Computers and Concrete, *Vol. 23, No. 2 (2019) 133-143*
DOI: https://doi.org/10.12989/cac.2019.23.2.133

Effect of ground granulated blast furnace slag on time-dependent tensile strength of concrete

M. Shariq[*1] and J. Prasad[2a]

[1]*Department of Civil Engineering, Aligarh Muslim University, Aligarh, India*
[2]*Department of Civil Engineering, Indian Institute of Technology Roorkee, India*

(Received May 8, 2018, Revised February 21, 2019, Accepted February 28, 2019)

Abstract. The paper presents the experimental investigations into the effect of ground granulated blast furnace slag (GGBFS) on the time-dependent tensile strength of concrete. The splitting and flexural tensile strength of concrete was determined at the ages of 3, 7, 28, 56, 90, 150 and 180 days using the cylindrical and prism specimens respectively for plain and GGBFS concrete. The amount of cement replacement by GGBFS was 0%, 40% and 60% on the weight basis. The maximum curing age was kept as 28 days. The results showed that the splitting and flexural tensile strength of concrete containing GGBFS has been found lower than the plain concrete at all ages and for all mixes. The tensile strength of 40 percent replacement has been found higher than the 60 percent at all ages and for all mixes. The rate of gain of splitting and flexural tensile strength of 40 percent GGBFS concrete is found higher than the plain concrete and 60 percent GGBFS concrete at the ages varying from 28 to 180 days. The experimental results of time-dependent tensile strength of concrete are compared with the available models. New models for the prediction of time-dependent splitting and flexural tensile strength of concrete containing GGBFS are proposed. The present experimental and analytical study will be helpful for the designers to know the time-dependent tensile properties of GGBFS concrete to meet the design requirements of liquid retaining reinforced and pre-stressed concrete structures.

Keywords: concrete; GGBFS; time-dependent; tensile strength; curing age

1. Introduction

The tensile strength of concrete is profound bearing on the performance of reinforced and pre-stressed concrete structures. In reinforced concrete structures, it is used to determine the deflection and minimum flexural reinforcement to control the cracking. In pre-stressed concrete structures, it prevents cracking in pre-stressed concrete members under permanent loading especially in segmental pre-stressed concrete bridges. Thus, the tensile strength of concrete plays important role for knowing the above properties of concrete structures (Legeron and Paultre 2000). In the recent years, the use of ground granulated blast furnace slag (GGBFS) in concrete as a mineral addition has gaining popularity. The use of GGBFS in concrete as partial replacement of cement serves dual purpose of imparting high resistance to chemical attack in marine environment as well as substantially reducing the heat of hydration in mass concreting structures and concrete pavements. The prevention and control of early age cracking (3 to 28 days) in mass concrete structures such as dams and concrete pavements is essential and it is necessary to study the tensile properties of such changing concrete. The past studies revealed that the tensile strength of concrete was influenced with the size of specimens, types of concrete and its compositions, curing conditions and testing methodology (Clayton 1990, Khan *et al*. 1996, Parra *et al*. 2011, Zhang and Zhao 2012, Zhao *et al*. 2017, Zhou *et al*. 1998). Based on the experimental results, the statistical and the time-dependent correlations between the splitting and flexural tensile strength with compressive strength of normal and high strength concrete have been proposed by (Arioglu *et al*. 2006, Behnood *et al*. 2015, Larrard and Malier 1992, Legeron and Paultre 2000, Oluokun *et al*. 1991, Oluokun 1991, Saridemir 2011, Xiao and Liu 2016, Zain *et al*. 2002).

However, the experimental studies on the tensile strength of GGBFS concrete are limited. It was observed that at the age of seven days or beyond, the modulus of rupture of GGBFS based concrete was higher than that of the plain concrete (Malhotra 1987). The modulus of rupture of concrete under different curing regimes was observed by (Swamy and Boukini 1990) and concluded that, after 7 days curing, the 50% and 65% slag concrete showed loss in modulus of rupture. The relationship between the compressive strength, the splitting tensile strength and the flexural tensile strength of high strength concrete made by using various types of mineral admixtures was observed by (Wee *et al*. 1995). It was revealed that the ratio of splitting tensile to compressive strength was independent on the type of mineral admixtures used. It was also observed that the ratio of flexural strength to compressive strength was dependent on the type of mineral admixtures used. The experimental data on the tensile strength of concrete with different grade of GGBFS was also reported by (ACI

∗Corresponding author, Assistant Professor
E-mail: mshariqdce@gmail.com
[a]Associate Professor
E-mail: jp746fce@gmail.com

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

committee 233 2000). It was concluded that the modulus of rupture of GGBFS concrete reduced at early ages and increased at later ages with higher grade of GGBFS. Further, the modulus of rupture was reduced at all ages with lower grade of GGBFS. The effect of GGBFS and SiO2 nanoparticles on the splitting tensile strength of concrete was investigated by Nazari and Riahi (2011a). They concluded that the GGBFS was found to improve the physical and the mechanical properties of concrete at later ages. It was also concluded that the splitting tensile strength of concrete containing GGBFS was reduced with increased in the SiO2 nanoparticles content in concrete. Ramadoss and Nagamani (2006) examined the tensile strength of high performance fibre reinforced concrete. The experimental results were compared with the available models and the relationship between flexural and splitting tensile strength was proposed. Nazari and Riahi (2011b) investigated that the modulus of rupture of concrete containing GGBFS was reduced with increased in the ZnO2 nanoparticles content in concrete. Kim *et al*. (2013) examined the flexural and splitting tensile strength of jute fibre concrete and found that the jute fibre can easily be used in normal strength and high-fluidity concrete. The jute fibre high-fluidity concrete showed better tensile strength than the normal strength concrete. Patra and Mukharjee (2016) conducted a literature survey on fresh and hardened properties of GGBFS concrete. They concluded that in some investigations, the tensile strength of GGBFS concrete increased with increase in the GGBFS content up to 40%, but in some other investigations, it was observed that the tensile strength decreased with increase in GGBFS content. Venkatesan and Pazhani (2016) investigated the effect of curing temperature on the mechanical properties of geopolymer concrete prepared with GGBFS and black rice husk ash. The experimental results showed that with increase in curing temperature, the strength of geopolymer concrete was also increased. Patra and Mukharjee (2017) determined the splitting and flexural tensile strength of concrete containing 20%, 40% and 60% GGBFS at the ages of 7, 28 and 90 days. They observed enhancement in tensile strength of concrete with the addition of GGBFS. Chougule *et al*. (2018) revealed that the splitting and flexural tensile strength of 50% GGBFS concrete cured under lime water was found higher than water curing. Yuan *et al*. (2018) also concluded that the 28-day flexural strength of 60% GGBFS concrete after steam curing was found higher than the ordinary cement concrete. Majhi *et al*. (2018) examined that the splitting and flexural tensile strength of recycled aggregate (50%) concrete containing 40% GGBFS was comparable with normal strength concrete. Aliabdo *et al*. (2019) concluded that the tensile strength of GGBFS concrete can be enhanced by increasing the sodium hydroxide molarity and sodium hydroxide to sodium silicate mass ratio.

