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Influence of Ground Granulated Blast Furnace Slag on the structural performance of Self Compacting Concrete

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Abstract

In the last decades, the utilization of industrial waste like ground granulated blast furnace slag (GGBFS) has proven itself a great asset in the modern construction industry. Aiming at promoting the green housing initiatives, the present study focuses on the study of the influence of GGBFS on the structural performance of Self Compacting Concrete (SCC). In the initial phase of the extensive experimental programme, concrete cubes were prepared with the partial replacements of GGBFS (10%, 15%, 20%, 25% and 30% with cement) and tested against the control mix in order to investigate the associated mechanical properties (compressive strength, tensile splitting strength and flexural strength). At 20% GGBFS replacement, the optimum compressive strength was noted and further addition of GGBFS caused a gradual decrease in the mechanical strength properties. This study further investigates the structural properties like axial load–displacement behavior and failure pattern of reinforced concrete (RC) columns and flexural performance of RC slabs with and without the addition of GGBFS. SCC with 20% GGBFS demonstrated relatively better structural performance, causing the formation of lesser crack width/depth/length as compared to the control mix. An empirical relationship was also proposed based on the experimental test results (in relation to the mechanical properties) in line with American and Indian standards code of practice.

Keywords: self-compacting concrete, slab, column, crack width**,** ground granulated blast furnace slag

INTRODUCTION

The production of Portland cement is increasing each year due to the rapidly growing demand of concrete in the construction industry. The last century has witnessed the significant increase in cement consumption per year (Monteiro et al., 2017; Schneider et al., 2011) and the excessive demand of cement outsized consumption of energy and also responsible for many adverse environmental conditions including huge emission of greenhouse gases causing depletion of the ozone layer (Ali et al., 2011; Bosoaga et al., 2009; Jamora et al., 2020; Sousa & Bogas, 2021; Van Oss & Padovani, 2003; Xu et al., 2012). It has been recorded that, an about one ton of CO_2 is emitted during the production of one ton of cement (Rangan & Hardjito, 2005). Apart from that, one twentieth of the global CO_2 emissions is associated only with the cement production industry (Huntzinger & Eatmon, 2009). Therefore, environmental damage caused due to largely growing cement industry cannot be unnoticed and this raise a necessity to find an alternative source to ordinary Portland cement (OPC) concrete (Damtoft et al., 2008).

In recent decades, several attempts have been made to find the most possible and practical alternative to the OPC-based building materials and different admixtures were introduced for the partial replacement of the OPC. Mineral admixtures produced as industrial wastes from various industries such as fly ash, silica fume, ground granulated blast furnace slag (GGBFS), rice husk ash etc., are enriched with Silica (SiO_2) and Alumina (Al_2O_3), can be utilized as a partial replacement of the OPC. GGBFS is an industrial waste product of iron and steel industry and recently been used as an essential alternative to cement in cement concrete. GGBFS serves as a supplementary cementitious material due to the formation of additional low-density calcium silicate hydrate (C– S–H) gel which helps in increasing the density of the matrix through a pore filling effect. The use of GGBFS also causes additional benefits like cost efficiency, energy savings, ecological balance and conservation of natural resources.

Many researchers (Aliabdo et al., 2019; Chidiac & Panesar, 2008; Fonseca et al., 2015; Gholampour & Ozbakkaloglu, 2017; Kumar et al., 2019; Kwon, 2005; G. Li & Zhao, 2003; S. Li et al., 2017; Özbay et al., 2016; Ramakrishnan et al., 2017; Shen et al., 2020; Shubbar et al., 2018; Verma & Dev, 2021; Zhu et al., 2020) have studied on the influence of physical and mechanical behavior of conventional concrete with GGBFS replacements. Wang (Wang, 2008) investigated the capillary effect of SCC with the presence of GGBFS and found that there is an decrease in porosity and increase in durability of concrete after addition of GGBFS or fly ash as GGBFS acts as a filler material and the nucleus for precipitation of cement hydration products as compared to the cementitious materials. GGBFS is found to be useful in dual purposes like imparting high resistance to chemical attack in the marine environment as well as substantially decreasing the heat of hydration (Salehi & Mazloom, 2019). Therefore, in mass concreting, either low heat cement is used or GGBFS is used to control the heat of hydration in high strength cement. Concrete properties like creep, modulus of rupture, modulus of elasticity, bond with steel and tensile strength are altered after the use of GGBFS (Mohd Shariq et al., 2010). These are the fundamental properties which control the structural performance of reinforced and pre-stressed concrete.

