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TECHNICAL PAPER

Strength characterization of concrete using industrial waste as cement replacing materials for rigid pavement

Hemant S. Chore[1] · **Mrunal P. Joshi**[2]

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Abstract

The excessive use of cement in the construction industry has caused many undesirable consequences. Replacement of cement with industrial by-products like fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume (SF), metakaolin, rice husk ash, etc., as the mineral admixtures offers several advantages in this modern era of sustainability in construction practice. This paper presents the experimental investigations for assessing the strength properties of the concrete made using the pozzolanic waste materials, i.e. supplementary cementitious materials (SCMs) such as FA, GGBFS and SF as the cement replacing materials. Eight trial mixes were prepared using these materials with varying amount of ordinary Portland cement. These SCMs were kept in equal proportions in all the eight trial mixes. Moreover, superplasticizer was also used for bringing improvement in the workability. The compressive strengths corresponding to the curing period of 7, 28, 40 and 90 days along with the flexural and indirect tensile strengths corresponding to 7, 28 and 40 days curing were evaluated. The study concludes that industrial waste materials can be used as partial replacement of cement and can render sustainable concrete for use in the rigid pavement construction.

Keywords Concrete · Strength · Pozzolanic materials · Fly ash (FA) · Ground granulated blast furnace slag (GGBFS) · Silica fume (SF) · Rigid pavement

Abbreviations

OPC	Ordinary Portland cement
SCMs	Supplementary cementitious materials
FA	Fly Ash
GGBFS	Ground granulated blast furnace slag
SF	Silica fume
w/*c*	Water cement ratio
O–F–G–S	OPC–FA–GGBFS–SF
O–F–G	OPC–FA–GGBFS
IRC	Indian Roads Congress

Introduction

The concrete is the prominent construction material due to several benefits with respect to strength, durability, adoptability and economy. Lot of efforts was taken for improving the quality of concrete by resorting to the various ways for maximizing its performance level. Nowadays, development of special types of concretes has necessitated the use of mineral and chemical admixtures for improving its performance. Various by-products generated by the industries find application in concrete in the context of economic viability, preservation of environment, improvement in the workability of wet concrete and strength and durability of the hardened concrete; and reduced heat of hydration. In developing country like India, more thrust is being given in the recent past on the construction of concrete pavements as a substitute to the flexible pavements due to the several advantages such as strength, longer life, durability and comparatively less maintenance cost. Construction of concrete pavements finds potential application of such pozzolanic waste materials as the cement replacing materials and sometimes, even as the substitute to fine aggregates. These materials are also called as the supplementary cementitious materials (SCMs).

✉ Hemant S. Chore
chorehs@nitj.ac.in

Mrunal P. Joshi
mpjoshi@rediffmail.com

[1] Department of Civil Engineering, Dr. B.R. Ambedkar National Institute of Technology Jalandhar, G.T. Road Bye Pass, Jalandhar, Punjab 144011, India

[2] Department of Civil Engineering, A.P. Shah Institute of Technology, Kasarvadavali, G.B. Road, Thane (West), Maharashtra 400615, India

Various researchers reported on the utilization of pozzolanic waste materials such as FA, GGBFS and SF. Malhotra [1] emphasized on the utilization of FA and other SCMs in concrete on large scale for reducing emission of carbon dioxide. Some of the researchers [2–8] worked on mechanical and durability characteristics of concrete made using FA along with few other such materials as partial cement replacing materials. Obla and Russell [2] worked on ultra-fine fly ash (UFFA) concrete. Alam and Akhtar [3] presented various ways of utilization of FA in different segments of the construction industry in the Indian context. Silva and Brito [4] worked on the self-consolidating concrete made with FA in conjunction with lime stone filler. Sunil et al. [5] used FA in conjunction with mine tailings. Paliwal and Maru [6] used FA and plastic (polythene) waste. Jena and Panda [7] used of FA and the silpozz (agro waste) as environmental friendly materials in construction industry. Saha and Sarker [8] used FA and ferronickel slag as partial replacement of cement and natural sand.

