Computers and Concrete, *Vol. 19, No. 1 (2017) 051-058*
DOI: https://doi.org/10.12989/cac.2017.19.1.051

Effect of GGBFS on time-dependent deflection of RC beams

M. Shariq[*1], H. Abbas[2a] and J. Prasad[3b]

[1]*Department of Civil Engineering, Aligarh Muslim University, Aligarh, India*
[2]*Chair of Research and Studies in Strengthening and Rehabilitation of Structures, Department of Civil Engineering, King Saud University, Riyadh 11421, Saudi Arabia*
[3]*Department of Civil Engineering, Indian Institute of Technology Roorkee, India*

(Received August 22, 2016, Revised October 16, 2016, Accepted October 18, 2016)

Abstract. The paper presents the experimental investigations for studying the effect of ground granulated blast furnace slag (GGBFS) on the time-dependent deflection of reinforced concrete (RC) beams due to creep and shrinkage. The RC beams were reinforced with 2-10 mm bars at tension side and subjected to constant sustained two-point loading for the period of 150 days. The amount of cement replacement by GGBFS was varied from 0 to 60% with an increment of 20%. The total deflection was measured at different ages of up to 150 days under sustained loads. The experiments revealed that the time-dependent deflection of the reinforced concrete RC beams containing GGBFS was higher than that of plain concrete RC beams. At 150 days, the average creep and shrinkage deflection of RC beams containing 20%, 40% and 60% GGBFS was 1.25, 1.45 and 1.75 times higher than the plain concrete beams. A new model, which is an extension of authors' earlier model, is proposed to incorporate the effect of GGBFS content in predicting the long-term deflection of RC beams. Besides validating the new model with the current data with higher percentage of tension reinforcement, it was also used to predict the authors' earlier data containing lesser percentage of tension reinforcement with reasonable accuracy.

Keywords: beams**;** creep: deflection; GGBFS; RC; shrinkage

1. Introduction

The estimation of time-dependent deflections due to creep and shrinkage is required for controlling delayed damage in non-structural elements and thus avoiding serviceability failures. The time-dependent response of reinforced concrete (RC) members is complex as it is significantly affected by the amounts of tensile and compressive reinforcements. The code provisions for predicting time-dependent deflections of concrete members containing different admixtures, especially the ground granulated blast furnace slag (GGBFS), are not appropriately and exhaustively covered.

The review of literature shows that the investigation of time-dependent deflection of RC beams was initiated more than five decades back (Yu and Winter 1960, Gesund 1962, Konyi 1963, Corley and Sozen 1966). Based on the experimental studies, the researchers proposed simple methods for instantaneous and long-term deflections under service loads due to shrinkage and creep effects. The shrinkage was found to be responsible for the non-coincidence of planes of zero stress and zero strain as their location was shown to depend on the concrete stress and bending moment. Branson (1971) incorporated the effect of compression steel on long-term deflection of RC beams. Bakoss *et al.* (1982) tested simply supported and continuous RC beams under sustained loads and compared measured beam deflections with different codes available at that time. Clarke *et al.* (1988) proposed a model to predict the creep deflection for cracked RC flexural member. Espion and Halleux (1990) studied the variability in the prediction of long-term deflection of RC beams. Paulson *et al.* (1991) tested high strength RC beams for long-term deflection under sustained load for one year. The test results indicated significant role of compression steel in controlling the long-term deflection of normal strength concrete beams as compared to high strength concrete beams. Li (1993) proposed the analytical solution for the long-term deflection of RC beams to fulfill the structural serviceability criterion. Ghali (1993) reviewed the code provisions for the prediction of instantaneous and long-term deflections of RC structural elements and proposed an improved method. In a later study, Ghali and Azarnejad (1999) further enhanced the analytical procedure to predict instantaneous and long-term deflections in RC members. Rosowsky *et al.* (2000) studied the effect of loading applied during the early age on the long-term deflection of RC beams and suggested a simplified model for incorporating the construction load sequence.

Zhou and Kokai (2010) proposed a procedure to calculate the long term deflection of RC flexural members. The procedure incorporates the load sequence during construction in equation provided in the Canadian standard (CSA A23.3–04). Authors highlighted the role of camber and construction load in controlling long term deflection.

∗Corresponding author, Assistant Professor
E-mail: mshariqdce@gmail.com
[a]Chair, Professor, E-mail: abbas_husain@hotmail.com
[b]Professor

http://www.techno-press.org/?journal=cac&subpage=8
ISSN: 1598-8198 (Print), 1598-818X (Online)

Table 1 Concrete mix proportion for 1 m^3 of concrete

Mix group	Mix ID	Binder (kg)		Aggregates (kg)		Water to binder ratio	Cylinder compressive strength of concrete, f_c' (MPa) (Shariq *et al.* 2010)
		Cement	GGBFS*	Fine	Coarse		
M1	M10	400	0	665	1107	0.45	36.81
	M11	320	80 (20%)	665	1107	0.45	30.77
	M12	240	160 (40%)	665	1107	0.45	28.47
	M13	160	240 (60%)	665	1107	0.45	24.16
M2	M20	350	0	680	1132	0.50	30.77
	M21	280	70 (20%)	680	1132	0.50	26.75
	M22	210	140 (40%)	680	1132	0.50	25.02
	M23	140	210 (60%)	680	1132	0.50	21.86
M3	M30	320	0	688	1145	0.55	22.43
	M31	256	64 (20%)	688	1145	0.55	19.85
	M32	192	128 (40%)	688	1145	0.55	18.69
	M33	128	192 (60%)	688	1145	0.55	15.53