Similarly, studies on the influence of GGBFS on the geopolymer concrete (Deb et al., 2014; Islam et al., 2014; Khan et al., 2016; Lau et al., 2019; Mehta & Siddique, 2018), recycled aggregate concrete (Hu et al., 2019; R. K. Majhi & Nayak, 2019; Rajib K. Majhi et al., 2020), alkali activated concrete (Bernal et al., 2011; Lee & Lee, 2013; Puertas et al., 2000) with the effect of different curing conditions (Rajarajeswari & Dhinakaran, 2016; Swamy & Bouikni, 1990; Yazici et al., 2009) are available. Similarly, creep and drying shrinkage (Hooton et al., 2009; M. Shariq et al., 2016), static modulus of elasticity of concrete (Mohd Shariq et al., 2013), concrete at different elevated temperature (Brooks & Al-Kaisi, 1990; Miura & Iwaki, 2000; Siddique & Kaur, 2012; Wang, 2008) have also investigated. Studies show that, the inclusion of GGBFS could result in rapid strength development because of the increased reaction kinetics (El-Hassan & Ismail, 2018; Puligilla & Mondal, 2013). A few studies (Mohd Shariq et al., 2010, 2013) have performed the experimental investigation to quantify the role of GGBFS on the time dependent strength development of concrete. Studies (Altoubat et al., 2016; Dinakar et al., 2013; Rajamallu et al., 2021; Revilla-Cuesta, Skaf, Espinosa, et al., 2021; Salehi & Mazloom, 2019; Vejmelková et al., 2011; Yazici, 2008; Zhao et al., 2015) are also available on physical, chemical and mechanical behavior of SCC containing GGBFS. The effect of Fly Ash, GGBFS, and Metakaolin on Mechanical and Durability Properties of SCC is also studied considering recycled aggregates (Djelloul et al., 2018; Gesoĝlu et al., 2012; Nandanam et al., 2021; Revilla-Cuesta, Skaf, Santamaría, et al., 2021; Sasanipour & Aslani, 2020).

The construction of high-rise buildings always requires a smaller and shallower reinforced concrete (RC) members in order to achieve more effective floor area which leads to the congestion of reinforcements at beam-column joints. Congestion of reinforcements can also be observed at high seismic zones where more steel area is needed in the beam-column joints. If these joints are not well designed and not handled well, then the overall performance of the concrete can be greatly affected. Self-compacting concrete (SCC), also termed as self-consolidating concrete has recently drawn the attention being one of the most important developments in building industry to prepare denser concrete (Brouwers & Radix, 2005). SCC requires a large amount of powder content compared to conventional vibrated concrete to produce a homogeneous and cohesive mix (Topçu & Uygunoğlu, 2010). But, the cost of preparation associated with SCC is high as it requires the compulsory use of chemical admixtures and a high volume of Portland cement. In this case, the admixtures like GGBFS, fly ash, natural pozzolans can be cost effective for SCC as they are the industrial waste by-products. Along with that, these the mineral additives add some extra features like, increased workability, durability and long-term properties to SCC (Bilodeau & Malhotra, 2000; Topçu & Boĝa, 2010).

RESEARCH SIGNIFICANCE

After an extensive review of literature, it was realized that there is hardly any study available on the influence of GGBFS on the structural performance of SCC. So, the prime objective of the present work is to investigate and perform a comparative study on the mechanical properties (compressive strength, tensile strength, flexural strength) of concrete cubes, axial load–displacement and failure pattern of column, flexural performance of reinforced slab prepared with regular SCC with OPC only and OPC replaced with various potions of GGBFS. Other important parameters like crack width propagation of structural members like column and slabs co-relating the mechanical properties were also examined. The outcomes of this experimental work are expected to assist in anticipating the accurate structural behaviour of SCC with partial replacement of GGBFS.