Tutmez (2009) developed a fuzzy model for the prediction of splitting tensile strength of high performance concrete. It was concluded that the fuzzy model is more accurate than the other available models. Roth *et al*. (2010) investigated the flexural and tensile properties of glass fibre reinforced ultra-high strength concrete. The experimental results were compared with the numerical analysis and developed a relationship between tension failure and flexural behavior of the concrete. The multivariable regression analysis was conducted by (Atici 2011) to predict the compressive strength of concrete containing blast furnace slag and fly ash. The results were compared with the artificial neural network and multivariable regression analysis. It was found that the multivariable regression analysis was more accurate in predicting the compressive strength of concrete. Mazloom and Yoosefi (2013) predicted the indirect tensile strength of self compacting concrete using artificial neural networks. Experiments were conducted to determine the flexural tensile strength of self-compacting concrete with different water-cement ratio and binder contents. It was concluded that the multi layer perceptron networks can predict the tensile strength of concrete in all conditions. Gulbandilar and Kocak (2016) also developed an artificial neural network and Adaptive Network-based Fuzzy Inference Systems models for the prediction of tensile strength of cement mortars containing GGBFS and found good agreement with experiments. Saridemir (2016) carried out the empirical modeling by using GEP to predict the flexural and splitting tensile strength of fly ash based concrete. Experimental data was used to validate the empirical models and found good prediction.

Literature revealed that the more experimental data are required pertaining to the tensile strength of GGBFS concrete. Further, the design codes of different countries are considering either splitting tensile strength or flexural tensile strength of concrete in the design. Therefore, keeping in view, the importance of tensile strength of GGBFS concrete for reinforced, pre-stressed and mass concrete structures and limited data on the time-dependent tensile strength of GGBFS concrete, in the present study, experiments were conducted to determine the time-dependent splitting and modulus of rupture or flexural tensile strength of concrete containing GGBFS as partial replacement of cement. Based on the experimental results, models for the prediction of time-dependent splitting and flexural tensile strength of GGBFS concrete are proposed. The present study is helpful for the designers in controlling cracking and computing deflection in the pre-stressed, reinforced and mass concrete structures when GGBFS is used as a constituent of concrete.

2. Experimental investigation

2.1 Materials properties

Ordinary Portland cement (OPC) 43 grade was used in this study. The physical properties of cement are given in Table 1. The properties of cement were determined as per (IS 4031 1988) and (IS 8112 1989). The GGBFS used in the present study was procured from the Indorama cement industry, Raipur, Maharashtra, India. The physical properties of GGBFS are also given in Table 1 confirming with (IS 12089 1999).

The locally available river sand passing through IS sieve

Table 1 Physical properties of OPC and GGBFS

Characteristics	OPC	GGBFS
Blaine's fineness (m^2/kg)	245	340
Specific gravity	3.15	2.86
Soundness (mm) (By Le Chatelier test)	1.5	1.5
Normal consistency (Percent by weight of cement)		
OPC + 0% GGBFS	27.0	-
OPC + 40% GGBFS	-	29.5
OPC + 60% GGBFS	-	31.0
Setting time (minutes)		
(i) Initial	105	150
(ii) Finall	180	309
Compressive strength (MPa)		
(i) 3 days	24.9	-
(ii) 7 days	34.4	25
(iii) 28 days	45.9	40

Table 2 Physical properties of materials

Characteristic	Fine aggregate	Coarse aggregate
Grading	Zone-II of (IS 383,1970)	-
Fineness modulus	2.45	6.8
Specific gravity	2.61	2.63
Density (Loose) (kN/m^3)	15.4	14.3
Water absorption (%)	0.85	1.5

of aperture 4.75 mm square and retained on IS sieve of 150 micron size was used as fine aggregate as recommended by (IS 383 2002). The physical properties of the fine aggregate are given in Table 2. The locally available crushed stone aggregate of maximum nominal size of 16 mm was used as coarse aggregate. The physical properties of the coarse aggregate as recommended by (IS 383 2002) are also given in Table 2. In the present study, the potable water was used for mixing and curing which was free from the injurious amount of the deleterious materials as prescribed by (IS 456 2000).

2.2 Concrete mixture proportions

Three plain concrete mixes designated as M10, M20 and M30 with the cylinder compressive strength of 36.8, 30.7 and 22.4 MPa respectively were prepared as per the guidelines of (IS 10620 2009). In all the concrete mixes, the ratio of fine to coarse aggregate was kept constant as 0.6 from the consideration of the maximum density of combined aggregate. Ten cylinders of 150 mm diameter and 300 mm height for each mix were cast for all the trial mixes. After 7 and 28 days of water curing of the plain concrete trial mixes, five specimens from each mix were tested under compression for deciding the mix proportions of plain concrete. The details of the plain concrete mixes and the properties are given in Table 3.

The GGBFS concrete mixes were prepared after re-proportioning of the plain concrete mixes. The fine to coarse aggregate ratio was kept constant throughout the investigation of mix proportioning of GGBFS concrete. The cement content used in the plain concrete mixes was directly replaced by the equal weights of 40% and 60% of GGBFS to obtain corresponding GGBFS concrete mixes. Thus, three mix group of concrete containing nine plain and GGBFS concrete mixes were designed. The range of variation of GGBFS content was based on the consideration that the replacement of 40% GGBFS may be useful for reinforced cement concrete and pre-stressed concrete works, whereas, 60% GGBFS replacement may be used for mass concrete works. The water to binder ratio for each mix group was also kept constant. The details of GGBFS concrete mixes and the properties are also given in the Table 3.