*Value within brackets is the percentage replacement by weight of cement

Mari *et al.* (2010) presented a simplified model for the calculation of time-dependent deflections in RC flexural members under sustained loads. Based on the experimental observations, the model assumes constant stress in the tensile reinforcement on the time-dependent behavior of cracked sections. The model was validated with the test results available in the literature and the results of time-dependent non-linear analysis of a large number of hypothetical beams. Gilbert (2012) proposed a method for predicting the long-term deflection of RC beams and slabs caused by creep and shrinkage. The method employs the age dependent elastic modulus and tension stiffening in concrete. Visintin *et al.* (2013) proposed a moment–rotation approach to model bond slip between concrete and rebars thereby incorporating tension stiffening and avoiding the need for the empirically derived flexural rigidity. For calculating long-term deflection, crack width and crack spacing of RC beams, authors derived flexural rigidities using moment-rotation approach. Choi and Yun (2013) studied experimentally the long-term flexural deformation of RC beams containing recycled aggregate under sustained loading for 380 days. The sustained load was 50% of the nominal flexural capacity of RC beams. A modification factor was suggested for incorporating the influence of recycled aggregate in ACI 318 Code (2011) provisions for the calculation of long-term deflection. Ezeberry *et al.* (2014) showed that the method proposed by EN 1992-1-1 (2004) underestimates the tension-stiffening effects. They suggested a simple modification for incorporating the shrinkage effects in the calculation of short-term deflection.

Miàs *et al.* (2013a) tested glass fiber reinforced polymer (GFRP) RC beams under sustained service load for 250 days. The reinforcement ratios and the level of sustained load were varied. The time-dependent deflections were found to be affected by the loading–unloading cycles and the reinforcement ratio but the level of sustained load had insignificant effect. The study suggested the use of modified time-dependent factor of ACI 440.1R-06 along with the modified Bischoff's equation to compute the immediate deflections due to sustained load. In another study, Miàs *et al.* (2013b) presented the test results of twenty beams reinforced with varying amounts of GFRP and steel bars under different levels of sustained loading which was applied for a period of 250 to 700 days. The test results showed that the increase in the reinforcement ratio and decrease in the compressive strength results in higher long-term deflection. Authors proposed multiplicative coefficients to modify the elastic modulus for calculating the long-term deflection.

Tan *et al.* (1994a, b) proposed analytical models by employing age-adjusted effective modulus for predicting the immediate and long-term deflections in RC beams containing steel fibers. Buratti *et al.* (2010) tested six pre-cracked beams of fiber reinforced concrete (FRC) in flexure under sustained load for studying the long-term deflection. They used self compacting concrete containing different proportions of steel and synthetic fibers. The tests showed greatest reduction in the delayed crack opening for concrete containing a mixture of steel and macro synthetic fibers. Zerbino and Barragán (2012) tested cracked steel fiber reinforced concrete (SFRC) beams under sustained loading for 21 months. The initial flexural cracks were induced through applied load to simulate different damage levels. They introduced crack-opening rate in the calculation of long-term deflection of SFRC beams. Vasanelli *et al.* (2013) studied the influence of short fibers (steel and polyester) on the long-term behavior of RC beams. The test results revealed the positive role of polymeric and steel fibers in controlling long-term deflection, crack width and carbonation depth. Kumutha and Vishnuram (2015) carried out experiments on geopolymer composite RC beams containing different proportions of steel, polypropylene and glass fibers. Authors used ANSYS program to reasonably predict the load-deflection behavior of geopolymer composite RC beams.

Bencardino and Condello (2014, 2015) performed

Table 2 Physical properties of materials

Characteristic	Experimental value	Recommended value
	Cement	
Blaine's fineness (m^2/kg)	245	225 (Min.) (IS 4031 1999)
Specific gravity	3.15	-
Soundness (mm)	1.5	10 (Max.) (IS 4031 1999)
Compressive strength (MPa)	45.9	43.0 (IS 8112 1989)
	GGBFS	
Fineness (m^2/kg)	340	275 (Min.) (BS 6699 1992)
Specific gravity	2.86	-
Soundness (mm)	1.5	10 (Max.) (BS 6699 1992)
Normal consistency (%)		
• OPC+0% GGBFS	27.0	-
• OPC+20% GGBFS	28.5	-
• OPC+40% GGBFS	29.5	-
• OPC+60% GGBFS	31.0	-
Compressive strength of mix having 30% GGBFS (MPa)	40	32.5 (BS 6699 1992)
	Fine aggregate	
Grading	Conforming to code (IS 383 1970)	Zone-II (IS 383 1970)
Fineness modulus	2.45	-
Specific gravity	2.61	-
Density in loose state (kN/m^3)	15.4	-
Water absorption (%)	0.85	-
	Coarse aggregate	
Fineness modulus	6.8	-
Specific gravity	2.63	-
Density in loose state (kN/m^3)	14.3	-
Water absorption (%)	1.5	-
	Steel rebars	
Yield strength (MPa)	445	415 (Min.) (IS 1786 1985)
Ultimate tensile strength (MPa)	515	
Percent elongation (%)	31	14.5% (IS 1786 1985)