EXPERIMENTAL PROGRAMME

The present experimental programme uses OPC of 43 grades conforming to IS 455: 1989 (Bureau of Indian Standards, 2015) and the physical and chemical components of the OPC were determined as per IS: 8112 -1989 (Bureau of Indian Standard, 2013) (see Table 1). GGBFS having specific gravity and fineness modulus, such as 2.84 and 2.29 was collected from Jindal Panther, Odisha, India as shown in Fig. 1. The physical and chemical properties of GGBFS were experimentally determined to confirm to IS 12089: 1987 (Bureau of Indian Standard, 1987) and ASTM C-618 (ASTM international, 2013) and presented in Table 2. Locally available natural river sand conforming to zone-III as per IS 383 1970 (Bureau of Indian Standards, 1970) was used as fine aggregates. The specific gravity and water absorption values of sand are obtained as 2·63 and 0·8% respectively. Angular graded crushed coarse aggregate having a nominal maximum size of 20 mm is also used with specific gravity and the water absorption of 2·67 and 0·4% respectively. Physical properties of coarse and fine aggregates are provided in Table 3 and the particle size distribution curve for the fine aggregates is shown in Fig. 2.

Mix Proportions

A set of total six numbers of concrete mixes was designed by partial replacement of GGBFS with cement (by weight). IS 10262:2019 (Bureau of Indian Standards, 2019) and EFNARC (EFNARC, 2005) were followed for designing the control mix (i.e. without GGBFS) to achieve characteristic design strength of 30 MPa followed by a weight batching with the cement content varying from 585.42 kg/m^3 to 409.79 kg/m^3. GGBFS replacement doses of 0% (Control Mix), 10%, 15%, 20%, 25% and 30% of the total cementitious materials are considered and the cement quantity all other ingredients remained constant to quantify the solo effect of GGBFS. Tap water was used in all mixes (curing tank at a temperature of 27^0 C ± 2^0 C) as per IS: 516-1959 (Bureau of Indian Standards, 2004) and all the concrete mixing was performed using a laboratory rotary mixture machine. The mix proportions of cement, GGBFS, natural sand, coarse aggregates, water and admixture for all the mixes are provided in Table 4. Sika Visco Crete Premier (from Sika brand) was used as a superplasticizer/viscosity-modifying admixture during the mix.

Preparation of specimens and test methods

Slump flow and V-funnel tests were prepared to quantify the deformability and viscosity of the SCC mix and the passing ability of SCC mix was tested by L-box test. Concrete cubes (54 units) of size 150 mm × 150 mm × 150 mm, cylindrical specimens (6 units) of size 150 mm (dia) × 300 mm (*l*) and concrete beam (6 units) of size 100 mm × 100 mm × 500 mm were tested to determine the compressive strength, tensile splitting strength and flexural strength as per IS: 516 - 1959 (Bureau of Indian Standards, 2004). Specimens were cast and cured for 7, 28 and 56 days. RC columns (a total of 6 numbers for each GGBFS replacements including control mix) and two-way slabs (one for the control mix and one for the 20% GGBFS mix) were also cast and tested to analyze load-deflection behavior along with the study of crack width propagation. Electronic universal testing machine (UTM) was used to generate the load–deflection and Crack scope was used to measure the crack width propagation. Form work of dimension 160 mm (dia.) × 750 mm (height) was used for casting the columns and 1.22 m (length) × 1.22 m (width) × 80 mm (depth) was used for casting the slabs. Capillary absorption tests to measure sorptivity were also conducted for the concrete samples of 110 mm (dia.) × 150 mm (height) which indirectly measures the durability aspect. Details of all test specimens are shown in the Fig. 3.

