Analysis and design of axially loaded columns with ternary mineral admixtures and glass fiber for sustainable concrete composite

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Abstract

Concrete is a composition of cement, aggregates, and H2O. An increase in the usage of cement for concrete leads to an increase in CO2 emissions and non-renewable resource usage is also increasing, which is very problematic for future generations. So, to minimize the CO2 emission which is released from the cement, the cement should be replaced by the mineral admixtures. In this research Fly ash and GGBS are used in two different grades of concrete i.e., M20-Ordinary Concrete, M40-Standard Concrete by the weight of cement. The replacement of fly ash and GGBS proportions are CM (0:100), RM (25:25:50), these proportions are followed in the above two grades of concrete. To enhance the performance of research work, columns are using as casting specimens. The dimensions of the columns are 1000mm×150mm×150mm. The axially loaded column is tested under the loading frame for an axial compressive load. Respectively 0.5% of glass fiber is added to the proportional mix by volume of concrete for two different grades of concrete, to enhance the strength parameters of the concrete and to decrease the cracks that are obtained on the specimen. The final experimental results are compared with the analytical results with Finite Element Analysis (FEM).

Keywords: Abaqus; Axial Compressive Load; Fly Ash; GGBS; Glass Fiber; Loading Frame.

1. Introduction

Concrete is the second most used material on the earth after the water. Cement is the expensive material among the materials present in the concrete. For the preparation of cement huge amount of limestone is used which is a non-renewable resource, to generate this process huge amount of fuel is utilized. It leads to the greenhouse gas effect i.e., CO2 emission. For clinker preparation, 130 kg of fuel and 110 kWh of power are consumed for each ton, approximately 845 kg of carbon dioxide emits. Manufacturing of ordinary Portland cement grants 8% of man-made CO2 emissions. Utilization of mineral admixtures is necessary among that fly ash and GGBS had been in use since the 20th century and 19th century.

To decrease the ratio of cement in the concrete, by using mineral admixtures we can decrease the ratio of the cement as well as the increase in mechanical properties of the concrete-like compressive strength (C.S), Tensile Strength (T.S), and Flexural Strength (F.S). These admixtures are by-products of industrial waste. These admixtures are replaced in the cement or fine aggregate[1]. Annually there are 20 billion tons of concrete are produced worldwide and an equal amount of components are also used like coarse aggregate, sand, etc.[2]. Including the mineral, admixtures help in the reduction of impact on the environment and at the same time, it will enhance the properties of concrete[3]. Impact on concrete enhances the durability and mechanical properties by adding the mineral admixtures whereas compared to conventional concrete [4].

Reinforced concrete has many disadvantages like low tensile and compressive strength, which causes early age cracks. Shrinkage in cold temperatures and expansion in hot temperature conditions so to overcome those disadvantages glass fiber plays a key role and also enhances the performance of concrete[5]. There are many glass fibers are available in the market on that AR glass fiber, carbon fiber, steel fiber, etc. In the current study Alkali
resistant glass fiber is used in the reinforced concrete to form a new composite material called glass fiber reinforced concrete[6], [7]. Fly ash (FA) is an industrial waste that is a by-product of a thermal power plant and it is also an easily available material in the market and fly ash is categorized into three different classes C, F, and N [8], [9]. The greatest advantage to use fly ash is that it will reduce the heat of hydration and it is also a good pozzolanic material [10]. Higher replacement of fly ash leads reduced shrinkage and also durable for chloride-ion penetration [11]. However, replacement of fly ash leads to an increase in the performance of fresh concrete properties and also hardened concrete properties of concrete [12].