numerical analysis for studying the behavior of strengthened RC beams by using steel reinforced grout. The interface between the parent concrete and strengthening layer was modeled using joint element with a suitable damage model. The effects of anchorages, concrete strength and the amount of internal tensile rebars were studied. Dias *et al.* (2015) studied long-term deflection of steel-concrete composite members under service loads through finite element analysis (FEA). The creep model was based on a Kelvin chain using Dirichlet series. The interaction at the slab-beam interface was simulated through shear studs. The model was validated with experimental results of two full-scale continuous composite beams.

In a recent study, authors investigated the effect of adding GGBFS in concrete on the long-term deflection of RC beams (Shariq *et al.* 2013). The percentage of GGBFS was varied from 0 to 60% as a partial replacement of cement. The shrinkage and creep deflections were measured at different ages of up to 150 days under sustained loading. The test results revealed increase in deflections with increase in the percentage of GGBFS in concrete. A new model was proposed to predict time-dependent deflection of RC beams containing GGBFS. The above review shows that there is no other study available in accessible literature for investigating the effect of GGBFS on creep and shrinkage deflections in RC beams. The present study is an extension of authors above study (Shariq *et al.* 2013) wherein the same concrete mixes but with higher percentage of tension reinforcement in RC beams was tested. Moreover the magnitude of sustained load was also increased for investigating the effect of load level. A new and improved model is developed for predicting the long-term deflections in RC beams containing GGBFS.

2. Experimental investigation

2.1 Concrete mixes and steel rebars

2.1.1 Concrete mixes

Three groups of four concrete mixes each, thus making a total of twelve mixes, were prepared by varying the proportion of cementitious material in each group, as considered in authors' earlier studies (Shariq *et al.* 2010, 2013). The GGBFS was used as a partial replacement of cement in each group. The proportions of GGBFS were

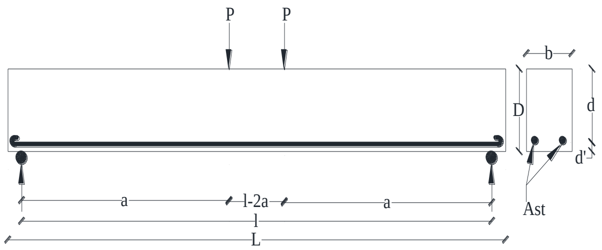

Fig. 1 Details of test specimen (b=100 mm, d=130 mm, D=150 mm, a=750 mm, l=1700 mm, L=1800 mm, $A_{st}=2\phi10$)

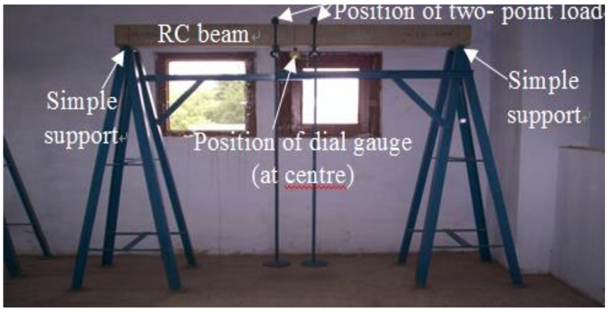

Fig. 2 Test setup for the measurement of time-dependent deflection of RC beam

Fig. 3 RC beam specimens under test

taken as 0%, 20%, 40% and 60% of cement by weight. The selection of GGBFS percentage was based on the intended application. The higher percentage of GGBFS (i.e., 60%) is suitable for applications in mass concreting whereas the lower percentages of GGBFS (i.e., 20% and 40%) are commonly used in RC and prestressed concrete. The mix design was based on the target compressive strength of plain concrete mix of the three groups (i.e., M1, M2 and M3) as 45, 35 and 25 MPa respectively. The quantity of fine aggregate in each mix was 60% of that of the coarse aggregate which was selected with the objective of maximizing the cumulative density of the aggregates. Table1 provides the proportions of constituent materials in different mixes.

The constituent materials were procured from local market. Ordinary Portland Cement 43 grade (OPC 43) was used in this study. The river sand was sieved and the content passing through 4.75 mm square sieve and retained on 150 micron sieve was used (IS 383 1970). The maximum size of crushed stone coarse aggregate was 16 mm. The physical properties of cement, fine and coarse aggregates are given in Table 2. The table shows that the materials used conformed to the relevant standard specifications, which are also listed in the table.

2.1.2 Steel rebars

The steel rebars were of thermo-mechanical treated steel. The rebars were tested as per Indian standard (IS 1786 1985) for establishing its mechanical properties, which are reported in Table 2.

