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ORIGINAL CONTRIBUTION

Compressive Strength and Elastic Modulus of Concretes with Fly Ash and Slag

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Abstract This paper presents the evolution of compressive strength and the modulus of elasticity of concretes with binary and ternary blends of ordinary Portland cement, fly ash and ground granulated blast-furnace slag (GGBS or slag). The study involved 54 concrete mixes with water–binder ratio (*w/b*) varying from 0.50 to 0.65 and the total binder content varying from 280 to 340 kg/m^3. The influence of w/b, type of binder and exposure period (or age) have been assessed. It is seen that the incorporation of slag contributes to both short- and long-term strength, whereas fly ash requires comparatively longer time to contribute to the compressive strength. The relationship between compressive strength and age and between the modulus of elasticity and compressive strength has been discussed.

Keywords Concrete · Blended binders · Strength · Modulus of elasticity · SCM · Fly ash · Slag

Introduction

Supplementary cementitious materials (SCMs), such as fly ash and ground granulated blast-furnace slag (GGBS), have been extensively used in the production of high-performance concretes as they can improve various properties of fresh and hardened concrete. The selection of these materials for a particular application often depends on the consideration of strength. The partial replacement of ordinary Portland cement (OPC) with fly ash and GGBS can have a significant influence on the rate of evolution of the compressive strength and modulus of elasticity, which in turn affects the manner of designing for the desired structural behaviour. This work presents the evolution of compressive strength over 2 days to 1 year, as well as the elastic modulus at 28 days, for concretes with and without SCMs.

The relevant literature on the mechanical properties of concretes with slag and fly ash does not reflect any consensus regarding the effects of their incorporation. Studies of Wainwright and Rey [1] concluded that early-age strength of slag-blended concrete was lower than that of OPC concrete. On the other hand, later-age strengths were found to be higher than those of OPC concrete when the replacement dosage was between 40 and 60% [2–4]. The strength was lower that of OPC concrete when slag replaced 80% of OPC in the concrete. Similarly, Hui-Shen et al. [5] concluded that a slag replacement level of 15–30% was optimal dosage to get the same strength as in OPC concrete at 28 days.

The dosage of fly ash is generally less than 40% by weight of cement to get the same compressive strength as an OPC concrete at 28 days [6]. Nevertheless, it has been confirmed that an increase in fly ash dosage decreases the early-age compressive strength. However, if early-age strength is not a concern, the replacement level could be more than 60% (as in high-volume fly ash; [7]. Many researchers [8–12] have attributed the decrease in the strength with the incorporation of fly ash the chemical reactivity of fly ash at early ages. Correspondingly, high-calcium fly ash (Class C) showed more rapid strength development at early age than low-calcium fly ash (Class F) [13]. The pozzolanic reactivity of the Class F fly ash leads to the significant long-term strength development [14, 15]. Along the lines of these studies, researchers

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[10, 16–18] have suggested that the combination of Class F and Class C fly ash is superior to the corresponding OPC mix or concrete containing only Class C fly ash.

Research Significance

The non-uniform physical characteristics and chemical composition of slag and fly ash from different sources in India have led to apprehensions about the performance of the concrete produced with fly ash and slag, the clarification of which has been the major motivation of this work. The data presented will add to the database of the use of SCM in the blended cement concrete in the Indian context.

Experimental Details

Materials and Mixture Proportion

Ordinary Portland cement (53 Grade conforming to IS 12269:2013 [19]) from two different brands was used in this study; they are denoted as CmP and CmA in this paper. Slag from two sources (SgA and SgB), Class F fly ash (FaF) and Class C fly ash (FaC) were used to produce the binary and ternary binder blends. Table 1 provides the physical properties and the oxide compositions of the materials used; it can be seen that the compositions of both cements are comparable and within the expected ranges. Both slags are similar in chemical composition. The calcium oxide (CaO) content of Class C fly ash is higher than that of Class F fly ash, as expected. Crushed granite in size fractions of 5–10 mm and 10–20 mm was used as the coarse aggregate, in the ratio of 40:60, and locally available river sand with maximum size of 5 mm was used as the fine aggregate. The coarse-to-fine aggregate ratio was 40:60. A sulphonated naphthalene formaldehyde (SNF)-based superplasticizer was used to obtain the target initial slump of 100 ± 30 mm. The mix design was done as per IS 10262:2010 [20], and the aggregates were assumed to be saturated surface dry (SSD). Concrete batches were prepared in a vertical-axis, forced-action pan mixer with a drum capacity of 250 litres, with the maximum volume of each batch being 100 litres. Before mixing, the moisture content of aggregates was determined (using the ASTM D4643:2008 [21]) and suitable corrections were done considering the aggregates to be in SSD condition. The sequence of mixing included initial dry mixing of the coarse and fine aggregates for 1 min; then, 20% of total measured mixing water was added to the aggregates and mixed for 2 min; followed by 4 min of rest; then, all the binder materials were mixed for 1 min; then, 60% of water was added and mixed for 1 min; and finally, superplasticizer and the remaining mixing water were added to the concrete and mixed for a minute.