Ground granulated blast furnace slag (GGBS) is an industrial waste which is a by-product of iron industries, iron or steel blast-furnaces are fed with a controlled mixture of limestone, iron ore, and coke at a temperature of 1500°C. So the above materials are melted in the blast furnace and form into molten slag. The molten slag is cooled through a high-pressure water jet, this cooling leads to the formation of crystals in the slag, so this granular particle should not be more than 5mm in size. So the granulated slag is dried and made into a fine powder which is called GGBS [13], [14]. It is possible to get the desired strength for optimum replacement of 50% GGBS [15], [16]. When GGBS is replaced with Portland cement it will be sustainable i.e., eco-friendly, economical and it is useful for society, it is also increasing the workability, durability, and strength characteristics [17], [18]. The permitted ratio of replacement of GGBS in ordinary Portland concrete is 25-70% (IS 455:1989) based on applications [19].

There are many casting specimens for testing in the concrete laboratory-like cube, prism, and cylinder, etc. When it comes to application-oriented specimens like a beam, column, slab, beam-column joint, etc. In the current study, columns are used as a casting specimen[20]. There are different types of loading which is given to column they are axial-loading, uniaxial-loading, and biaxial-loading [21]. There is a possibility to enhance the performance of hardened concrete like to replace the mineral admixture without losing its strength properties, column jacketing, adding fibers to it, etc [22]. Analysis and design of axially loaded columns are done experimentally and it is compared in the finite element analysis software Abaqus[23]. The specimens are tested by four-point loading using non-linear analysis using Abaqus software which is FEM analysis software [24].

It was observed that, day by day the increase in the usage of cement leads to an increase in CO2 emission (greenhouse gases) and also a lot of non-renewable resources are used in the preparation of cement manufacturing. The other problem that we have found is that nowadays replacement of Mineral admixtures in cement is widely using in construction or research work, but when it comes to high-level replacement many of them were failed due to bleeding or segregation. So to overcome these problems which we are facing in the current scenario, we need to find out some solution. This current research is going under this problem statement. The objective of this research is to determine the behavior of the ternary Mineral admixture and glass fiber material in strength characteristics of the column for Sustainable concrete composite. To justify the term sustainability, at least it should satisfy a few conditions on that it should be eco-friendly, it should be economical, it should be useful for society or industries. As we are replacing the fly ash, GGBS, and Glass fiber in M20 and M40 it leads to reduce the CO2 emission as well as it is eco-friendly. By replacing the mineral admixtures, it will decrease the cost of construction. As we are decreasing the CO2 emission and also decreasing the cost of construction to some extent so it is useful for society. We termed the concrete as sustainable concrete and this research is justifying the term Sustainability. The experimental work is clearly explained in the above lines and we are using the axially loaded column as our casting specimen it is done experimentally in a concrete laboratory and it is compared with the analytical results (Abaqus).
2. Materials and Mix proportions

In this paper, the strength of concrete is based on the application of axial compressive load on different columns (specimens) in different grades of concrete. The specimens are cured about 56 days and they are tested in a loading frame, the load that is given to specimens is that axial compressive load. In this research M20, M40 grades of concrete with varying replacement of GGBS and fly ash with cement content proportions were used. Respectively glass fiber is added to the replaced mix by the volume of the concrete. The proportions are named as replaced mix (RM) for 50% (25% GGBS and 25% fly ash) and glass fiber (GF) + replaced mix (RM) is (25% GGBS and 25% fly ash + 0.5% by the volume of concrete) for cement. So, the above proportions are compared with the common mix (CM) of respective individual grades.

![Fig.2.materials: (a) Cement, (b) GGBS, (c) Fly ash, (d) AR Glass fiber.](image)

2.1. Material

OPC 53 grade cement is used in the current research confirming to IS: 12269-1987 [25] specifications are used in this study. The physical parameters and chemical compositions of cement are expressed in table 1 and table 2 respectively as per the reports. Fly ash is used as a mineral admixture in the current research, and it is collected from the Vijayawada thermal power station (VTPS).