2.2 Details of test specimens

Fig. 1 shows the details of the RC beam specimens used in the study. The cross-section of beams was 100×150 mm (deep). The total length of the specimens was 1800 mm whereas the effective span was 1700 mm thus leaving an overhang of 50 mm on both sides. The 8 mm diameter rebars used in the previous study (Shariq *et al.* 2013) were replaced by 10 mm diameter rebars thus increasing the percentage of tension reinforcement from 0.77% to 1.21%.

For the determination of first crack load, two RC beam specimens of each plain concrete mix (i.e., M10, M20 and M30) were prepared. For studying the time-dependent deflection, two beams specimen for each concrete mix were cast thus making a total of thirty test specimens. The beams were demoulded after 24 hours of casting and subsequently water cured for a period of 28 days. The test specimens were air dried before testing.

The RC beam specimens of plain concrete mix (i.e., M10, M20 and M30), meant for the determination of the first crack load, were tested to failure. The average ultimate loads of these specimens were 26, 23 and 18 kN, respectively, whereas the first crack loads were 14, 12 and 10 kN, respectively, which was 52.2% to 55.6% of the ultimate load. The magnitude of sustained load for the determination of creep deflection was taken as one-fourth of the first crack load. The low magnitude of sustained load was kept to keep concrete uncracked for all mixes and during the whole duration of the study.

2.3 Test setup and testing procedure

For the measurement of time-dependent deflection, the beams were subjected to two sustained point loads, 200 mm apart, placed symmetrically on beam span (Fig. 1). The load on the beam was applied at 28 days using concrete and steel blocks. The test setup for the measurement of time-dependent deflection due to creep and shrinkage is shown in Fig. 2. Fig. 3 shows beams loaded with sustained loads during the test. The mid-span deflection of beams was measured using a dial gauge with a least count of 0.01 mm.

The alignment of the beam specimens during the test was properly maintained. The tests were performed at room temperature of 27±2°C and relative humidity of 60-65%. The instantaneous deflection was recorded soon after the application of sustained point loads. The subsequent measurements of beam deflection were taken at 1, 3, 7, 14, 21, 30, 60, 90, 120 and 150 days after the application of loads. There was no sign of cracking under the sustained loading throughout the duration of the test.

3. Results and dıscussıon

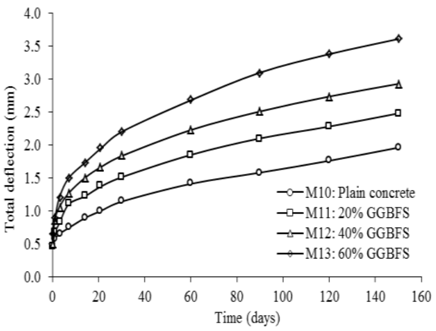

Fig. 4 Mid-span deflection of RC beams of mix group M1

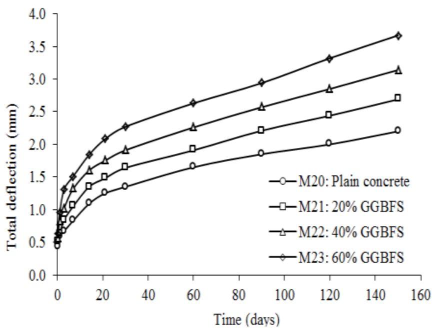

Fig. 5 Mid-span deflection of RC beams of mix group M2

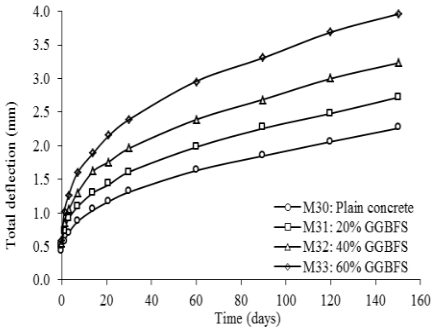

Fig. 6 Mid-span deflection of RC beams of mix group M3

Table 3 Contribution of time-dependent deflection in total deflection of RC Beams (%)

Mix group	Mix ID	GGBFS content (%)	Contribution of time-dependent deflection in total deflection (%) with age (days)									
			1	3	7	14	21	30	60	90	120	150
M1	M10	0	21	31	39	49	55	61	68	72	74	77
	M11	20	30	44	44	58	62	66	70	75	78	82
	M12	40	43	53	61	67	70	73	78	80	82	83
	M13	60	28	47	57	63	67	71	76	79	81	82
M2	M20	0	27	36	48	61	66	68	74	77	79	80
	M21	20	21	41	52	63	66	70	74	77	80	81
	M22	40	31	45	58	65	68	71	75	78	80	82
	M23	60	34	52	58	66	70	72	76	74	81	83
M3	M30	0	23	37	49	58	62	66	73	76	79	81
	M31	20	30	44	53	61	64	68	74	77	79	81
	M32	40	35	46	57	65	68	71	77	79	81	83
	M33	60	41	52	63	68	72	75	80	82	83	85

3.1 Time-dependent deflection of RC beams

Figs. 4 to 6 show the variation of the total time-dependent deflection of the mid-span of RC beams with time. The total deflection is the sum of initial elastic deflection and the time-dependent creep and shrinkage deflections. It is seen from the figures that the rate of increase in deflection for all mixes is more during the early age of about one month and the increase in later ages is at a slower rate. The addition of GGBFS is found to enhance the total deflection of beams. At the age of 150 days after loading, the total deflection of beams containing 20%, 40% and 60% of GGBFS is about 1.25, 1.45 and 1.75 times the deflection of corresponding plain concrete beams (i.e., no GGBFS) for the three concrete mix groups respectively.