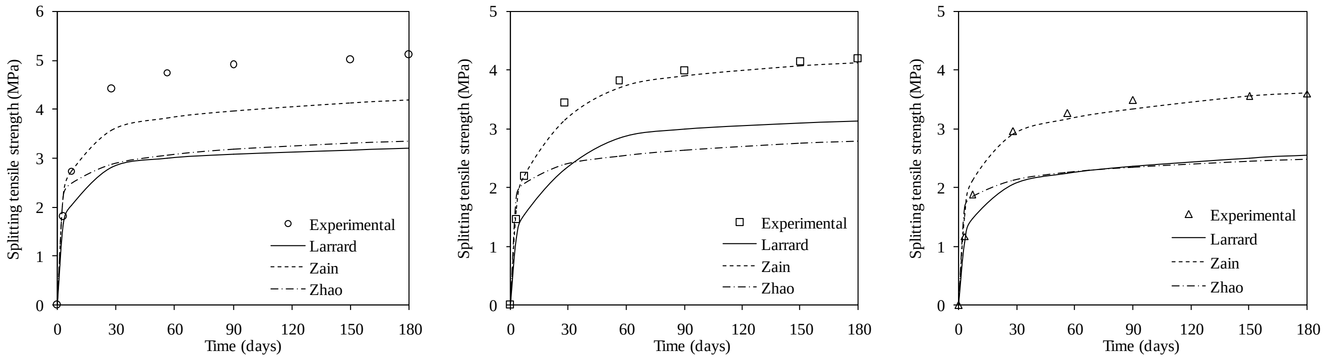
2.3 Casting, curing and testing procedure

Cylindrical specimens of 150 mm diameter and 300 mm long were prepared for the measurement of splitting tensile strength of concretes and prism specimens of 100×100×500 mm were prepared for the measurement of flexural tensile strength of concretes. After 24 hours, the specimens were demoulded and cured under water or submerged condition for 3, 7 and 28 days. To find the early age splitting and flexural tensile strength, the tests were carried out on the surface dry condition after 3 and 7 days of curing of the specimens. After 28 days curing, specimens were taken out from the water curing tank and five specimens from each

Table 3 Concrete mix proportioning

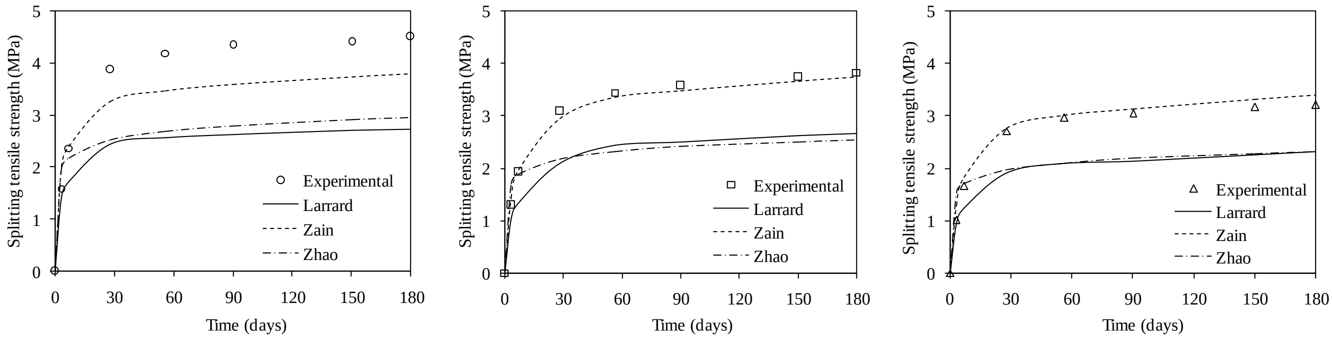
Mix group	Mix ID	Direct replacement of GGBFS (%)	Cement (kg/m^3)	GGBFS (kg/m^3)	*FA* (kg/m^3)	*CA* (kg/m^3)	*w/b* ratio	Slump (mm)	CF	28-day cylinder compressive strength of concrete (MPa) (Shariq *et al.* 2010)
M1	M10	0	400	0	665	1107	0.45	41	0.90	36.81
	M11	40	240	160				49	0.92	28.47
	M12	60	160	240				51	0.91	24.16
M2	M20	0	350	0	680	1132	0.50	46	0.91	30.77
	M21	40	210	140				51	0.92	25.02
	M22	60	140	210				54	0.90	21.86
M3	M30	0	320	0	688	1145	0.55	51	0.92	22.43
	M31	40	192	128				59	0.95	18.69
	M32	60	128	192				61	0.96	15.53

* FA = Fine aggregate; CA = Coarse aggregate; w/b = water to binder ratio; CF = Compaction factor



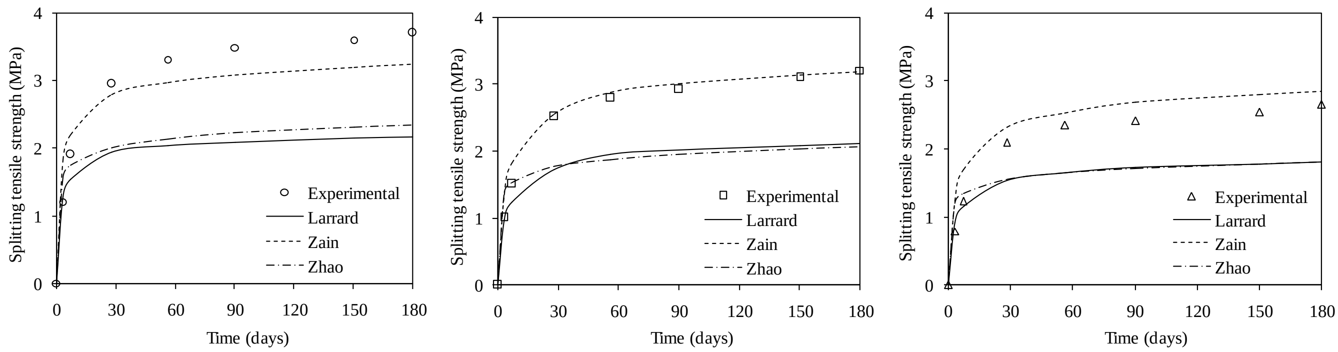
(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 1 Development of splitting tensile strength of concrete with age for mix group M1



(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 2 Development of splitting tensile strength of concrete with age for mix group M2