Some of the researchers [9–11] dealt with workability, performance and durability of concrete made with GGBFS as the cementitious material. Few of them studied effect of plasticizers as well on the performance. Few researchers [12, 13] studied performance of concrete made from FA and GGBFS as the partially cement replacing materials.

Several researchers [14–21] worked on concrete containing silica fume (SF). The different aspects such as mechanical properties, durability, permeability, chemical attack resistance and creep rate also formed the basis of the study. One of them [18] reported long-term study on high strength SF concrete. Mane et al. [22] observed that around 20% SF and 60% manufactured sand as the replacement for cement and natural sand, respectively, yielded maximum tensile strength and improved the microstructure.

Some of the researchers [23–25] observed improvement in the quality of the concrete comprising FA in conjunction with silica fume as cement replacing materials. Laldji and Tagnit-Hamou [26] reported the properties of ternary and quaternary concrete with alternative cementitious materials with glass frit. Ali et al. [27] found increase in strength and aggregate-cement bond; improvement in pore structure and significantly better effect on transport characteristics of binary and ternary mixes of concrete using FA and SF. Ibrahim et al. [28] reviewed the effect of pozzolanic materials on properties of the concrete. Gesoglu et al. [29] studied properties of the self-compacting concrete. They used FA, blast furnace slag and SF in binary, ternary and quaternary mixes. Patel and Sheth [30] studied properties of high performance concrete made using cement, FA, micro-silica and ultra-fine slag. Ganjigatti et al. [31] pointed out higher compressive strength, enhanced setting time and low heat of hydration in the concrete using pozzolanas such as SF, GGBFS and FA along with metakaolin as cement replacing materials. Rashad [32] reported potential of SF and slag as the cement replacing materials in HVFA concrete subjected to raised temperatures. Kim et al. [33] studied mechanical properties binary, ternary and quaternary blended concrete with respect to energy efficiency and using FA, blast furnace slag and SF. Praveen Kumar and Prasad [34] worked on concrete with FA, SF and lime sludge as a partial replacement of cement.

Based on aforementioned literature review, this investigation aims at studying strength properties of concrete made using fly ash (FA), ground granulated blast furnace slag (GGBFS) and silica fume (SF). These materials were used as partially cement replacing materials. The suitability of such concrete is discussed for its potential use as the pavement quality concrete.

Experimental programme

Materials

The materials used in the study include: ordinary Portland cement (OPC-53 Grade) conforming to IS: 12269 [35], river sand (FA) and crushed angular graded coarse aggregates (Metal I and II), SCMs such as FA, GGBFS and silica fume SF; and the chemical admixture (super plasticizer). The potable water was added for obtaining concrete mix. The properties of different constituents of concrete following various laboratory investigations are presented in Table 1.

The Class-F FA (Pozzocrete 60) conforming to IS: 3812 [36] (Source: Nasik Thermal Power Station, India) was used in the study (Fig.1a). The GGBFS (Durocem BS 6699) conforming to IS: 12089 [37] was procured from

Table 1 Properties of used cement and aggregates

Properties	Values
Cement (OPC-53 Grade)	
Fineness	305 (Minimum 225 cm^2/gm)
Consistency	28%
Specific gravity	3
Initial setting time	130 Min
Final setting time	221 Min
Compressive strength (MPa) for 3, 7 and 28 day's curing	29, 36 and 54
FA (Tapi River, Gujarat, India)	
Specific gravity of fine aggregates	2.72
Water absorption	0.9
CA (Local Quarry, Turbhe, New Mumbai, India)	
Specific gravity (10 mm and 20 mm size)	2.7 and 2.82
Water absorption	0.48
Crushing value	22%