At 150 days, 75% of the total deflection of RC beams occurs within 60 days of loading for all plain concrete and 20% GGBFS mixes of the three mix groups (i.e., M10, M11, M20, M21, M30 and M31). Whereas for 40% GGBFS concrete mixes (i.e., M12, M22 and M32), 75% of the total deflection of RC beams at 150 days occurs within 90, 60 and 60 days for mix groups 1, 2 and 3 respectively. On the other hand, for the beams containing 60% GGBFS (i.e., M13, M23 and M33), 75% of the total deflection of RC beams at 150 days occurs within 90 days of loading for the three mix groups.

A comparison of the rate of growth of total deflection of RC beams with age indicates that it is slightly more in RC beams containing GGBFS as compared to the plain concrete mixes. For plain concrete mixes of the three groups (i.e., M10, M20 and M30), the average increase in the total deflection of RC beams from 30 to 150 days is 59.2%. Whereas, for RC beams containing 20%, 40% and 60% GGBFS of three mix groups, the average increase in total deflection from 28 to 150 days is 65.7% (i.e., average of M11, M21 and M31), 63.0% (i.e., average of M12, M22 and M32) and 63.8% (i.e., average of M13, M23 and M33) respectively. Thus the increase in deflection with age during the period from 30 to 150 days is slightly more for higher GGBFS content. This is mainly because of the application of sustained load before attaining maturity in GGBFS concrete as the addition of GGBFS delays the process of hydration (Shariq *et al.* 2010). The trend of increase in total deflection at the end of the study period (i.e., 150 days) shows that the deflection is still showing increasing trend. Thus the longer period of sustained loads would result in still higher deflections.

From the above observations, it has been found that the total deflection increases with the GGBFS content in concrete. The ratio of total deflection at a particular age to the initial elastic deflection increases with the increase in the quantity of GGBFS. This may be because of the variations in the constituents of concrete such as composition and volume of paste in concrete, compressive strength of concrete at 30 days, magnitude of sustained load and the age at the time of loading. It is worth noting that the addition of GGBFS in concrete mix increases the volume of paste and reduces the 28 days compressive strength because of the delay in the process of hydration (Shariq *et al.* 2010). These are the major contributors responsible for increasing

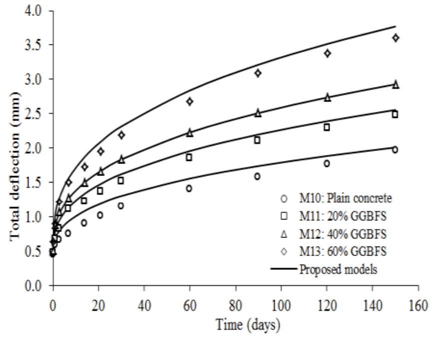

Fig. 7 Comparison between predicted and experimental total deflection for mix group M1

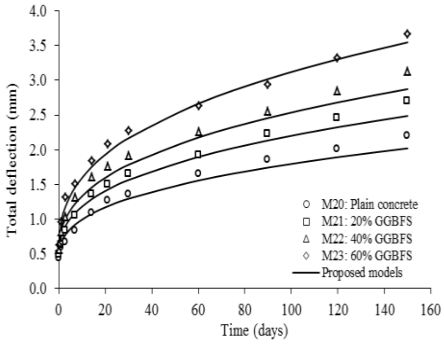

Fig. 8 Comparison between predicted and experimental total deflection for mix group M2

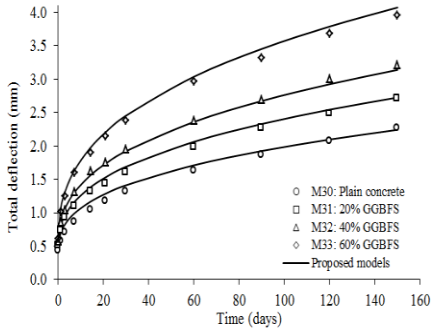

Fig. 9 Comparison between predicted and experimental total deflection for mix group M3

the total deflection in GGBFS based concrete beams. As the present study is restricted to low magnitude of sustained loads, which was only 25% of the first crack load for keeping the entire beam section uncracked, therefore further studies are required to study the effect of the magnitude of sustained loads.

3.2 Contribution of time-dependent deflection in total deflection

The total deflection of RC beams at a particular age is the sum of the initial elastic deflection and a time dependent component due to shrinkage and creep of concrete. The contribution of time-dependent deflection due to shrinkage and creep in total deflection of RC beams at different ages of concrete is given in Table 3.