![Fig.3. Materials: (a) Fine aggregate (b) 10 mm coarse aggregate (c) 12 mm coarse aggregate (d) Super plasticizer.](image)

The chemical composition of fly ash is expressed in table 3. JSW-HYD GGBS was used as a mineral admixture in the present studies. The specific gravity of GGBS is 2.81. The chemical composition of GGBS is expressed in table 4. Alkali Resistant glass fiber is used in the current research of 12 mm length and the colour is white. Reinforcement bars of 8mm diameter stirrups and 12mm main bars are used in the concrete columns. Properties are mentioned in table 8. Nearby river sand is used as a fine aggregate in the current research [26]. Local available 10mm and 20mm coarse aggregates, which are free from dust and soil are purchased from the market and used in the research [26]. ECMAS superplasticizer is used in the current research represented in fig.3. Water; Potable water is used [27].

| S. No | Chemical Parameter       | Requirements   | Result |
|-------|--------------------------|----------------|--------|
| 1     | Lime saturation factor   | 0.80–1.02      | 0.83   |
| 2     | Insoluble residue (%)    | 5.0 Max.       | 3.53   |
| 3     | Chloride (%)             | 0.10 Max.      | 0.02   |
| 4     | SO₃ (%)                  | 3.5 Max        | 2.26   |
| 5     | Loss of ignition (%)     | 4.0 Max.       | 3.49   |
| 6     | Magnesium (%)            | 6.0 Max.       | 0.95   |
Table 2. Physical parameters of Cement.

| S.No | Physical parameter           | Requirements | Results |
|------|------------------------------|--------------|---------|
| 1    | Initial setting time         | 30 Min.      | 140     |
| 2    | Final setting time           | 600 Max.     | 240     |
| 3    | Soundness Le-Chatlier (mm)   | 10 Max.      | 01      |
| 4    | Specific surface (m²/Kg)     | 225 Min.     | 296     |

Table 3. Chemical composition of Fly ash.

| S.No | Chemical Characteristics       | Requirement | Results  |
|------|--------------------------------|-------------|----------|
| 1    | SiO₂ + Al₂O₃ + Fe₂O₃ (%)       | 70.0 Min.   | 88.0–96.0|
| 2    | Magnesium oxide MgO (%)        | 5.0 Max.    | 2.0      |
| 3    | Total sulphur trioxide SO₃ (%) | 3.0 Max.    | 1.0      |
| 4    | Sodium oxide Na₂O (%)          | 1.5 Max.    | 1.0      |
| 5    | Loss of Ignition (%)           | 5.0 Max.    | 0.5–1.0  |
| 6    | Chlorides (%)                  | 0.05 Max.   | 0.05     |
| 7    | Reactive Silica (%)            | 20.0 Min.   | 25.0     |
| 8    | Silicon dioxide SiO₂ (%)       | 35.0 Min.   | 55.0     |

Table 4. Chemical composition of GGBS.

| S.No | Chemical parameter           | Requirement | Results |
|------|------------------------------|-------------|---------|
| 1    | CaO                          | –           | 37.34%  |
| 2    | Magnesium Oxide (MgO)        | 17.0%       | 8.71% Max.|
| 3    | Manganese Oxide (MnO)        | 5.5%        | 0.02% Max.|
| 4    | SiO₂                         | –           | 37.73%  |
| 5    | Fe₂O₃                        | –           | 1.11%   |
| 6    | Al₂O₃                        | –           | 14.42%  |
| 7    | Glass Content (%)            | 85%         | 92% Min.|
| 8    | Sulphidesulphur              | 2.0%        | 0.39% Max.|
| 9    | Insoluble Residue            | 5%          | 1.59% Max.|
| 10   | Loss of Ignition             | –           | 1.41%   |

2.2. Mix Proportions

Common Mix (CM): Common mix is completely cement that is 100% (Fly Ash-0% + GGBS-0% + cement 100%). Replaced Mix (RM): Replaced mix is that cement is replaced by 50% mineral admixtures (Fly Ash-25% + GGBS-25% + cement 50%). Replaced Mix with Glass Fiber (RM+GF): Respectively glass fiber is added to the replaced mix i.e., (Fly Ash-25% + GGBS-25% + cement 50%) + 0.5% by the volume of concrete.