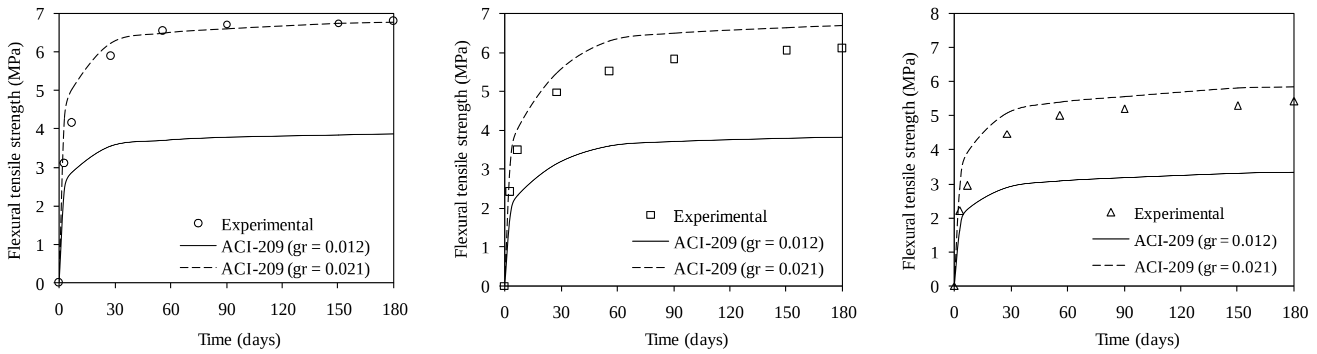


(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 3 Development of splitting tensile strength of concrete with age for mix group M3

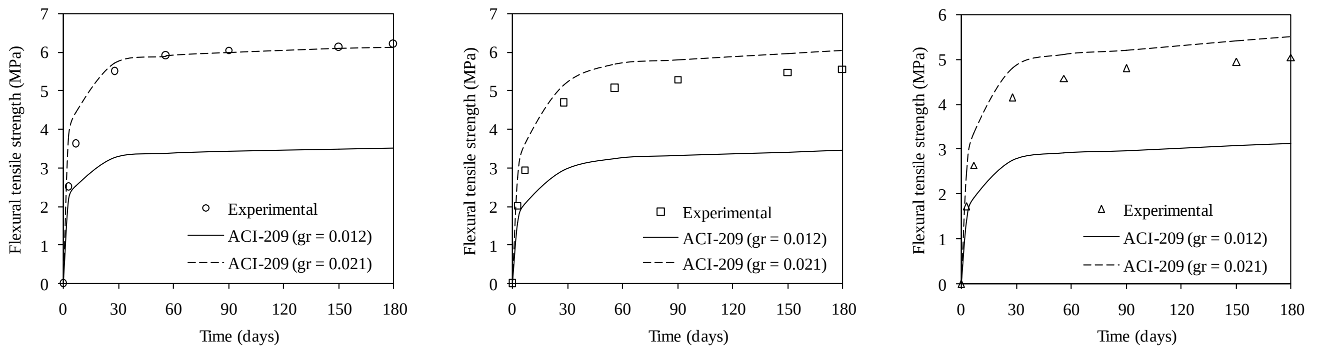
mix were tested to find the 28-day splitting and flexural tensile strength of concrete and remaining samples were stored at ambient temperature (i.e., the specimens were stored at room temperature of 27±2°C and relative humidity of 60 to 65%) for testing at later ages. These specimens were tested at the ages of 56, 90, 150 and 180 days. The splitting and flexural tensile strength tests were carried as per the guidelines of (IS 5816 1970) and (IS 516 2004) respectively. Data was generated for all nine plain and GGBFS concrete mixes at the ages of 3, 7, 28, 56, 90, 150 and 180 days. For each mix and age, the average of 5 cylinders and 5 prisms has been reported. The total number of cylinders and prisms tested were 10 (5 each)×7 (Ages)×9 (no. of mixes)=630. The total numbers of cubes of 150 mm equal to number of cylinders were also tested for the cube compressive strength of concrete at all ages and for all the concrete mixes. The splitting tensile strength tests were performed under 2000 kN compression testing machine and the flexural tensile tests were performed under 50 kN universal testing machine.

The experimental data on the time-dependent cube and cylinder compressive strength of plain and GGBFS concrete and the author's earlier model (Shariq *et al*. 2010) for the prediction of cylinder compressive strength of GGBFS concrete with age is considered in the present study for establishing the time-dependent relations between the splitting and flexural tensile strength with the cylinder compressive strength of GGBFS concrete.



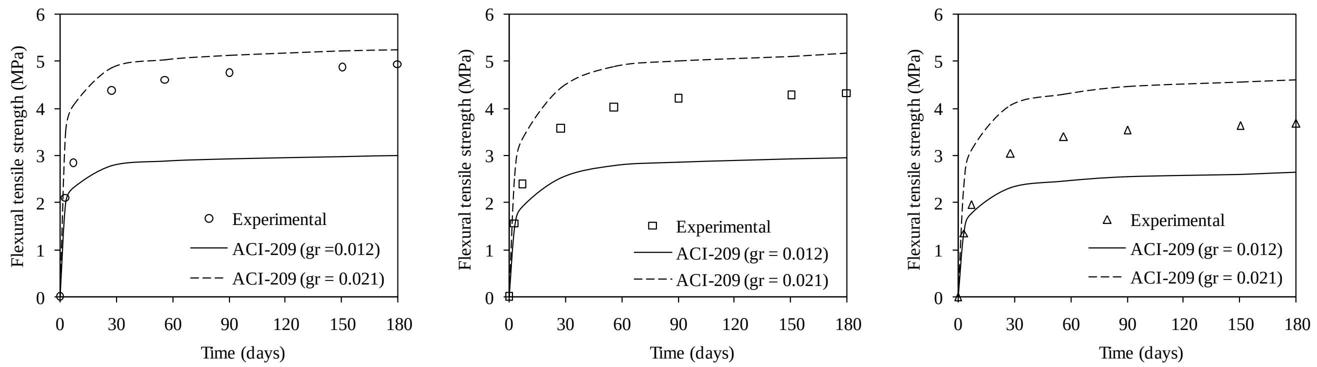
(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 4 Development of flexural tensile strength of concrete with age for mix group M1



(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 5 Development of flexural tensile strength of concrete with age for mix group M2



(a) 0% GGBFS (b) 40% GGBFS (c) 60% GGBFS

Fig. 6 Development of flexural tensile strength of concrete with age for mix group M3

3. Results and discussion

3.1 Time-dependent tensile strength of concrete

The experimental development of splitting and flexural tensile of plain and GGBFS concrete with age has been shown in Figs. 1-6 for all three mix groups M1, M2 and M3, respectively. The experimental results of splitting and flexural tensile strength of concrete with age have also been compared with the available models in the literature and the design codes. The time-dependent splitting tensile strength of concrete has been compared with time-dependent Larrard and Malier model (Larrard and Malier 1992), Zain model (Zain *et al*. 2002) and Zhao model (Zhao *et al*. 2017) as shown in Figs. 1-3. Similarly, the time-dependent flexural tensile strength of concrete has been compared with the time-dependent ACI 209 model (ACI 209 1999) as shown in Figs. 4-6. These time-dependent models for the prediction of splitting and flexural tensile strength of concrete are given in Table 4.