RESULTS AND DISCUSSION

Fresh properties of SCC

Significant improvements in fresh properties were observed after the replacement of GGBFS with OPC. The slump flow values were found to vary from 687 mm to 768 mm depending upon the partial replacement of GGBFS percentage (range). The self-compatibility properties of SCC with and without replacement of GGBFS are represented in Table 5. As per EFNARC (EFNARC, 2005), these ranges of slump flow come under flow classes of 2 and 3 (SF2 & SF3) and under these ranges, SCC will be suitable for casting columns and slabs. The slump flow was found to be holding an inverse relationship with the successive addition of GGBFS which may be due to the agglomeration of cement particles which can be dispersed by slag particles (Nehdi et al., 2004; Sethy et al., 2016). It was also observed that when an extra amount of slag is added as a partial replacement of cement, lesser amount of superplasticizer is required to maintain desired workability. Bleeding and aggregate segregation were taken care off and visually examined throughout the experimental campaign.

It was observed that, the T50 flow decreases as the slump flow value increases. Again, with the increasing replacements of GGBFS, the T50 flow was found to be decreased from 4.1*s* to 3.1*s*. Passing ability of the SCC is checked through L-box test and was found to be sensitive to blocking. This ratio lies between 0.86 to 0.98 corresponding to different slag doses of GGBFS exhibiting satisfactory blocking ability. Again, the V-funnel time was found to be decreasing as the slump value increases and the increase in time (values vary from 6.2s to 8.1s) is due to the presence of the increased slag content. The results also show that, irrespective of effective water-cement ratio, the V-funnel time decreases with increased slag content (Nehdi et al., 2004). Fig. 4 shows a surface plot between slump flow, T-50 flow and V-funnel values obtained experimentally. Fig.4 shows that, the slump flow value increases with increased dose of GGBFS keeping the superplastisizer the dose constant. This may be due to the superplastisizer does not react with the slag particles producing a repulsive force while, the action of the superplasticizers will be only with the cement particles (Wattanalamlerd & Ouchi, 2005). Another reason may be due to the spherical nature of slag particles which acts as a lubricant. During these experiments, doses of the superplastisizers were kept constant to quantify the effect of GGBFS in the mechanical properties of concrete.

Compressive strength, splitting tensile strength and flexural strength

Compressive strength test on cube specimens was carried out in 7, 28 and 56 days and the results are presented in Fig. 5. Fig. 5 describes the variation in the compressive strengths with the curing age for all considered specimens (with and without GGBFS replacements). As expected, with the ageing of concrete, there is a significant increase in the compressive strength of all SCC samples with GGBFS replacements. It may be due to the pozzolanic reaction of slag with the calcium hydroxide liberated during cement hydration. The fineness and the hydraulic properties of the slag also contributed to the strength development. At 7 days, the SCC with GGBFS attained a lower strength as compared to the control mix. But a noticeable increment in the strength of SCC with GGBFS was observed for 28 and 56 days. Fig.5 shows that, the compressive strength increases with the increased amount of GGBFS (within a range of 10% to 20%). At 20% replacement of GGBFS, the compressive strength decreases by 4.61% for 7 days while, it again increases by 15.37% and 21.46% at 28 and 56 days respectively. Optimum strength was achieved at 20% GGBFS replacement. A gradual decrease in the compressive strength was observed beyond 20% GGBFS replacement which may be attributed to the irregularity in the matrix formation. It is evident from the above study that the maximum strength of SCC can be obtained only at a particular level of slag replacement. This concludes the restrictions on the maximum replacement of slag for any specific strength. In the meanwhile, from the current experimental study the slag replacement for developing the desired strength of SCC can easily be predicted.

The splitting and flexural tensile strength of GGBFS self-compacting concrete was also studied and the computations are presented in Fig. 6. It can be seen from Fig. 6a that, the tensile splitting strength decreases at a replacement ratio of 10% and again increases in the range of 10% to 20% of GGBFS. The increment observed was about 14% and 8% at the age of 28 and 56 days. However, the further addition of GGBFS results in decrease of splitting tensile strength. At a lower percentage of GGBFS replacement, the difference in strength is higher, whereas at a higher percentage of GGBFS replacement, the difference is minimal. Again, at a higher percentage of replacement, the loss in split tensile strength is very pronounced as it is sensitive to cracks either on a macro or micro-scale.