So, respectively the above three mixes are involved in M20, M40 grades of concrete. The common mixes (CM), Replaced Mix (RM), Replaced Mix with Glass Fiber (RM+GF) with values are represented in table 5.
Table 5. Mix proportion details

| Mix    | W/B Ratio | Water Kg/m³ | Cement Kg/m³ | 20mm Kg/m³ | 10mm Kg/m³ | Sand Kg/m³ | Admixture Kg/m³ | Fly ash Kg/m³ | GGBS Kg/m³ | Glass Fiber Kg/m³ |
|--------|-----------|-------------|--------------|------------|------------|------------|----------------|--------------|------------|------------------|
| M20-CM | 0.55      | 197         | 358.18       | 673.00     | 450.00     | 731.00     | -              | -            | -          | -                |
| M20-RM | 0.55      | 197         | 179.09       | 655.60     | 438.68     | 712.32     | -              | 89.54        | 89.54      | 13.4             |
| M20-GF | 0.55      | 197         | 179.09       | 650.72     | 435.41     | 707.02     | -              | 89.54        | 89.54      | -                |
| M40-CM | 0.40      | 152         | 380.00       | 706.33     | 472.62     | 767.44     | 3.80           | -            | 95         | 95               |
| M40-RM | 0.40      | 152         | 190.00       | 688.77     | 460.87     | 748.36     | 3.80           | 95           | 95         | -                |
| M40-GF | 0.40      | 152         | 190.00       | 683.89     | 457.60     | 743.06     | 3.80           | 95           | 95         | 13.4             |

3. Methodology

3.1. Specimen preparation and test procedure

Preparation of steel reinforcement; as we are using columns as our casting specimens, for that reinforcement is designed. We got 4 longitudinal bars which are main bars of 12mm diameter and stirrups are of 8mm diameter are used in the column, properties of steel shown in table 8. Casting of specimens; a total of 6 columns are cast for 6 different proportions as mentioned in table 5. To maintain uniform workability water binder ratio is maintained thoroughly. After completion of casting the columns, they are supposed to keep them for about 24hrs in the mould and it is demoulded after 24hrs and after demoulding the columns are placed in a fresh water-filled curing tank for about 56 days’ period. After completion of 56 days curing period, the columns are dried for about 24 hours and then they are wiped off with a cloth and the surface cleaned with sandpaper and then sandstone for about 20cm×20cm and then with the help of rebound hammer equipment the non-destructive test is performed for all the columns as shown in fig.4. Testing the specimens; after completion of NDT, the columns are coated with whitewash, and then they are lined horizontally and vertically by giving 4 cm space line to line. Then is placed in the loading frame and the LVDT tool is placed for deflection and axial load is given respectively for the remaining columns as shown in fig.4. Analysis in the software; the load-deflection values are obtained from the experimental tests and these load-deflections values are mentioned in the simulation and compared these results with the experimental results. Comparing the results; finally, we got the results from NDT as well as from the loading frame of experimental values and we got results from simulation work. So both the results of the method were compared and concluded.

4. Experimental Work

Some preliminary tests have been done on cementitious materials on that specific gravity of CA, FA, GGBS, FA, GF, cement, initial and final setting time of cement, and fineness test of cement.