The other available empirical relationship between the tensile strength and the compressive strength of concrete given in the literature and the design codes of different countries (Arioglu *et al*. 2006, Legeron and Paultre 2000, Oluokun *et al*. 1991, Oluokun 1991, ACI 209 1999, IS 456 2000) can be written as

$$f_{spt} = A\left(f_c'\right)^B \text{ and } \quad f_r = A\left(f_c' or\ f_c\right)^B \tag{1}$$

Table 4 Models for time-dependent tensile strength of concrete

Model reference	Formula*
Larrard and Malier (1992)	$f_{spt,t} = 0.6 + 0.06 f'_{c,t}$
Zain *et al*. (2002)	$f_{spt,t} = 0.59\sqrt{f'_{c,t}}\left(\frac{t}{t_{28}}\right)^{0.04}$
Zhao *et al*. (2017)	$f_{spt,t} = 0.217\left(1+0.3\lg\left(\frac{t}{28}\right)\right)^{0.716}\left(f'_{c,28}\right)^{0.716}$
ACI-209 (1999)	$f_{r,t} = g_r\left(\rho_c f'_{c,t}\right)^{0.5}$

Where, $f_{spt,t}$ is the splitting tensile strength of concrete at '*t*' days; $f'_{c,t}$=cylinder compressive strength at '*t*' days; t_{28}=28 days; $f'_{c,28}$= cylinder compressive strength at 28 days; $f_{r,t}$=flexural tensile strength of concrete at '*t*' days; ρ_c=density of concrete in kg/m^3; g_r=constant (0.012 to 0.021); *t*=age in days

where, f_{spt} and f_r is the splitting and flexural tensile strength of concrete in MPa respectively, f'_c and f_c is the cylinder and cube compressive strength of concrete at 28 days in MPa respectively, *A* and *B* are the model parameters whose values are given in the range of: *A*=0.185 to 0.59 and *B*=0.5 to 0.735; for splitting tensile strength of concrete and *A*=0.3 to 0.94 and *B*=0.5 to 0.67; for flexural tensile strength of concrete.

It is worth mentioning here that none of the above models contains the percentage of GGBFS in concrete. This may be due the fact that these models are not developed for GGBFS concrete and it is assumed that the GGBFS content is indirectly incorporated in the compressive strength of concrete. Further, the Larrard and Zain model was proposed for the prediction of splitting tensile strength of high performance concrete and is not valid for high strength concrete. The model proposed by Zhao was developed for the prediction of splitting tensile strength of concrete made with manufactured sand. Therefore, above models cannot predict the splitting tensile strength of all types of concrete including GGBFS concrete.

Similarly, in empirical relations, it is also assumed that the GGBFS content and age to be indirectly incorporation in the compressive strength of concrete. Further, the available empirical relations between compressive and tensile strength of concrete are based on both cube and cylinder compressive strength of concrete. It was observed that the cube compressive strength is 1.25 times the cylinder compressive strength for plain as well as the GGBFS concrete at all ages (Shariq *et al*. 2010). Hence for the sake of simplicity and uniformity, cylinder compressive strength of concrete has been mentioned and used in the present study.

3.2 Effect of GGBFS on splitting tensile strength of concrete with time

The trend of variation of time-dependent splitting tensile strength of plain and GGBFS concretes is shown in Figures. 1, 2 and 3 for the three concrete mix groups M1, M2 and M3, respectively and discussed in the following.

(i) As expected, the splitting tensile strength increases with time at a decreasing rate for all the concrete mixes. The pattern of strength development is same in all the concrete mixes.

(ii) The splitting tensile strength of GGBFS concrete has been observed to be lower than the plain concrete for all percent replacements of cement by GGBFS at all ages and for all the concrete mixes. The lower splitting tensile strength of GGBFS concrete is probably due to the weak bond between the paste and the aggregate and secondly, due to the slow rate of hydration in GGBFS concrete. The reason of weak bond and slow rate of hydration in GGBFS concrete is due the age of curing (i.e., 28 days).

(ii) At the age of 28 days, the average splitting tensile strength of 40% and 60% GGBFS concrete is observed to be 81% and 69% respectively of that of the plain concrete. Whereas, at the age of 180 days, the average splitting tensile strength of 40% and 60% GGBFS concrete is 84% and 71.3% respectively of that of the plain concrete.

(iv) It is observed that the average gain in splitting tensile strength of plain concrete from 28 to 180 days is 19.3% for all the plain concrete mixes. Whereas, the average gain in splitting tensile strength of 40% GGBFS concrete from 28 to 180 days is 24.5% and for 60% GGBFS content, this strength gain is 22.3%. The optimum rate of gain of splitting tensile strength development among all the mixes has been found for 40% GGBFS content.

3.3 Effect of GGBFS on flexural tensile strength of concrete with time

The trend of variation of the flexural tensile strength of all the three concrete mix groups M1, M2 and M3 are shown in Figs. 4, 5 and 6, respectively and discussed in the following.

(i) Similar pattern has also been obtained for flexural tensile strength of concrete as in the splitting tensile strength development of concrete with age. Figures clearly show that the flexural tensile strength increases with age at a decreasing rate and the pattern of strength development is same in all the concrete mixes.

(ii) The flexural tensile strength development of concrete containing 40% and 60% GGBFS is found lower as compared with the plain concrete mixes at all ages. At the age of 28 days, the average flexural tensile strength of 40% and 60% GGBFS concrete is found to be 84% and 74% respectively of that of the plain concrete. Whereas, at 180 days the average flexural tensile strength is 89.3% and 79% for 40% and 60% GGBFS concrete respectively of that of the plain concrete. The flexural tensile strength development with age for the plain concrete has been observed to be almost equal for all the mixes.