Mix Description and Testing Methodology

Two series of concrete mixtures were prepared with CmP and CmA cements for combinations of w/b and total binder content as 0.65 and 280 kg/m^3, 0.55 and 340 kg/m^3, 0.50 and 310 kg/m^3, and 0.60 and 310 kg/m^3. Mixes were prepared with different cement replacement levels with four SCMs, as listed in Table 2. The mix nomenclature style is shown in Fig. 1. 'Mx' indicates the mix identification number. The next three letters indicate the cement type (e.g., 'CmP'), and the next two numbers and three letters represent the level of binder replacement by the SCM (in %) and its type in binary blends. For ternary blends, this is followed by the level of binder replacement by the second SCM and its type. For example, a ternary blend with

Table 1 Chemical composition and physical properties of binder

Oxide composition/physical properties	Binders[a]					
	CmP	CmA	SgA	SgB	FaF	FaC
Al_2O_3	4.07	4.73	17.38	21.06	29.95	31.46
CaO	59.61	65.11	35.61	31.46	1.28	13.76
Fe_2O_3	5.37	3.86	1.04	1.87	4.32	6.17
K_2O	0.27	0.54	0.58	0.88	1.44	0.12
MgO	0.82	1.20	8.03	8.57	0.61	2.28
Na_2O	0.23	0.50	0.36	0.36	0.16	0.59
SiO_2	20.42	19.44	33.82	32.38	59.32	39.89
SO_3	–	–	–	–	0.16	3.19
Specific gravity	3.18	3.15	2.86	2.89	2.49	2.46
Surface area (m^2/kg)	320	340	360	430	330	390

[a] CmP—Cement P; CmA—Cement A; SgA—Slag A; SgB—Slag B; FaF—Class F fly ash; FaC—Class C fly ash

Table 2 Mixture proportions and fresh properties of concrete

Mix no.	Nomenclature	Composition (kg/m^3)	SP (% solids by weight of cement)	Slump (mm)		Air content (%)	Unit weight (kg/m^3)
				Initial	After 30 min		
M1	CmP-NoSCM-0.65-280	FA: 744	–	90	50	2.4	2385
M2	CmP-30SgA-0.65-280	CA (10 mm): 477	–	135	90	2.6	2400
M3	CmP-30SgB-0.65-280	CA (20 mm): 716	0.05	80	40	2.0	2400
M4	CmP-30FaF-0.65-280	Water: 182	–	95	30	2.1	2385
M5	CmP-NoSCM-0.55-340	FA: 719	–	100	75	2.1	2400
M6	CmP-15SgA-0.55-340	CA (10 mm): 461	–	120	90	2.0	2360
M7	CmP-15SgB-0.55-340	CA (20 mm): 692	0.02	85	35	1.8	2400
M8	CmP-15FaF-0.55-340	Water: 187	0.03	130	100	1.2	2405
M9	CmP-15FaC-0.55-340		0.55	95	50	1.5	2360
M10	CmP-NoSCM-0.50-310	FA: 743	0.02	100	55	1.8	2370
M11	CmP-15SgA-0.50-310	CA (10 mm): 477	0.18	95	40	2.1	2400
M12	CmP-15SgB-0.50-310	CA (20 mm): 715	0.11	130	80	2.5	2370
M13	CmP-15FaF-0.50-310	Water: 155	–	100	55	2.4	2405
M14	CmP-15FaC-0.50-310		0.19	95	50	1.8	2370
M15	CmP-30SgB-0.50-310		0.30	80	30	2.1	2390
M16	CmP-30FaF-0.50-310		0.10	100	55	2.1	2390
M17	CmP-30FaC-0.50-310		0.14	100	50	2.0	2360
M18	CmP-50SgB-0.50-310		0.30	95	30	2.2	2440
M19	CmP-50FaF-0.50-310		0.30	95	30	1.7	2370
M20	CmP-20SgB-20FaF-0.50-310		0.55	95	50	1.4	2360
M21	CmP-20SgB-20FaC-0.50-310		0.55	85	45	1.3	2365
M22	CmP-20FaF-20FaC-0.50-310		0.36	100	40	1.5	2360
M23	CmP-NoSCM-0.60-310	FA: 731	0.36	85	50	2.0	2360
M24	CmP-15SgA-0.60-310	CA (10 mm): 469	–	100	60	2.2	2390
M25	CmP-15SgB-0.60-310	CA (20 mm): 704	0.05	120	50	1.9	2385
M26	CmP-15FaF-0.60-310	Water: 186	0.36	110	45	2.0	2400
M27	CmP-15FaC-0.60-310		0.36	80	35	1.8	2360
M28	CmA-NoSCM-0.65-280	FA: 685	0.05	100	45	2.4	2290
M29	CmA-30SgA-0.65-280	CA (10 mm): 529	0.06	100	40	2.5	2430
M30	CmA-30SgB-0.65-280	CA (20 mm): 797	0.08	105	40	2.4	2360
M31	CmA-30FaF-0.65-280	Water: 182	0.05	85	40	2.5	2430
M32	CmA-NoSCM-0.55-340	FA: 662	–	95	50	2.3	2440
M33	CmA-15SgA-0.55-340	CA (10 mm): 512	0.03	130	45	2.4	2430
M34	CmA-15SgB-0.55-340	CA (20 mm): 768	0.12	95	35	2.5	2315
M35	CmA-15FaF-0.55-340	Water: 187	–	85	55	2.0	2430
M36	CmA-15FaC-0.55-340		0.03	95	40	1.2	2460
M37	CmA-NoSCM-0.50-310	FA: 684	0.40	80	35	2.5	2490
M38	CmA-15SgA-0.50-310	CA (10 mm): 529	0.45	80	50	2.0	2425
M39	CmA-15SgB-0.50-310	CA (20 mm): 793	0.48	110	50	2.2	2360
M40	CmA-15FaF-0.50-310	Water: 155	0.30	90	50	1.8	2450