Table 6. Preliminary tests data

| S. No | TESTS                  | VALUES |
|-------|------------------------|--------|
| 1     | Specific Gravity of Coarse Aggregate | 2.71   |
| 2     | Specific Gravity of Fine Aggregate  | 2.65   |
| 3     | Specific Gravity of GGBS    | 2.81   |
| 4     | Specific Gravity of Fly Ash | 2.11   |
| 5     | Specific Gravity of Glass Fiber | 2.68   |
| 6     | Specific Gravity of cement  | 3.15   |
| 7     | Consistency of cement      | 6 mm   |
| 8     | Fineness Test of cement    | 8%     |
Mix design details are mentioned clearly in table 5. Many trail mixes were done before casting the original mix. The water-cement ratio is taken through the code IS: 456-2000 and it is fixed after the trail mixes have been done. To mix the different materials for concrete, a concrete mixer machine and trail mix materials are mixed in a small concrete mixer due to the low quantity of materials.

The steel reinforcement of the column is clearly explained in point 3.1 and the properties of the steel reinforcement are mentioned in table 8. The procedure that has been followed for the casting of columns is that initially the moulds are placed at a plane surface and mud oil is applied to the moulds. Then the mixed concrete is poured into the moulds up to the clear cover then the reinforcement is placed, and the left gap is filled with the concrete and it is vibrated using a vibrator. The surface is inflated with the trowel and the final stage of fresh concrete in the mould.

The specimens are done with Non-Destructive Testing (NDT), the machine that had used for this test is that rebound hammer equipment, without destructing the columns the compressive strength of the column is known and it is explained in 3.1. The NDT compressive strength values of M20 and M40 grades are mentioned in table 7.

| Grade               | Compressive Strength(N/mm²) |
|---------------------|----------------------------|
| M20 – Common Mix    | 30.33                      |
| M20 – Replaced Mix  | 23.56                      |
| M20 – Glass fiber mix | 26.68                      |
| M40 – Common Mix    | 48.44                      |
| M40 – Replaced Mix  | 44.74                      |
| M40 – Glass fiber mix | 44.00                      |

The specimens are tested in the loading frame for axial compressive load and deflection, the detailing is shown in fig 5.
5. Simulation Work

5.1. Analytical Steps

In the part module, need to give the column dimensions as 150 X 150 mm as width and breadth and 1000 mm as the column length or height. After the column dimensions, stirrup dimensions are given. In the Property Module, so for any FEM analysis properties are very important to compare the experimental results with the simulation work for that here we have given different kinds of steel and concrete properties which we have obtained from the experimental values with some formulas and the properties are mentioned in Table 8.

| S. No | Material                      | Type                    | Density (N/mm$^2$) | Young’s Modulus (Mpa) | Poisson’s Ratio |
|-------|-------------------------------|-------------------------|--------------------|-----------------------|-----------------|
| 1     | Ordinary concrete             | Solid, homogeneous      | 2.4e-6             | 5000√fck              | 0.1             |
| 2     | Standard concrete             | Solid, homogeneous      | 2.4e-6             | 5000√fck              | 0.2             |
| 3     | BAR 8mm&12mm HYSD             | HYSD (High Yield Strength Deformed Bars) | 7.8e-6         | 200e3                 | 0.3             |

In the Assembly Module to get the longitudinal bars in the column assembly module is used and according to the clear cover the dimensions will be given, and it is properly inserted at the specific point after the dimensions are given to the assembly module according to the column design details for experimental work. In the Step Module to get the accurate values when it is compared with the experimental values, we must be very keen so, the load is given in one end that is considered as a free end and the side which is at the bottom is considered as the fixed end. In the Load Module, this is one of the main steps in the simulation work; we got the load and deflection from the experimental test which is conducted on the column by a loading frame. The obtained load and deflection values are given in the load module respectively, give in table 9. In the Mesh Module After the completion of the load module meshing should be done, it is a simple task, and the final steps to give input for the specimen, once the mesh module is given the work is done, and then goes to the job module and give names and take results. The below figs are of different specimens deformation.
Table 9. Axial-load and Deflection values of column

| S.No | Grade-Mix | Deflection (mm) | Designed Load (kN) | Axial Load (kN) |
|------|-----------|-----------------|--------------------|-----------------|
| 1    | M20-CM    | 2.09            | 302                | 398.13          |
| 2    | M20-RM    | 3.44            | 302                | 342.15          |
| 3    | M20-GF    | 3.76            | 302                | 359.85          |
| 4    | M40-CM    | 3.28            | 479                | 560.7           |
| 5    | M40-RM    | 3.07            | 479                | 530.45          |
| 6    | M40-GF    | 3.32            | 479                | 542.15          |

Fig.6. FEM analysis results for M20-CM, (a) Deformation failure, (b) Von-mises stress.