(iii) The average gain in flexural tensile strength of concrete from 28 to 180 days is 13.9% for all the plain concrete mixes. Whereas, the average gain in flexural tensile strength of 40% and 60% GGBFS concrete from

Table 5 Tensile strength development of plain and GGBFS concrete

Concrete type	Mix ID	Rate of gain of tensile strength from 28 to 180 days (%)			
		Splitting tensile strength		Flexural tensile strength	
		Each mix	Average	Each mix	Average
Plain concrete	M10	15.9	19.3	15.4	13.9
	M20	16.2		12.9	
	M30	25.8		13.3	
40% GGBFS concrete	M11	22.2	24.5	22.5	21.1
	M21	23.9		19.1	
	M31	27.4		21.6	
60% GGBFS concrete	M12	21.6	22.3	21.0	21.1
	M22	18.5		21.7	
	M32	26.8		20.7	

28 to 180 days is 21.1%. Marginal variation in flexural tensile strength development from 28 to 180 days for 60 percent GGBFS concrete has been found as compared to 40 percent GGBFS concrete. The rate of gain of flexural tensile strength of GGBFS concrete from 28 to 180 days is found higher than the plain concrete. Therefore, it can be observed that the optimum rate of gain of flexural tensile strength development among all the mixes has been found for 60% GGBFS concrete.

From the above analysis, it can be observed that the splitting and flexural tensile strength development of GGBFS concrete from 28 to 180 days has been found to be higher than the strength of plain concrete. The splitting and flexural tensile strength development of plain and GGBFS concrete mixes from 28 to 180 days is also given in Table 5. This is due to the strong bond between the cement, GGBFS and aggregate and also because of the increase in denseness of the paste due to the shape and surface texture of GGBFS particles. The higher rate of gain of splitting and flexural tensile strength of GGBFS concrete shows the strong bond formation.

3.4 Assessment of available models

The splitting and flexural tensile strength of plain and GGBFS concrete are predicted by available models is discussed in the following:

Splitting tensile strength:

(i) The values predicted by Zain model are closer to the experimental values for all the GGBFS concrete mixes and the values are underestimated for all the plain concrete mixes. The prediction of splitting tensile strength by Larrard and Zhao models are greatly underestimated as compared with the experimental values for all concrete mixes.

(ii) The development of gain in splitting tensile strength with age for Zain model is same with experimental values. But, for Larrard and Zhao models, the trend of gain with age is slow beyond the age of 7 days.

(iii) For all concrete mixes (i.e., $15.5 < f_c^{'} < 36.8$), the prediction of splitting tensile strength by Zain model is higher than the Larrard and Zhao models and the lowest prediction is indicated by Zhao model. For the concrete mixes ranging from $15.5< f_c^{'} <25$, the prediction by Zain model is close to the experimental values.

(iv) For all plain concrete mixes, the Larrard model is predicted the lowest among all the models. For GGBFS concrete mixes, the prediction by Zhao model is lowest and the gap between Larrard and Zhao models reduces for lower strength of concrete.

(v) At early age of concrete (t<28 days), the values predicted by all the models indicate sharp increase in the splitting tensile strength of concrete for all concrete mixes.

(vi) The increase in the splitting tensile strength of plain concrete from 28 days to 180 days as predicted by Larrard, Zain and Zhao models is 11.2-13.9%, 15.9-16.9% and 16.8%, respectively but for GGBFS concrete mixes, this range is 18-35.7%, 22.6-31.2% and 16.8%, respectively. It shows that for GGBFS concrete mixes, Larrard and Zain models are predicted higher gain in splitting tensile strength which is closer to the experimental gain in splitting tensile strength.

Flexural tensile strength:

(i) The development of flexural tensile strength with age predicted by ACI-209 model is almost same for all the concrete mixes. The values predicted by ACI-209 model (gr=0.021) are closed to the experimental values for all plain concrete mixes. For GGBFS concrete mixes, the predicted values are higher than the experimental values.

(ii) The values predicted by ACI-209 model (gr=0.012) are greatly underestimated the flexural tensile strength of concrete as compared with the experimental values for all concrete mixes and at all ages.

(iii) The rate of gain in flexural tensile strength of plain concrete from 28 days to 180 days as predicted by ACI-209 model (gr=0.021) is 8.4%-19.1% and for GGBFS concrete, it is 16.2%-21.7% and 13.8%-15.7% for 40% and 60% replacement respectively. This rate of gain in the flexural tensile strength is also same as predicted by ACI-209 (gr=0.012) for all concrete mixes.

(iv) The strength deviation between experimental and predicted values is higher for lower strength of concrete. The percentage of strength deviation is found higher for 60 percent GGBFS concrete mixes. This variation may be due to the constant (gr) used in the ACI-209 model which is not clearly defined for the prediction of flexural tensile strength of GGBFS concrete.

4. Model for the prediction of time-dependent tensile strength of concrete

The tensile strength of concrete is intrinsically linked to the compressive strength in the sense that both increase simultaneously, though not in the same proportion. The flexural tensile strength differs from the splitting tensile strength in the sense that splitting stress is nearly uniform

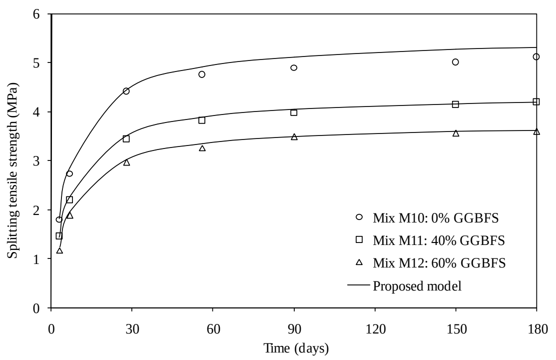


Fig. 7 Validation of proposed model with experimental results for the prediction of splitting tensile strength with age for mix group M1

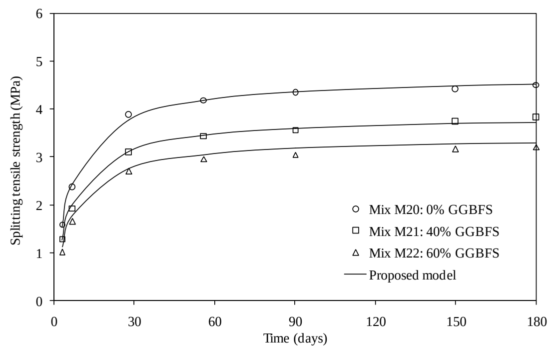


Fig. 8 Validation of proposed model with experimental results for the prediction of splitting tensile strength with age for mix group M2