It is observed from Table 3 that the increase in the GGBFS content causes small increase in the contribution of time-dependent deflection in total deflection. The average value of the contribution of time-dependent deflection of RC beams of plain concrete at 150 days is 79.3% of the total deflection. This percentage of the contribution of time-dependent deflection in total deflection of RC beams at 150 days gets increased to 80%-85% for concrete containing GGBFS. At 30 days, the contribution of time-dependent deflection in total deflection for plain concrete RC beams is more than 50% of the total deflection at 150 days. The incorporation of GGBFS in concrete causes small change in this percentage as it varies from 45% to 52% for RC beams containing GGBFS.

4. Model for the prediction of total time-dependent deflection

The aforementioned review of literature highlighted the need of a new model for predicting the time-dependent deflection of RC beams containing GGBFS. Moreover, the long-term deflection formula available in different codes and guidelines are silent about the influence of GGBFS mainly because of the paucity of research in this area. Thus a new model, which is an extension of authors' earlier model (Shariq *et al.* 2013), is proposed to account for the presence of GGBFS in concrete mix. The new model is more rational as it replaces the parameter K of the earlier model, which was simply based on the statistical fitting, by making it dependent on the compressive strength of concrete. Moreover, besides validating the new model with the current data with higher percentage of tension reinforcement, it has also been shown later to predict the authors' earlier data with reasonable accuracy. For predicting the total time-dependent deflection, the following model is used

$$\delta_t = \left[1 + \frac{C_1 f_c^{'C_2} t^{C_3} e^{C_4 p_s}}{C_5 + C_6 t^{C_3}}\right]\delta_i \tag{1}$$

Where, δ_t is total deflection in mm, t is time or age in days; $f_c^{'}$ is the cylinder compressive strength of concrete in MPa; p_s is the percentage of GGBFS content by weight of cement, δ_i is initial or instantaneous deflection in mm, C_1, C_2, C_3, C_4, C_5 and C_6 are the model parameters. The total time-dependent deflection, given by the above equation, includes instantaneous, creep and shrinkage deflections. The model parameters were derived based on multiple variable regression analysis of the test data, thus giving

$$\delta_t = \left[1 + \frac{80 t^{0.38} e^{0.5 p_s}}{\sqrt{f_c^{'}}\left(24 + 0.1 t^{0.38}\right)}\right]\delta_i \tag{2}$$

Besides the age (i.e., time t), the above equation indicates the dependence of total time-dependent deflection on the compressive strength of concrete and the percentage of GGBFS as partial replacement of cement. Because of the limited range of GGBFS percentage used in these studies, the proposed model may be used for GGBFS percentage of up to 60%.

The instantaneous deflection, required in Eq. (1), is the elastic deflection of RC beam that can be calculated based on the applied loads. For the two point loads considered in the experiments of this study, the initial elastic deflection before cracking can be calculated using

$$\delta_i = \frac{Pa}{24 E_c I_g}\left(3l^2 - 4a^2\right) \tag{3}$$

Where, l is the effective span of the beam (=1700 mm), P is the magnitude of external point loads (Fig. 1), a is the shear span (=750 mm), E_c=4700$\sqrt{f_c^{'}}$ is the elastic

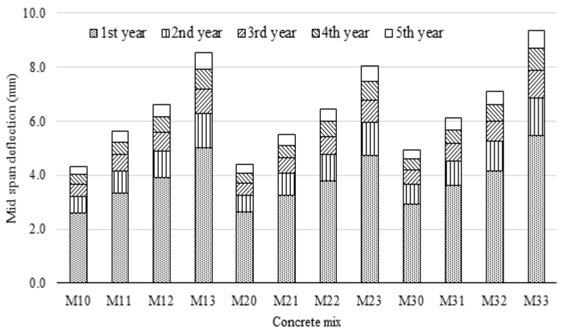

Fig. 10 Year-wise growth of deflection predicted by the proposed model

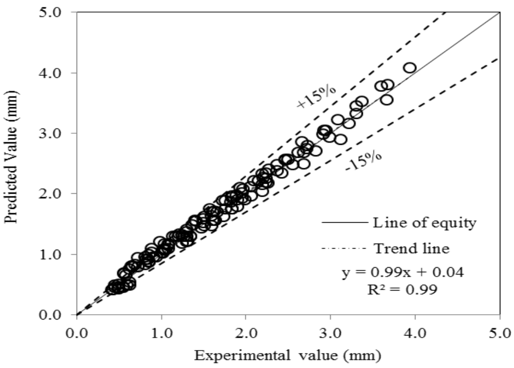

Fig. 11 Comparison between predicted and experimental total deflection for all data points of the present study

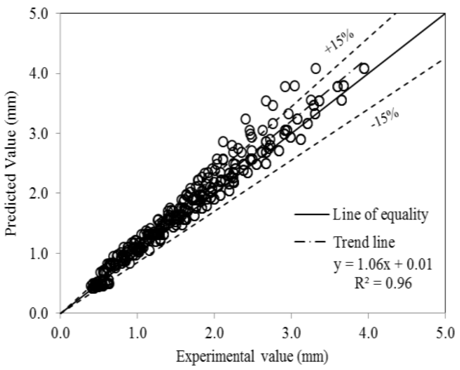

Fig. 12 Comparison between predicted and experimental total deflection for all data points including the data of previous study (Shariq *et al.* 2013)

modulus of concrete according to ACI 318 code (2011) and I_g is the gross moment of inertia of RC beam section.