Similar to splitting tensile strength, at 10% of GGBFS replacement, there is a decrease in the flexural strength for tested specimens as compared to the control mix observed for both at the age of 28 and 56 days. However, a gradual increment in strength with the increase of GGBFS replacement is observed (Fig. 6b) until it reaches the optimal value of 8.45 at 28 days and 8·97 MPa at 56 days with 20% GGBFS replacement (see Fig. 6b). The flexural strength follows a trend slightly different than that of the compressive strength, but quite identical to the tensile splitting strength.

Correlation between the mechanical properties of GGBFS SCC concrete

Concrete design codes treat the compressive strength (f_{ck}) as a significant parameter for the assessment of quality of concrete and other parameters like flexural strength (f_r) and tensile splitting strength (f_t) are expressed with respect to f_{ck}. So, based on the present experimental test results, an empirical relation is proposed as Eq. 1 (with $R^2 = 0.80$) and shown in Fig. 7a similar to that proposed in the ACI building code 318 (American Concrete Institute, 2014).

$$f_t = 0.348 \times f_{ck}^{\ 0.608} \qquad \text{(Eq. 1)}$$

Similarly, an empirical prediction is established between compressive strength and modulus of rupture based on the experimental test results (Eq. 2) with $R^2= 0.98$ is proposed. This relationship is presented in Fig. 7b.

$$f_r = 2.14 \times f_{ck}^{\ 0.355} \qquad \text{(Eq. 2)}$$

Eq. 3 presents the relationship between the modulus of rupture of concrete (f_r) and the specified f_{ck} as per ACI Building Code 318 (American Concrete Institute, 2014). Similarly the relationship between the tensile and the compressive strength of concrete is established as Eq. 4 by the ACI building code 318 (American Concrete Institute, 2014) expressed as follows;

$$f_{ct} = 0.56\sqrt{f_c} \qquad \text{(Eq. 3)}$$

$$f_r = 0.62\sqrt{f_c} \qquad \text{(Eq. 4)}$$

Again, as per Indian standard IS 456:2000 (Bureau of Indian Standards, 2000), the relationship between f_{cr} and f_{ck} are established as follows (Eq. 5):

$$f_{cr} = 0.7\sqrt{f_{ck}} \qquad \text{(Eq. 5)}$$

Fig. 8a presents a comparison of predicted modulus of rupture determined from compressive strength using the model developed in present study (Eq. 1) and compared with the models of ACI and IS standards to study the differences in the experimental data and code predicted. Similarly, Fig. 8b presents a comparison of predicted splitting tensile strength determined from compressive strength (Eq. 2). It may be observed from Fig. 8a that the modulus of rupture predicted from the model developed in the present study are much higher than that predicted from ACI 318 (American Concrete Institute, 2014) and IS 456:2000 (Bureau of Indian Standards, 2000) code provisions. Unlike flexural strength, an opposite trend is observed in case of tensile splitting strength (see Fig. 8b). However, predicted splitting tensile strength using the model developed in the present study are lower than the predicted values determined from the ACI 318 (American Concrete Institute, 2014) and IS 456:2000 (Bureau of Indian Standards, 2000).

Effect on Sorptivity with addition of GGBFS

Capillary action through the concrete is quantified by the mass method using concrete cylindrical specimens. After 28 days of curing, the cylindrical specimens were oven dried at 105^0C until the gain of constant weight. Capillary action was measured through a one-dimensional water flow by coating the cylinder with epoxy resins, except the top and bottom surfaces. Fig. 9 represents the cumulative amount of water per unit area (kg/m^2) in terms of square root of time in hours. It was noticed that the initial rate of absorption of GGBFS mix was quite lower than that of the control mix concrete and at 20-25% replacement of GGBFS, the rate of absorption was found to be increasing as compared to other replacement percentages. This indicates, denser concrete is formed after a certain range of GGBFS replacement.