(a) Fly ash (b) GGBFS (c) Silica fume

Fig. 1 SCMs used in the study

Table 2 Properties of pozzolanic materials used

Physical properties	FA	GGBFS	SF	Chemical composition (%)	FA	GGBFS	SF
Loss on ignition (%)	1.3	0.71	2.6	$SiO_2+Al_2O3+Fe_2O_3$	93.54	53.5	92.78
Specific gravity	2.13	2.56	2.2	Silicon dioxide (SiO_2)	60.5	36.53	92.1
Water requirement (%)	85	–	–	Alumina (Al_2O_3)	27.5	16.32	0.6
Moisture content (%)	0.4	–	–	Iron oxide (Fe_2O_3)	5.32	0.65	0.08
Blaine’s fineness (m^2/kg)	345	–	22,000	Calcium oxide (CaO)	1.55	35.66	0.3
Autoclave expansion (%)	0.06	–	–	Magnesium oxide (MgO)	0.49	10.93	0.3
Lime reactivity (MPa)	–	–	8.5	Sulphur trioxide (SO_3)	0.22	0.16	0.06
–	–	–	–	Alkalies (Na_2O+K_2O)	1.81%	0.55%	0.6
–	–	–	–	Chlorides	0.38%	0.001%	0.001

Table 3 Technical data for chemical admixture used

Base	Sulphonated melamine formaldehyde resin
Dosage	0.5–2% (by weight of cement) as per the requirement of the workability
Type	Type F conforming to IS: 9103 [39]
Colour	Clear to little hazy
Water reduction	Between 15–20%
pH	> 8
Stability	12 months in closed container

Heidelberg Cement India Limited, Pen (India) (Fig. 1b). Silica fume (SF) conforming to IS: 15388 [38] was procured from Oriental Trexim Pvt. Ltd. from Bhiwandi (Maharashtra, India). For the present study, densified SF of Grade 90 D was used (Fig. 1c).

The properties of the supplementary cementitious materials (SCMs) provided by the suppliers are presented in Table 2.

High-range water-reducing admixture (superplasticizer) Supercon -100 (Type –F) was also used in the present study. The technical data for Supercon -100 are given in Table 3.

Mix preparation

The experimental programme entailed different combinations of ordinary Portland cement (OPC) and mineral admixtures such as FA, GGBFS and SF. The parameters such as water cement (w/c) ratio, percentage of cement, FA, GGBFS, SF, fine and coarse aggregates; and superplasticizer were varied. Following literature review, the percentage variation in cement and replacing materials was decided. In all, eight trial mixes were prepared, and further, for each mix, the cubes, beams and cylinders (12 Nos., 3 Nos. and 3 Nos.) were cast. The particulars of the proportion of ingredients of different trials are indicated in Table 4.

The particulars of the mix preparation have already been discussed by the authors [13] The samples (cubes, beams and cylinders) were air-dried for a period of 24 h at 30 °C and 55% relative humidity; and then, they were weighed to find out their weights prior curing. Thereafter, they were immersed in water at 29 °C. Four curing periods (7, 28, 40 and 90 days) were considered for cubes while three (7, 28 and 40 days) for beams and cylinders. The samples were tested for various strengths [40, 41].

Table 4 Contents of trial mixes considered in the present study and reported in literature

Trial	Present study						Chore and Joshi [13]			
	w/*c* ratio	Cement (%)	FA (%)	GGBFS (%)	SF (%)	Admix (%)	*w*/*c* ratio	Cement (%)	FA (%)	GGBFS (%)
T-1	0.47	55	15	15	15	0.3	0.47	55	22.5	22.5
T-2	0.45	60	13.34	13.34	13.34	0.4	0.45	60	20	20
T-3	0.43	65	11.67	11.67	11.67	0.5	0.43	65	17.5	17.5
T-4	0.41	70	10	10	10	0.6	0.41	70	15	15
T-5	0.39	75	8.34	8.34	8.34	0.7	0.39	75	12.5	12.5
T-6	0.37	80	6.67	6.67	6.67	0.8	0.37	80	10	10
T-7	0.35	85	5	5	5	0.9	0.35	85	7.5	7.5
T-8	0.33	90	3.34	3.34	3.34	1.0	0.33	90	5	5