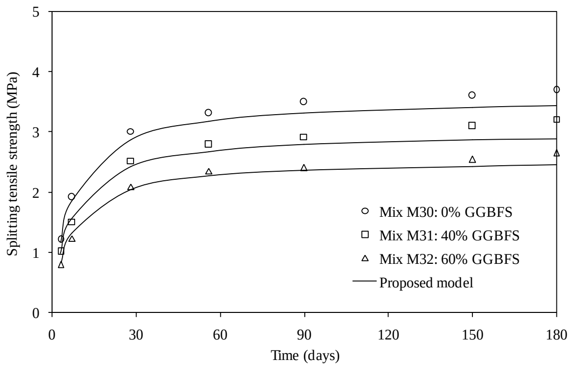


Fig. 9 Validation of proposed model with experimental results for the prediction of splitting tensile strength with age for mix group M3

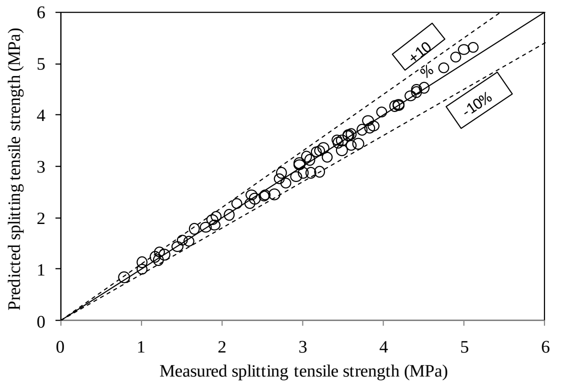


Fig. 10 Comparison of experimental and predicted splitting tensile strength at different ages for all mix groups

across the cross-section where as flexure causes linearly varying tensile as well as compressive stresses. The literature reveals that limited data is available on the splitting and the flexural tensile strength of concrete containing GGBFS and the time-dependent prediction models for the splitting and the flexural tensile strength of GGBFS concrete is not available in the literature. The tests carried out in the present study reveals that the splitting and the flexural tensile strength of concrete depends upon the water to binder ratio, age in days and percentage replacements of cement by GGBFS. Therefore, new models are proposed for the prediction of splitting and flexural tensile strength of concrete as function of time, cylinder compressive strength at 28 days, water to binder ratio and percent replacements of GGBFS. The following models are proposed based upon best fit multiple variable regression analysis of the test data:

Proposed model for the prediction of splitting tensile strength of GGBFS concrete

$$\left(f_{spt}\right)_t = 0.2\left[\left(\frac{t}{6.494+0.8t}\right)(w/b)^{-0.09}\exp\left(-0.048p_s\right)\left(f_c^{'}\right)_{28}\right]^{0.85} \quad (2)$$

Proposed model for the prediction of flexural tensile strength of GGBFS concrete

$$\left(f_r\right)_t = 0.37\left[\left(\frac{t}{6.494+0.8t}\right)(w/b)^{-0.09}\exp\left(-0.048p_s\right)\left(f_c^{'}\right)_{28}\right]^{0.78} \quad (3)$$

where, $(f_{spt})_t$ is the splitting tensile strength of concrete at any age 't' in days; $(f_r)_t$ is the flexural tensile strength of concrete at any age 't' in days; 't' is the age of concrete in days, $\left(f_c^{'}\right)_{28}$ is the cylinder compressive strength of concrete at 28 days; (w/b) is water to binder ratio and 'p_s' is the percentage of GGBFS content.

The predicted time-dependent splitting tensile strength using the proposed model (Eq. (2)) with experimental results is shown in Figs. 7 to 9 for all mix groups and at all ages. The trend of development of the splitting tensile strength of concrete with age predicted from proposed model shows a good correlation for all the mixes. The comparison between experimental and predicted time-dependent splitting tensile strength of concrete for all mix groups is shown in Fig. 10. It is observed that high percentage (96.8%) of the data points lies within an error band of ±10 percent. Similarly, Figs. 11 to 13 also show the variation of predicted time-dependent flexural tensile strength of concrete using the proposed model given in Eq. (3) for all mixes and at all ages. Figures show good agreement between the experimental and the predicted time-dependent flexural tensile strength of concrete for all mixes. A comparison between the experimental and the predicted flexural tensile strength of concrete for all mixes is shown in Fig. 14. It is observed from the figure that 93.7% data points predicted by proposed correlation is in agreement with the experimentally obtained data with an

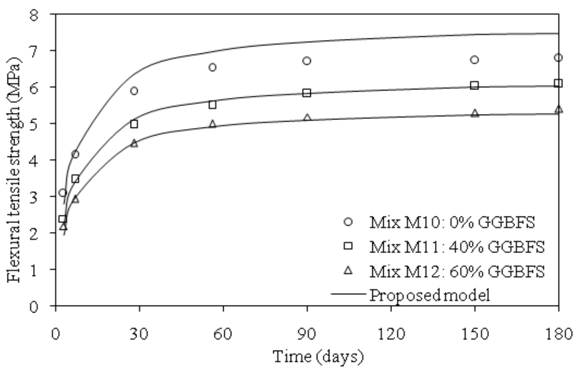


Fig. 11 Validation of proposed model with experimental results for the prediction of flexural tensile strength with age for mix group M1

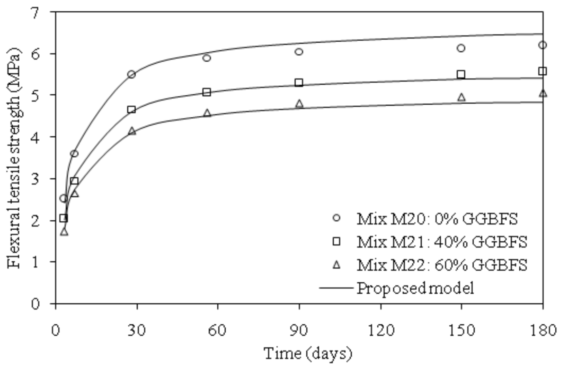


Fig. 12 Validation of proposed model with experimental results for the prediction of flexural tensile strength with age for mix group M2