Axial load–axial displacement behavior and failure pattern of column

The axial load resistance of the columns shows a linearly ascending load–displacement behavior until the first axial peak load is achieved (Fig. 10). It is clearly visible from Fig. 10 that, the axial stiffness of 20% GGBFS replaced columns is slightly higher that of the control mix, resulting a better load carrying capacity and sectional axial stability by reducing the lateral expansion of the section. A delay in the crack propagation of the columns replaced with GGBFS was observed as compared to the column prepared with control mix. The post peak behavior was significantly improved after adding GGBFS due to the increase in the axial stiffness. The ultimate load carrying capacity of all the specimens tested at 28 days is tabulated in the Table 6. RC columns with GGBFS replacements show a better axial strength which may be due to the effective role enhancement of the overall behavior of both the cover concrete and core concrete by arresting the micro cracks and bridging across the cracks.

Fig. 11 represents the failure pattern of all the tested column specimens. Initial cracks were formed near the end of the columns which are vertical in nature. These cracks were found to be gradually propagating through the entire height with increasing vertical load. Finally, crushing failure occurred due to the brittle nature of the specimen. It was noticed that, cover concrete spalled down in each specimen at the midsection whereas the core concrete was found to be intact. The control column was remained undamaged until 76.4 kN load applied, resulting initial crack formation (15% of the ultimate load). But in GGBFS RC column, initial cracks were appearing at 125.2 kN (20% of the ultimate load). Further increment of the load leads to an increased number of crack formations with thicker crack widths both in vertical and horizontal fashion. Vertical cracks could be related to the compression of the concrete. In addition, new flexural cracks and vertical cracks appeared on both sides of the column. At this stage, spalling of the concrete cover was also occurring on the right side of the column, which was mostly near to the mid of the length and originated from the ends. Slight buckling of the longitudinal steel bars was also observed on the right side of the column. The width of the cracks increased with the successive increment of load. Flexural cracks further penetrated towards the centre of the column. Initially observed cracks further propagated and the columns were seriously damaged due to spalling of concrete. Although the fresh concrete was packed and distributed evenly using a vibrator in order to make the concrete as homogeneous as possible, it was noticed that the appearance of cracks on the left and right side of the column observed might be slightly different. This may be because the concrete is not a homogeneous material in nature. All the cracks observed in the above tests was found to be flexural cracks and the behavior of the column seemed to be dominated by flexure only (no shear crack was observed).

Crack width and depth propagation of column

Measurement of crack width and the corresponding depth are measured through crack scope and the cross marks in Fig. 12a shows where the crack width and depth are measured. In a concrete column with GGBFS, 20 numbers of marking were considered in the measurement, whereas 12 numbers of markings are taken in case of the control mix sample. It shows that, the addition of GGBFS is responsible for causing thinner crack width and smaller crack length propagation compared to the control mix. It is confirmed from the Fig. 12b, that GGBFS can produce more toughness in concrete, which will help in reduced crack depth/width (see Fig. 13).

Flexural performance of RC slabs

Control mix and 20% GGBFS mix (replacement demonstrating the best mechanical properties compared to other replacement ratios as described in the above section) were taken into consideration for casting and testing the slab for flexure. Monotonic compressive loading was applied through a hydraulic jack in the centre of the slab which is shown Fig. 14. All the four sides of the RC slab were supported on four columns with a free edge condition (see Fig. 14).

A manual inspection was carried out during the test to quantify the appearance, position and extent of the crack and marked accordingly. It was observed that the slab with GGBFS replacement responded with more stiffness and possess higher flexural strength capacity as compared to the concrete slab with control mix. The number of cracks and its widths obtained in case of GGBFS slab was lesser and thinner than that of the control mix slab which is clearly visible from Fig. 15. It was noticed that, during the time of failure that, the GGBFS concrete slabs form a saucer-like shape where as in case of control mix concrete slab, a relatively faster progression of crushing and spalling of concrete with a minimum of plastic strain was observed. The load deflection behavior was monitored through dial gauges continuously and presented in the Fig. 16.