Fig.7. FEM analysis results for M20-RM, (a) Deformation failure, (b) Von-mises stress.

Fig.8. FEM analysis results for M20-GF, (a) Deformation failure, (b) Von-mises stress.
Fig. 9. FEM analysis results for M40-CM, (a) Deformation failure, (b) Von-mises stress.

Fig. 10. FEM analysis results for M40-RM, (a) Deformation failure, (b) Von-mises stress.

Fig. 11. FEM analysis results for M40-GF, (a) Deformation failure, (b) Von-mises stress.

6. Results and Discussion

Compared the experimental and analytical results through a bar graph to show the slight changes that have occurred in the ultimate load for the columns. In the bar graph, it is mentioned that in the X-axis the grades and proportion details are given, and, in the Y-axis, the ultimate load is given, the experimental and analytical results were compared clearly with different colours.
Load – deformation values are compared through the graph individually for each grade of concrete and proportions, shown in figures 13 and 14 of M20 grade experimental and analytical results. There is a slight change in the load and deformation when it is compared to the experimental data with analytical data.

Fig.13. Load – deformation curve for M20 grade of concrete (Experimental columns).
Fig. 14. Load – deformation curve for M20 grade of concrete (Analytical columns).

Load – deformation values are compared through the graph individually for each grade of concrete and proportions, shown in figs 15 and 16 of M40 grade experimental and analytical graphs. There is a slight change in the load and deformation when it is compared to the experimental data with analytical data.

Fig. 15. Load – deformation curve for M40 grade of concrete (Experimental columns).

Fig. 16. Load – deformation curve for M40 grade of concrete (Analytical columns).
7. Conclusion

The present work represents the comparative results between experimental and analytical analysis of M20 and M40 grades of concrete. Following are the conclusions of both experimental and analytical analysis:

- At the age of 56 days curing both the M20 grade and M40 grade of concretes has achieved complete strength concerning the load.
- The water binder ratio plays a key role in achieving good strength.
- With the high-level replacement of mineral admixtures in the cement, the curing period should be more because the strength does not achieve at an early age.
- The deformation in M20 grade of concrete common mix column got less deformation compared to other mixes of columns and when it comes to M40 grade of concrete replaced mix column got less deformation compared to other mixes of columns in both experimental and simulation.
- As we have done high-level replacement though every individual mix specimen got a very good axial-load compared to the design load.
- Common mix columns got increased axial-load when it is compared to the designed load by 31.83% in M20 grade of concrete and 30.88% in M40 grade of concrete in experimental columns and 17.05% in M20 grade of concrete and 18.84% in M40 grade of concrete in analytical columns.
- Replaced mix columns got increased axial-load when it is compared to the designed load by 13.29% in M20 grade of concrete and 14.79% in M40 grade of concrete in experimental columns and 10.74% in M20 grade of concrete and 10.30% in M40 grade of concrete in analytical columns.
- Glass-fiber mix columns got increased axial-load when it is compared to the designed load by 19.15% in M20 grade of concrete and 19.06% in M40 grade of concrete in experimental columns and 13.18% in M20 grade of concrete and 15.37% in M40 grade of concrete in analytical columns.

8. Future Scope

Further work can be carried out by replacing high proportions of mineral admixtures in the cement and it is applied in different applications for strength parameters and the curing period also would be increased to 90 days to get the maximum strength in concrete. M60 grade of concrete is used to know the high strength properties of concrete by the influence of mineral admixtures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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