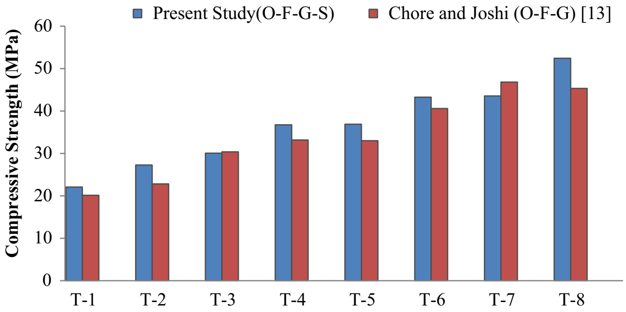

Fig. 2 Compressive strength (7 days curing)

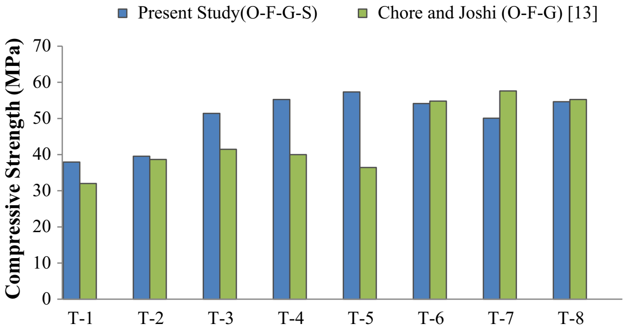

Fig. 3 Compressive strength (28 days curing)

Results

The influence of cement replacing materials such as FA, GGBFS and silica fume used in various proportions for different trials for different water–cement ratio is examined on mechanical properties of concrete through different tests on hardened concrete. The results obtained in this investigations are compared with the one reported by authors [13] in which only FA and GGBFS were used, and further, the cement contents and the water–cement ratio were kept same as that in the present investigation.

Compressive strength

The compressive strengths observed with respect to different curing periods for various trials in this investigation are indicated in Figs. 2, 3, 4 and 5. Further, the strengths reported for the corresponding curing period in the published work [13] are also indicated in Figs. 2, 3, 4 and 5 for the purpose of comparison.

It is observed that with the increase in cement contents and decrease in water–cement (*w*/*c*) ratio, the compressive strength increases in all the mixes with respect to 7 days curing. For 28 days curing, it is seen that the strength

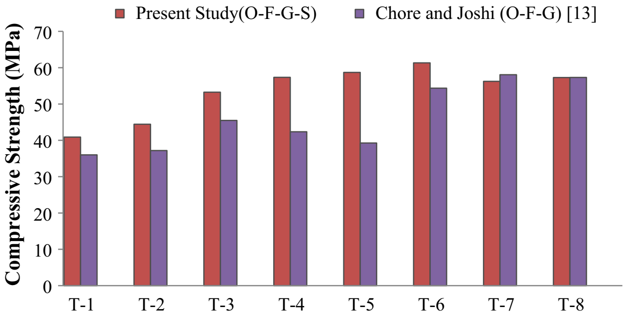

Fig. 4 Compressive strength (40 days curing)

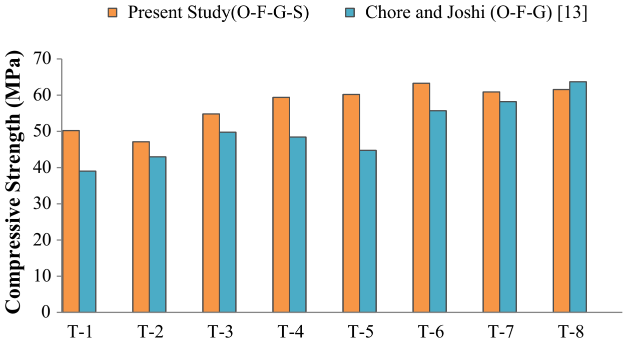

Fig. 5 Compressive strength (90 days curing)

increases up to trial mix 5, reduces for next mix and then, again increases for next last two trial mixes. For next two higher curing periods (40 days and 90 days), the strength is seen increasing up to trial mix 6, reduce for next trial and again increase for last trial. Though, for three higher curing periods, the trend of decrease in strength in case of one of last few mixes and again increase in the strength is seen, difference in variation is not that significant.