"As per IS 456 (Bureau of Indian Standards, 2000), the permissible deflection under working load should be less than $l_x/28$ i.e., 1220/28 = 43. However, the measured deflection at failure load for both normal concrete and GGBFS concrete are found to be less than the code permissible value. Again, the immediate deflection determined experimentally is less than the limiting immediate deflection as per ACI 318 (American Concrete Institute, 2014) i.e. span/360."

Less number of cracks having a smaller crack width and depths are mostly due to the high compressive strength and higher modulus of elasticity of GGBFS concrete. At the initial phase of loading to slabs, the deflection at the mid-span was minimum and as the load increases, successive cracks were obtained in the concrete followed by the yielding of steel. For slabs with GGBFS, a remarkable increase in deflection was recorded as compared to control mix slab. The first crack was obtained 38.57 kN and 30.2 kN for GGBFS and control mix concrete for the corresponding deflection, such as 5.60 mm and 4.64 mm respectively.

The first crack in both the cases influenced by the flexural strength of concrete and it initiated at the centre-bottom face of the slab. The deflection at the mid span increased with the successive increment of load followed by the yielding of reinforcements and beyond this point the concrete is no more taking the loads and larger cracks are formed in the bottom face of the slabs. At this stage, the. The ultimate load carrying capacity of the GGBFS concrete slab was around 12% more than control mix slab Fig. 16.

CONCLUSIONS

An extensive experimental investigation was carried out to study the mechanical properties SCC with GGBFS replacements and the structural performance, such as axial load–axial displacement and failure pattern of the column, crack width propagation and flexural behavior of reinforced slabs were studied. The key outcomes of the present study are listed below;

- It was interesting to see that, the addition GGBFS reduces the requirement of superplasticizer to maintain desired workability. This increased slump flow value with increased dose of GGBFS at a constant dose of superplasticizer is due to the inertness of the superplastisizer with the slag particles (spherical nature of slag particles which acts as a lubricant) and produce a repulsive force while the action of the superplasticizers.
- There is a significant increase in the compressive strength with the addition of GGBFS due to the pozzolanic reaction of slag with the calcium hydroxide liberated during cement hydration. Optimum increment was achieved at 20% replacement of GGBFS followed by a gradual decrease. It may be attributed to the irregularity in the matrix formation. In the meanwhile, from the current experimental study, the slag replacement for developing the desired strength of SCC can easily be predicted.
- The tensile splitting strength tends to decrease at a GGBFS replacement ratio of 10% and then found to be maximum between 10-20%. However, further addition of GGBFS results in decrease of

splitting tensile strength. The flexural strength follows a trend slightly different from that of compressive strength, but quite identical to tensile splitting strength. Based on the present experimental results, empirical relations were developed for both tensile and flexural strengths and proposed in Eq. 1 and 2.

- While investigating the capillary effect of SCC with GGBFS, it was noticed that the initial rate of absorption of GGBFS mix was quite lower than that of the control mix concrete and at 20-25% replacement of GGBFS, the rate of absorption was found to be increasing as compared to other replacement percentages. This indicates, denser concrete is formed after a certain range of GGBFS replacement.
- The axial stiffness of GGBFS RC columns are higher with better load carrying capacity and sectional axial stability. A delay in the crack propagation in the GGBFS RC columns were observed as compared to the RC control mix columns. The post peak behavior was also significantly improved after adding GGBFS due to the effective role enhancement of the overall behavior of both the cover concrete and core concrete by arresting the micro cracks and bridging across the cracks. The addition of GGBFS is responsible for causing thinner crack width and smaller crack length propagation compared to control mix.
- The GGBFS slab possesses higher stiffness and flexural strength capacity as compared to concrete slab control mix. The number of cracks and the crack widths of GGBFS slab was lesser and thinner than that of the slab with control mix. The GGBFS RC slabs delayed the progression in crushing and spalling of concrete with minimum plastic strain as compared to the control mix. A remarkable increase in deflection was recorded for GGBFS slabs as compared to control mix. The ultimate load carrying capacity of the GGBFS concrete slab was around 12% more than control mix slab.

Data Availability

b. All data, models, and code generated or used during the study appear in the submitted article.

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