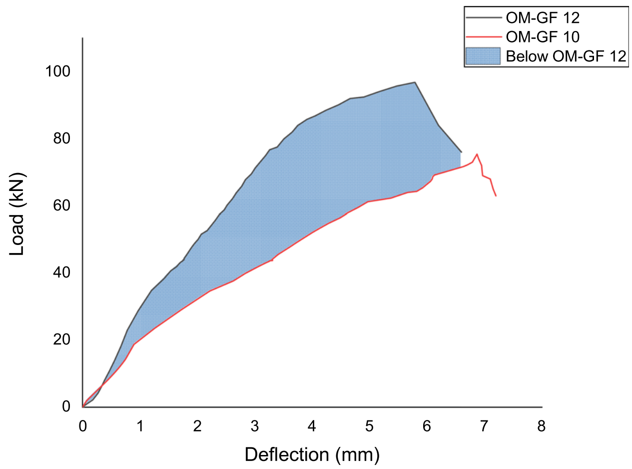

Fig. 7 Load and deflection graph of OM-GF 10 and OM-GF 12 Dia

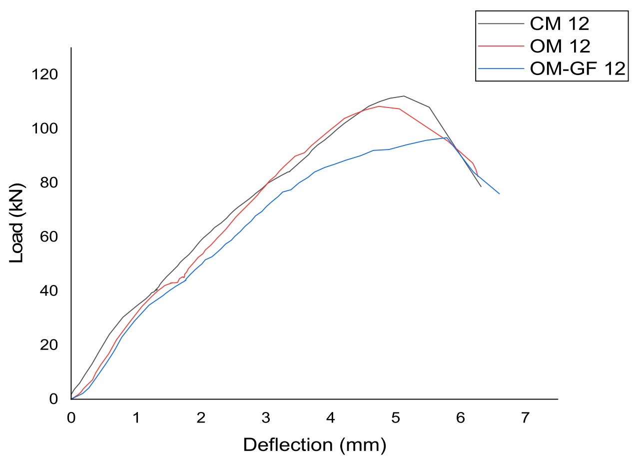

Fig. 8 Load and defection graph of CM 12, OM 12, OM- GF 12 Dia

OM-GF 12 have failed at 112.1 kN, 108.3 kN, and 96.8 kN, respectively. The OM 12 beam has a 96.61% similarity in load-carrying capacity, whereas OM-GF has an 86.35% similarity in load-carrying capacity. The beams CM 12, OM 12, and OM-GF 12 deflected 6.32 mm, 6.27 mm, and 6.6 mm, respectively. The cracking pattern in beams OM 12 is lower than CM 12 beam, and its deflection is reduced by 1.8% to that of the CM 12 beam. The deflection of the OM-GF 12 beam has increased by 4.43% compared to that of the CM 12 beam because of more minor and hairline cracks than CM 12 and OM 12. The use of glass fibres, improved the cracking behaviour of the beam.

Figure 9 shows the behaviour of beams containing 10 mm steel bars as primary reinforcement. The beams CM 10, OM 10, and OM-GF 10 have failed at 89.3 kN, 81.3 kN, and 75.4 kN, respectively. The OM 10 beam has a 91.10% similarity in load-carrying capacity, whereas OM-GF 10 has an 84.45% similarity in load-carrying capacity. The beams CM 10, OM 10, and OM-GF 10 deflect 5.9 mm, 6.75 mm, and 7.2 mm,