The increase in cement contents and curing period renders more alkali (a by-product of hydration of cement) available for pozzolanic reaction. This increases the compressive strength of the concrete. Moreover, the rate of strength gain is seen to be more for higher curing periods. With decrease in the percentage of cement replacing materials and increase in percentage of cement in the mixes, the strength is found to be on more for most of the trial mixes barring last two trials. The strength slightly is found to be on relatively lower side in case of trial mixes 5 and 6 in respect of some of the higher curing periods, but again found to increase for the last trial mix. This can be because of the effect of water cement ratio as well.

For mix with higher *w/c* ratio of 0.47 and lower cement contents, the increase in strength is observed in the range of 71.8–127.5% for 28, 40 and 90 day's curing periods, respectively, with respect to that observed for 7 day's curing. The corresponding increase is observed to be in the range of 4.2–17.4% for the last trial with lower *w/c* ratio and higher cement contents. The increase in the strength corresponding to 28 day's curing with respect to 7 days curing is seen to be 4.2–71.9%; for 40 days curing period in the range of 9.2–85.3%; and that for 90 days curing, 17.4–127.5%.

Further, the results of compressive strength obtained are compared with those reported in the literature [13]. It is seen that the trend of increase in strength with curing period is similar in both the studies barring few exceptions in the trend reported in published literature. All the same, the trend remains same. Further, the strength observed in the present study for different trial mixes is more as compared to that observed in [13] for corresponding trial mixes. This can be because of the presence of the silica fume in the mixes considered in the present investigation. The addition of SF imparts chemical reaction with calcium hydroxide (CH) and produces additional calcium silicate hydrates (CSH). This results in the increased compressive strength as seen in the present investigation and the chemical resistance. Further, SF is 100 to 150 times smaller than cement particle. The SF can fill the voids created by free water in the matrix. This function is referred to as the particle packing, and it, further, refines the microstructure of the concrete and develops much denser pore structure.

The compressive strength of the design mix [42–44] corresponding to 0.37 *w/c* ratio with respect to 7 and 28 day's curing is indicated in Table 5. The strengths of the controlled mix with *w/c* ratio of 0.37 are also indicated in Table 5.

Table 5 Compressive strength (MPa) of design and controlled trial

Design mix [44]		Controlled mix			
		Present study (O–F–G–S)		Chore and Joshi (O–F–G) [13]	
7 days	28 days	7 days	28 days	7 days	28 days
36	54	43.26	54.15	40.59	54.81
Percentage increase		20.16	0.27	12.75	1.5

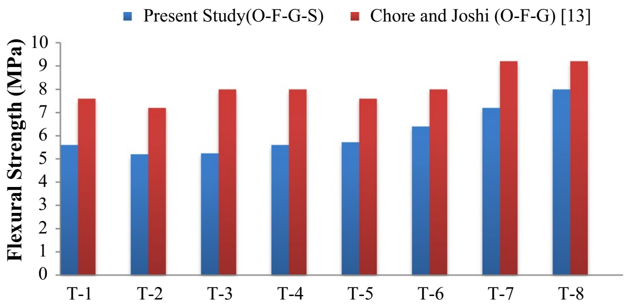

Fig. 6 Flexural strength (7 days curing)

The compressive strength of controlled mix for 7 days curing is found to be 20.16% more than that of the design mix. But it is, further, seen that the increase is reduced for 28 days' curing period. The strength of controlled mix is observed just 0.27% more than the design mix for 28 days curing. When increase in the strength of the controlled and that of design mix observed in the published literature [13] is compared, strength of the former mix is observed 12.75 and 1.5% more.

Along similar lines, the modulus of elasticity with respect to the actual compressive strength observed in all trial mixes and that of strength of the design mix are determined as per the guideline given in IS: 456 [45]. The modulus is found to be 34.90×10^3 MPa in case of former whereas in case of latter, 36.74×10^3 MPa.