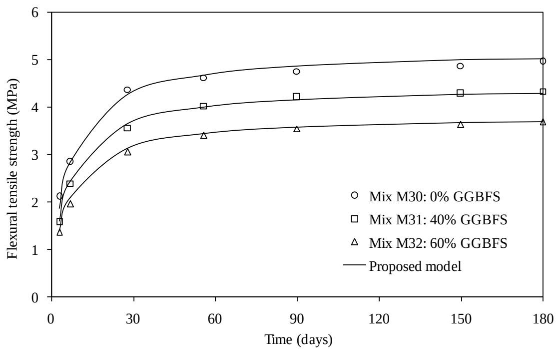


Fig. 13 Validation of proposed model with experimental results for the prediction of flexural tensile strength with age for mix group M3

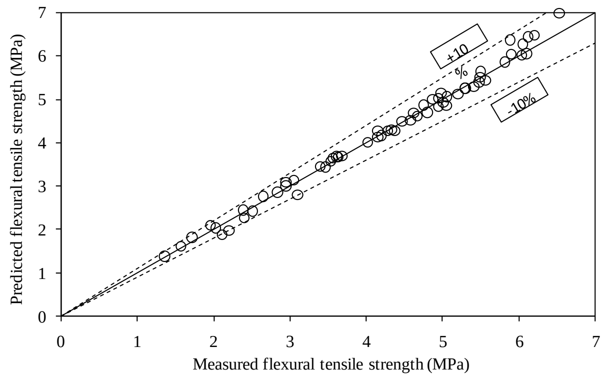


Fig. 14 Comparison of experimental and predicted flexural tensile strength at different ages for all mix groups

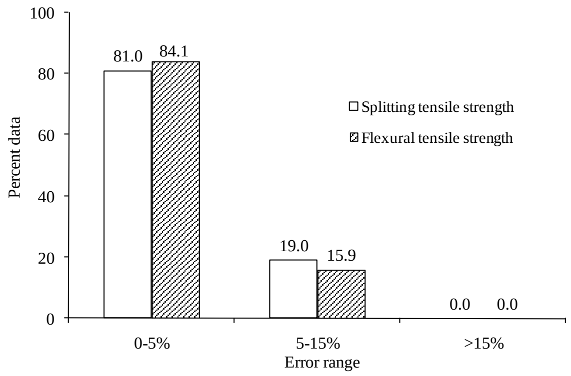


Fig. 15 Histogram of error in the prediction of splitting and flexural tensile strength using proposed models for all mixes

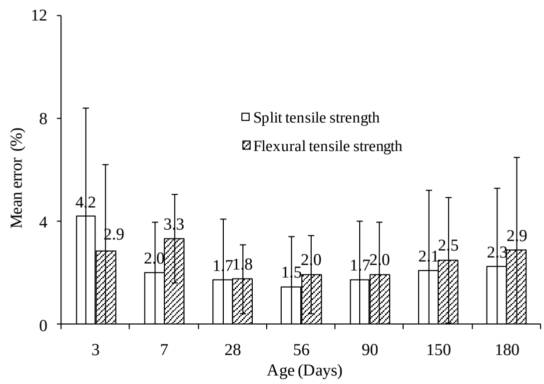


Fig. 16 Mean error with error bars for the prediction of splitting and flexural tensile strength at all ages

error band of ±10 percent.

The histogram of error in the prediction of splitting and flexural tensile strength covering all data points for all mixes is plotted in Fig. 15. It can be observed from the figure that the error is less than 5% for most of the data i.e., 81% data of splitting tensile strength and 84.1% data of flexural tensile strength and only 19% data of splitting tensile strength show error less than 15%, whereas, 15.9% data of flexural tensile strength show error lies within an error band of 5-15%. Thus, the proposed equations for the prediction of tensile strength of GGBFS concrete fits quite well with the experimental data. Fig. 16 shows the mean error with error bars in the prediction of splitting and flexural tensile strength using proposed models at all ages. It is observed from the figure that the mean error from 3 to 180 days lies in the range of 1.5-4.2% and 1.8-3.3% in the prediction of splitting and flexural tensile strength respectively for all the concrete mixes. The comparison between the experimental and the predicted splitting and flexural tensile strength of concrete for all mixes and high R^2=0.99 values confirming the validity of the proposed models in predicting the time-dependent tensile strength of concrete containing GGBFS.

5. Conclusions

Time-dependent splitting and flexural tensile strength of concrete containing GGBFS has been studied keeping in view the initiation of failure of concrete. Because, tensile strength of concrete is an important parameter in the design of liquid retaining reinforced and pre-stressed concrete structures. GGBFS based concrete is expected to be a little less brittle, compared with plain concrete, and hence is expected to perform better under tensile stresses. The conclusions derived from the study are described hereunder:

- The splitting and the flexural tensile strength is less in GGBFS concrete as compared to plain concrete at all ages and for all mixes. At 28 days, the average splitting tensile strength for 40% and 60% GGBFS concrete are 81% and 69% respectively, whereas the average flexural tensile strength are 84% and 74% respectively of that of plain concrete strength.
- At 180 days, the average splitting tensile strength for 40% and 60% GGBFS concrete are 84% and 71.3% respectively, whereas the average flexural tensile strength are 89.3% and 79% respectively of that of plain concrete strength.
- Lower maturity concrete (up to 28 days) exhibit lower rate of gain of splitting and flexural tensile strength of GGBFS concrete. But, from 28 days to 180 days, The rate of gain of splitting tensile strength for 40 percent GGBFS concrete is found to be higher than the plain concrete and concrete containing 60 percent GGBFS.
- For all concrete mixes, the prediction of splitting tensile strength by Zain model is higher than the Larrard and Zhao models whereas prediction by Zhao model is lowest among all the models. The prediction of flexural tensile strength by ACI-209 (*gr*=0.021) is higher than ACI-209 (*gr*=0.012) for all concrete mixes and at all ages.
- For GGBFS concrete mixes, the rate of gain in splitting tensile strength from 28 days to 180 days as predicted by Larrard and Zain models are higher and closer to the rate of gain in experimental splitting tensile strength than the prediction by Zhao model. The rate of gain in flexural tensile strength from 28 days to 180 days as predicted by ACI-209 (*gr*=0.021) is same as predicted by ACI-209 (*gr*=0.012) for all concrete mixes. But, the prediction of flexural tensile strength by ACI-209 (*gr*=0.021) is close to the experiments.
- The proposed new models for the prediction of time-dependent splitting and flexural tensile strength of plain and GGBFS concrete has been found good agreement with experiments.
- The present study will be helpful for the designers to know the time-dependent tensile properties of GGBFS concrete to meet the design requirements of liquid retaining reinforced and pre-stressed concrete structures.

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