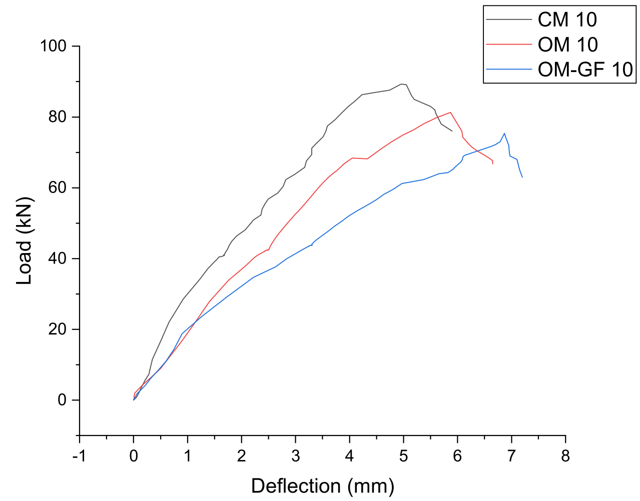

Fig. 9 Load and defection graph of CM 10, OM 10, OM- GF 10 Dia

Table 5 The experimental values of maximum stress and maximum strain values

Beam	Maximum stress (N/mm^2)	Maximum strain
CM 12	4.982222	0.009029
OM 12	4.813333	0.008957
OM-GF 12	4.302222	0.009429
CM 10	3.968889	0.008429
OM 10	3.613333	0.0095
OM-GF 10	3.351111	0.010286

respectively. The cracking pattern in beams OM 10 is lower than CM 12 beam, and its deflection is increased by 14.4% to that of the CM 10 beam. The deflection of the OM-GF 10 beam has increased by 22.03%the CM 10 beam because of fewer cracks and hairline cracks than CM 10 and OM 10. Due to the usage of glass fibers, the cracking behaviour of the beam improved.

The maximum stress and strain values of three different concrete beams of CM, OM, and OM-GF have shown in Table 5.

Based on Fig. 10, The following are the conclusions.

1. The beam CM 12 failed at 112.1 kN with a 6.32 mm deflection at mid-span.
2. The CM 10 beam failed at 89.3 kN, with a 5.9 mm deflection reported at mid-span.
3. The beam OM 12 failed at 108.3 kN with a 6.27 mm deflection at mid-span.
4. The beam OM 10 failed at 81.3 kN with a 6.75 mm deflection at mid-span.
5. The beam OM-GF 12 failed at 96.8 kN with a 6.6 mm deflection at mid-span.

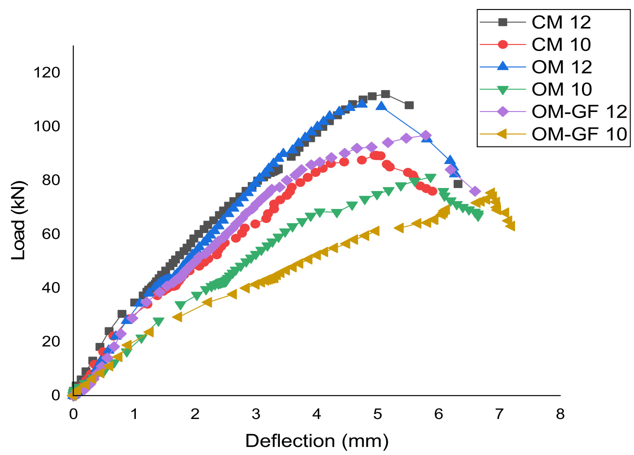

Fig. 10 Difference between the load and defection graph of CM, OM, OM-GF 10 and CM, OM, OM-GF 12

6. The OM-GF 10 beam failed at 75.4 kN, with a 7.2 mm deflection detected at mid-span.
7. They are increasing the size of the reinforcement and enhancing load-carrying capacity while slightly reducing beam deflection.

4 Conclusion

The present work represents the flexural strength results between experimental and analytical analysis of M40 grade concrete. Following are the conclusions of both experimental and analytical analysis.

- The water binder ratio is important in achieving good strength. At the age of this sustainable concrete will archive with a minimum curing period of 56 days.
- With the high-level replacement of mineral admixtures in the cement, the curing period should be longer because good strength of strength does not achieve at an early age.
- The deformation in the M40 grade of concrete replaced mix beam received less deformation compared to other mixes of beams in both experimental and simulation.'

The characteristics of sustainable materials like fly ash, GGBS, and glass fibers may vary when induced. This minor change may significantly impact the structure's safety and stability when we use this type of concrete for structural elements. Experiments were conducted on three separate grades or types of M40 concrete, with each type being subjected to varying conditions that included additional materials that could affect concrete properties.

The loading behaviour of CM beams is similar to the OM and OM-GF beams by an average of 93.82% and 85.36%, respectively. Compared to CM beams, the OM and OM-GF beams have more deflection since the number of cracks and crack width are less. The results of the FEM model match the experimental results by 81.93%. Finally, we may deduce that we can achieve desirable behaviour by using the optimum mix by making concrete green, producing a lower carbon footprint, and being more cost-effective than traditional concrete.

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