Flexural strength

The flexural strength observed for different trial mixes in the present investigation that considers the combination of O-F-G-S corresponding to three different curing periods with respect to modulus of rupture are shown in Figs. 6, 7 and 8. Similarly, the flexural strengths observed in the published work [13] are also indicated in Figs. 6, 7 and 8 for the purpose of comparison.

When the effect of increase in cement contents for with respect to 7 days curing on the flexural strength is studied,

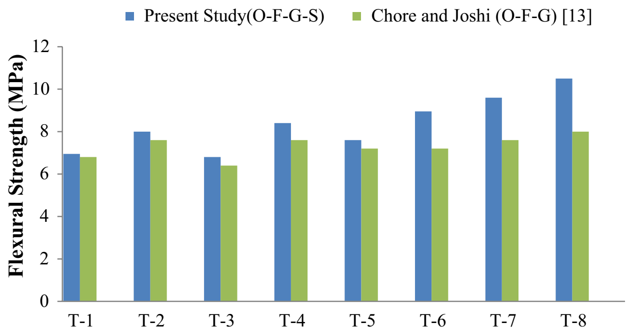

Fig. 7 Flexural strength (28 days curing)

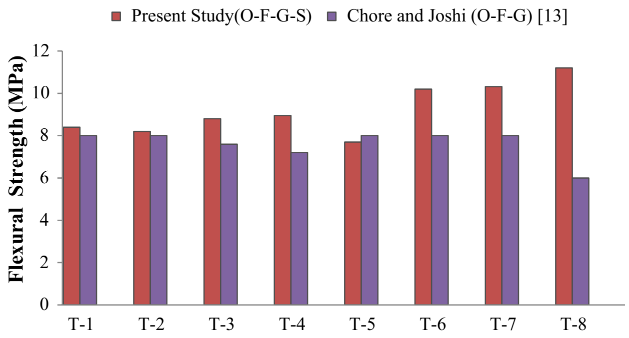

Fig. 8 Flexural strength (40 days curing)

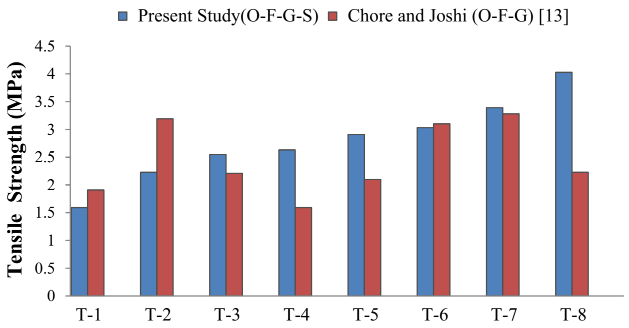

Fig. 9 Indirect tensile strength (7 days curing)

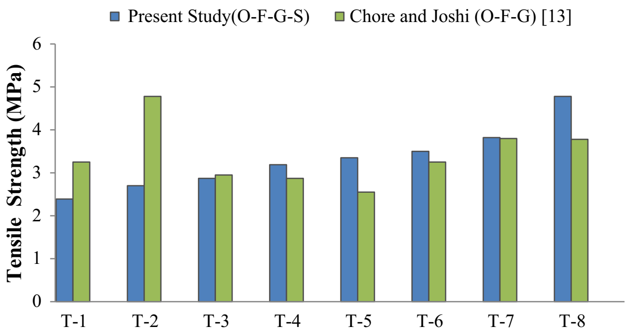

Fig. 10 Indirect tensile strength (28 days curing)

it is seen that the flexural strength decreases for trial mix 2 and increases thereafter. For 28 days curing, it is found to increase gradually up to trial mix 2 and thereafter, reduce for trial mix 3; again increase for trial mix 4 followed by further decrease for trial mix 5. However, thereafter the strength is found to increase for all next trials. For 40 days curing, it reduces for trial mix 2, again increases for next two trials, i.e. trial mixes 3 and 4 followed by further reduction in mix 5. Thereafter, the strength increases for all next trials, i.e. mixes 6, 7 and 8.