Figs. 7 to 9 show the variation of predicted total deflection with age using the proposed model given by Eq. (2). The experimental data is also plotted in these figures. A comparison of the trend of increase in total deflection with age obtained from the predicted model indicates a good correlation for all mixes.

Although the validation of the proposed model in Figs. 7 to 9 has been shown up to 150 days, the duration of the experimental study, but the model predictions for longer duration of up to five years are shown in Fig. 10. It is observed from the figure that the year-wise prediction of mid-span deflection of tested RC beams is reducing with the passage of time. The average increment in second year, as a percentage of first year, is 25% which reduces to 12% in the fifth year.

Fig. 11 shows a comparison between the experimental and predicted total deflection of RC beams. It is observed that 87% of the data points lie within an error band of ±15%. The R^2 value of 0.99 also indicates a good correlation. The validity of the proposed model is further verified by including authors' previous data for lesser percentage of tension reinforcement along with the current data in Fig. 12. The R^2 value of 0.96 and high percentage of data point (70%) lying within ±15% error band further confirms the potential of the proposed equation in experimental study, but the model predictions for longer duration of up to five years are shown in Fig. 10. It is observed from the figure that the year-wise prediction of mid-span deflection of tested RC beams is reducing with the passage of time. The average increment in second year, predicting long-term deflection of RC beam containing GGBFS.

5. Conclusions

The long-term flexural deflections of structural elements occurring due to creep and shrinkage in concrete are important for maintaining serviceability and thus the prediction of time-dependent deflection is of great significance. In the present study, singly reinforced concrete beams containing GGBFS were tested under the action of two sustained point loads for a period of 150 days. Three percentages (20%, 40% and 60%) of cement replacement by GGBFS were used. Major conclusions derived from the study are given in the following:

• Experiments revealed that the RC beams containing GGBFS undergo higher deflection than the plain concrete beams. Typically, time-dependent deflections of RC beams containing 20%, 40% and 60% GGBFS are 1.25, 1.45 and 1.75 times higher than those of the plain concrete beams over a period of 150 days of sustained loading.

• The increasing trend of total deflection at the end of the study period (i.e., 150 days) indicates that the longer period of sustained loads would result in still higher deflections.

• As the present study is restricted to low magnitude of sustained loads, which was only 25% of the first crack load, keeping uncracked section of the beams, therefore further studies are required to study the effect of the higher magnitude of sustained loads which cause cracking of concrete.

• A new model, which is an extension of authors' earlier model, is proposed to account for the presence of GGBFS content in predicting the long-term deflection of RC beam. Besides validating the new model with the current data with higher percentage of tension reinforcement, it was also used to predict the authors' earlier data containing lesser percentage of tension reinforcement with reasonable accuracy.

References

ACI 318 (2011), *Building Codes Requirements for Structural Concrete and Commentary*, ACI, Farmington Hills, Michigan, USA, ACI Committee 318.

ACI 440.1R (2006), *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*, ACI, Farmington Hills, Michigan, USA, ACI Committee 440.

Bakoss, S.L., Gilbert, R.I., Faulkes, K.A. and Pulmano, V.A. (1982), "Long-term deflections of reinforced concrete beams", *Mag. Concrete Res.*, **34**(121), 203-212.

Bencardino, F. and Condello, A. (2014), "Experimental study and numerical investigation of behavior of RC beams strengthened with steel reinforced grout", *Comput. Concrete*, **14**(6), 411-425.

Bencardino, F. and Condello, A. (2015), "SRG/SRP-concrete bond-slip laws for externally strengthened RC beams", *Compos. Struct.*, **132**, 804-815.

Branson, D.E. (1971), "Compression steel effect on long-time deflection", *ACI J.*, **68**(8), 555-559.

BS 6699 (1992), *Specification for Ground Granulated Blast Furnace Slag for Use with Portland Cement*, British Standard Institution, London, UK.

Buratti, N., Mazzotti, C. and Savoia, M. (2010), "Long-term behaviour of fiber-reinforced self-compacting concrete beams", *Des. Product. Placem. Self-Consolid. Concrete*, RILEM, **1**, 439-450.

Choi, W. and Yun, H. (2013), "Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate", *Mater. Des.*, **51**, 742-750.

Clarke, G., Scholz, H. and Alexander, M. (1988), "New method to predict the creep deflection of cracked reinforced concrete flexural members", *ACI Mater. J.*, **85**(2), 95-101.

Corley, W.G. and Sozen, M.A. (1966), "Time-dependent deflection of reinforced concrete beams", *ACI J.*, **63**(3), 373-386.

CSA A23.3-04 (2004), *Canadian Standard Association Design of Concrete Structures*, Ontario, Canada.

Dias, M.M., Tamayo, J.L.P., Morsch, I.B. and Awruch, A.M. (2015), "Time dependent finite element analysis of steel-concrete composite beams considering partial interaction", *Comput. Concrete*, **15**(4), 687-707.