The effect of curing indicates increase in the flexural strength in respect of all the mixes. The gain in strength is found to be 24% for trial mix 1 and in the range of 50–54% for trial mixes 2 and 4 for 28 days curing. In case of all other mixes, increase is found to be in the range of 30–40%. Further, when the rate of strength gain is considered for curing period of 40 days, a significant gain is seen in case of trial mixes 1, 3 and 6. For all other trial mixes, the gain is comparatively less. The increase in flexural strength for 28 days curing period with respect to 7 days is seen to be 24.1–53.54% and that for 40 days curing, in the range of 34.6–68%, irrespective of all the trial mixes.

When the flexural strength obtained in this study is compared with the one published in the literature [13], it is observed that values of the strength obtained in this study is on lower side with respect to 7 days curing. However, flexural strength in all the trials considered in the present investigation corresponding to 28 days curing period are more when compared with that reported in the literature [13]. Similar is the analogy seen in case of the strengths corresponding to 40 days curing barring one exception, i.e. in respect of trial mix 5 where the strength in the present investigation is less. All the same, the variation is marginal. As regards the trend of variation of the flexural strength with curing period in the present study, it is found to increase for all the trials as against that seen in the published literature [13]. The finding from the similar work [13] remarked that strength would reduce for 28 days curing and thereafter increase in most of the trials barring two exceptions. For mix 2, it was found to increase with curing and for mix 4, decrease.

Indirect tensile strength

The indirect tensile strength observed for various mixes and corresponding to different curing periods considered in this study is shown in Figs. 9, 10 and 11. Similarly, the indirect tensile strength observed in the published literature [13] in the context of corresponding trial mixes is also indicated in Figs. 9, 10 and 11.

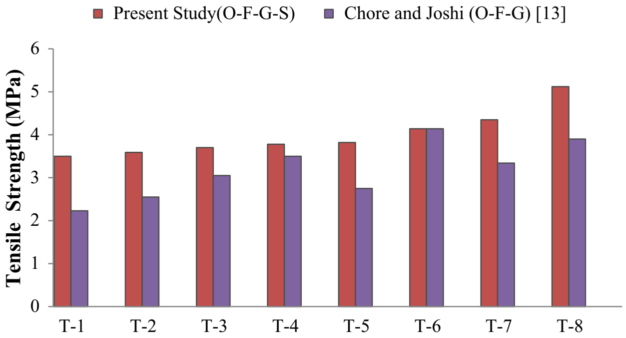

Fig. 11 Indirect tensile strength (40 days curing)

When the effect of cement contents is studied on the indirect tensile strength, the same is seen to increase with cement contents and decrease in water contents for 7 days curing with respect to all the mixes. Similar trend is observed for next higher curing periods of 28 and 40 days. It is, further, seen that strength increases with curing period. This holds good for all the mixes considered in this study.

The increase in indirect tensile strength for 28 days curing period with respect to 7 days curing is observed to be 12.5–50.3% and for 40 days curing period, 27–120%, irrespective of all the trial mixes.

The effect of curing indicates that the indirect tensile strength increases for all trial mixes. Gain in strength is found to be 50% for trial mix 1 and in the range of 12.5–21.3% for all other trial mixes, i.e. mix 2–8. Further, significant gain in strength is seen in case of trial mix 1 for higher curing period of 40 days with percentage increase of 120%. For next three trials, i.e. trial mixes 2, 3 and 4, the increase is observed to be in the range of 43.7–61%. For all other trial mixes, the gain in tensile strength is seen to be 27–37%.

When the values of the indirect tensile strength obtained in this study are compared with that published in literature [13] carried out only two SCMs (FA and GGBFS), it can be seen that strength obtained in this study are on lower side with respect to 7 and 28 days curing for first two trial mixes. However, the strength, in the present investigation, is found to be on higher side corresponding to these curing periods as compared to that reported in literature [13]. Further, when the strength in both the studies is compared in the context of higher curing period of 40 days, it is found to be on higher side in the present study.