EN 1992-1-1 (2004), *European Standard Eurocode 2: Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings*, Brussels.

Espion, B. and Halleux, P. (1990), "Long-term deflections of reinforced concrete beams: Reconsideration of their variability", *ACI Struct. J.*, **87**(2), 232-236.

Ezeberry, P.J., Corres, P.H., Viktor, G. and Perez, C.A. (2014), "Investigating deformations of RC beams: Experimental and analytical study", *Comput. Concrete*, **13**(6), 799-827.

Gesund, H. (1962), "Shrinkage and creep influence on deflections and moments of reinforced concrete beams", *ACI J.*, **59**(5), 687-704.

Ghali, A. (1993), "Deflection of reinforced concrete members: A critical review", *ACI Struct. J.*, **90**(4), 364-373.

Ghali, A. and Azarnejad, A. (1999), "Deflection prediction of members of any concrete strength", *ACI Struct. J.*, **96**(5), 807-816.

Gilbert, R.I. (2012), "Creep and shrinkage induced deflections in RC beams and slabs", *ACI Spec. Publ.*, **284**, 1-16.

IS 1786 (1985), *Indian Standard Specification for High Strength Deformed Steel Bars and Wires for Concrete Reinforcement*, Bureau of Indian Standard, New Delhi, India.

IS 383 (1970), *Indian Standard Specification for Coarse and Fine Aggregate from Natural Sources for Concrete*, Bureau of Indian Standard, New Delhi, India.

IS 4031 (1999), *Indian Standard Methods of Physical Tests for Hydraulic Cement (Part 1 to 15)*, Bureau of Indian Standard, New Delhi, India.

IS 8112 (1989), *Indian Standard Ordinary Portland Cement, 43 Grade-Specification*, Bureau of Indian Standard, New Delhi, India.

Konyi, K.H. (1963), "Tests on beams with sustained loading", *Mag. Concrete Res.*, **15**(43), 3-14.

Kumutha, R. and Vishnuram, B.G. (2015), "Flexural behaviour of fibre reinforced geopolymer concrete composite beams", *Comput. Concrete*, **15**(3), 437-459.

Li, C.Q. (1993), "Time-dependent structural serviceability analysis of concrete structures", *ACI Struct. J.*, **90**(2), 204-209.

Mari, A.R., Bairan, J.R. and Duarte, N. (2010), "Long-term deflections in cracked reinforced concrete flexural members", *Eng. Struct.*, **32**(3), 829-842.

Miàs, C., Torres, L., Turon, A. and Barris, C. (2013a), "Experimental study of immediate and time-dependent deflections of GFRP reinforced concrete beams", *Compos. Struct.*, **96**, 279-285.

Miàs, C., Torres, L., Turon, A. and Sharaky, I.A. (2013b), "Effect of material properties on long-term deflections of GFRP reinforced concrete beams", *Const. Build. Mater.*, **41**, 99-108.

Paulson, K.A., Nilson, A.H. and Hover, K.C. (1991), "Long-term deflection of high-strength concrete beams", *ACI Mater. J.*, **88**(2), 197-206.

Rosowsky, D.V., Stewart, M.G. and Khor, E.H. (2000), "Early-aged loading and long-term deflections of reinforced concrete beams", *ACI Struct. J.*, **97**(3), 517-524.

Shariq, M. Prasad, J. and Abbas, H. (2013), "Long-term deflection of RC beams containing GGBFS", *Constr. Build. Mater.*, **65**(24), 1441-1462.

Shariq, M. Prasad, J. and Masood, A. (2010), "Effect of GGBFS on time dependent compressive strength of concrete", *Constr. Build. Mater.*, **24**, 1469-1478.

Tan, K.H., Paramasivam, P. and Tan, K.C. (1994a), "Instantaneous and long-term deflections of steel fiber reinforced concrete beams", *ACI Struct. J.*, **91**(4), 384-393.

Tan, K.H., Paramasivam, P. and Tan, K.C. (1994b), "Creep and shrinkage deflections of RC beams with steel fibers", *ASCE J. Mater. Civil Eng.*, **6**(4), 474-494.

Vasanelli, E., Micelli, F., Aiello, M.A. and Plizzari, G. (2013), "Long term behavior of FRC flexural beams under sustained load", *Eng. Struct.*, **56**, 1858-1867.

Visintin, P., Oehlers, D.J. and Haskett, M. (2013), "Partial-interaction time dependent behaviour of reinforced concrete beams", *Eng. Struct.*, **49**, 408-420.

Yu, W.W. and Winter, G. (1960), "Instantaneous and long-term deflections of reinforced concrete beams under working loads", *ACI J.*, **57**(7), 29-50.

Zerbino, R.L. and Barragán, B.E. (2012), "Long-term behavior of cracked steel fiber-reinforced concrete beams under sustained loading", *ACI Mater. J.*, **109**(2), 215-224.

Zhou, W. and Kokai, T. (2010), "Deflection calculation and control for reinforced concrete flexural members", *J. Civil Eng.*, **37**(1), 131-134.

CC