Discussion on suitability as the rigid pavement material

The suitability of the concrete considered in this investigation is examined in Indian context and pursuant to the guidelines specified in different specifications brought out by Indian Roads Congress (IRC). IRC: 58 [43] specifies minimum grade of the concrete as M-40 for pavement quality concrete (PQC) in the construction of rigid pavement with compressive strength corresponding to 28 days curing as 40 MPa and states that flexural strength corresponding to 28 days curing should be 4.5 MPa. The trial mixes 3–8 are found to satisfy the requirement of the compressive strength to render the suitability of the mix to be used in PQC and all the trial mixes satisfy the requirement of the flexural strength for use in PQC. However, trial mix 3 gives the most optimized combination of the supplementary cementitious materials with 28 days' compressive strength as 51.4 MPa, higher than 40 MPa and flexural strength of 6.8 MPa, i.e. considerably greater than 4.5 MPa.

Further, IRC: 44 [44] specifies minimum grade of the concrete for use in the rigid pavement catering to the low traffic volume as M-30 corresponding to 28 days' compressive strength of 30 MPa. The corresponding flexural strength should be 3.8 MPa. Trial mixes 1 and 2 are found to give the compressive strength with respect to 28 days curing in the range of 37.9–39.5 MPa and therefore can be considered as the suitable mixes for low volume road on the basis of the compressive strength. The flexural strength of the corresponding mixes is observed 6.9 MPa and 7.6 MPa, i.e. significantly higher than the required value of the flexural strength of 3.8 MPa. However, trial mix 1 gives the most viable option for the use in construction of rigid pavement with respect to low volume rural roads.

The minimum grade of concrete suggested for the purpose of white topping is M-50 [44]. The trial mixes 4 to 8 comply with the requirement of the concrete for white topping. However, the mix 4 yields the most optimized combination for the use in white topping.

Conclusions

The experimental study reported in this paper was aimed at assessing the suitability of the industrial waste comprising SCMs such as FA, GGBFS and SF as cement replacing materials in concrete as the alternative construction material, especially, in the context of their use in the construction of the rigid pavements. Based on the findings from this study, following are the broad conclusions.

- The compressive, flexural and splitting tensile strengths are increased with cement contents and curing period.
- The percentage increase in compressive strength with respect to 7 days' curing for 28, 40 and 90 days curing is found in the range of 4.2–71.9, 9.2–85.3 and 17.4–127.5, respectively.
- An increase in the flexural strength with respect to 7 days' curing for 28 and 90 days curing is found in the

range of 24.1–53.54% and 34.6–68%, respectively. Along similar lines, an increase in the indirect tensile strength for the aforementioned curing period is found in the range of 12.5–50.3% and 27–120%, respectively.

- The mixes containing SCMs such as FA, GGBFS and SF in different proportions comply with the requirement of the concrete to be used in the construction of rigid pavement for high and low traffic volume roads; and also for the white topping on the basis of various criteria of compressive strength and flexural strength.
- Combined use of 45% of SCMs considered in the present investigation (in equal proportions) as partial replacement of cement yields optimum mix for pavement quality concrete (PQC) for low volume road.
- The combined use of 35% of such materials as a partial substitute to cement gives the optimized mix for application in PQC for high traffic volume roads. Along similar lines, the mix containing 30% of SCMs as a substitute to the cement renders the suitable mix for the application in white topping.

Thus, it can be concluded that the industrial wastes such as fly ash, ground granulated blast furnace slag and silica fume containing pozzolanic properties can be advantageously utilized in the pavement construction as a sustainable material and will address to the problem of waste disposal to the considerable extent and reduce the environmental concern as well.

Authors contributions HSC designed and co-ordinated this research and drafted the manuscript. MPJ carried out the experimental work and data analysis. The manuscript is a part of the work pursued by MPJ for her PG Dissertation submitted to the University of Mumbai through Datta Meghe College of Engineering, Airoli, New Mumbai (India) under the supervision of HSC when he was associated with Datta Meghe College of Engineering. The authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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