Table 2 continued

Mix no.	Nomenclature	Composition (kg/m^3)	SP (% solids by weight of cement)	Slump (mm)		Air content (%)	Unit weight (kg/m^3)
				Initial	After 30 min		
M41	CmA-15FaC-0.50-310	FA: 684	0.30	90	40	1.4	2430
M42	CmA-30SgB-0.50-310	CA (10 mm): 529	0.52	110	45	2.0	2460
M43	CmA-30FaF-0.50-310	CA (20 mm): 793	0.30	110	35	1.5	2430
M44	CmA-30FaC-0.50-310	Water: 155	0.40	125	50	1.3	2430
M45	CmA-50SgB-0.50-310		0.59	120	40	2.0	2430
M46	CmA-50FaF-0.50-310		0.25	100	30	1.8	2460
M47	CmA-20SgB-20FaF-0.50-310		0.12	110	45	1.8	2460
M48	CmA-20SgB-20FaC-0.50-310		0.42	95	55	1.5	2430
M49	CmA-20-FaF-20FaC-0.50-310		0.30	80	50	1.8	2430
M50	CmA-NoSCM-0.60-310	FA: 673	0.05	120	55	1.4	2425
M51	CmA-15SgA-0.60-310	CA (10 mm): 520	0.05	110	55	2.4	2430
M52	CmA-15SgB-0.60-310	CA (20 mm): 781	0.04	70	50	2.2	2460
M53	CmA-15FaF-0.60-310	Water: 186	0.10	90	50	2.0	2360
M54	CmA-15FaC-0.60-310		0.15	90	40	1.4	2430

20% Slag B and 20% Class F fly ash will be denoted as '20SgB-20FaF'. If there is no SCM in the mix, then it is denoted as 'NoSCM'. The two numbers following this indicate the w/b (e.g., '-0.55-'). The last three digits indicate the total binder content. For example: CmP-15gSgA-0.50-310 represents the mix with cement CmP and 15% replacement by Slag A (SgA) for w/b of 0.50 and total binder content of 310 kg/m^3.

For each concrete, 100 mm cube specimens were prepared and cured, until testing, in a moist room at a temperature of approximately 25 ± 3 °C. Immediately after the specified curing period, three specimens were tested for compressive strength in each case. A testing frame of 3000 kN capacity was used and the loading rate was controlled at 140 kgf/cm^2/min, as recommended by IS 516:2004 [22]. This was used as an input parameter for the elastic modulus tests, as discussed later. For each concrete, the static elastic modulus of three cylindrical specimens of 150 mm diameter and 300 mm height (cured for 28 days) was determined by following the ASTM C 469: 2010 [23] method (see the inset in Fig. 2 for details). Before testing, both ends of the cylinder specimens were sulphur-capped for uniform contact and load distribution. Three electronic compressometers with gauge length of 150 mm and least count of 0.02 microns were used to measure the longitudinal strains. The load was applied in three cycles between 5 and 40% of the average 28-day compressive strength. Figure 2 shows a typical stress versus strain curve (inset shows the cyclic loading pattern load versus time curve). The output was recorded by a computer-based data acquisition system. The slope of the loading portion of the third cycle was used to calculate the elastic modulus of the concrete.

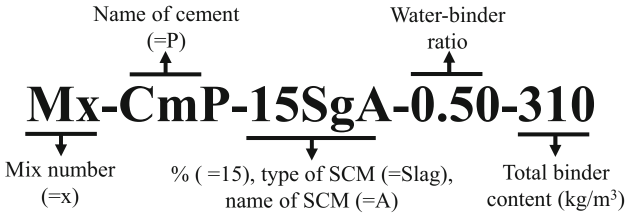

Fig. 1 Nomenclature for the concrete mixes

Results and Discussion

Fresh Concrete Properties

Table 2 shows the fresh concrete properties such as initial slump, slump at 30 min, air content and density of various concretes. The ASTM C231:1997 [24] standard pressure method (Type B) for the determination of air content in the freshly mixed concrete was followed. The density and air content in the mixes were found to be reasonable for normal concrete. The slump was seen to decrease from about 100 mm to about 65 mm after 30 min.

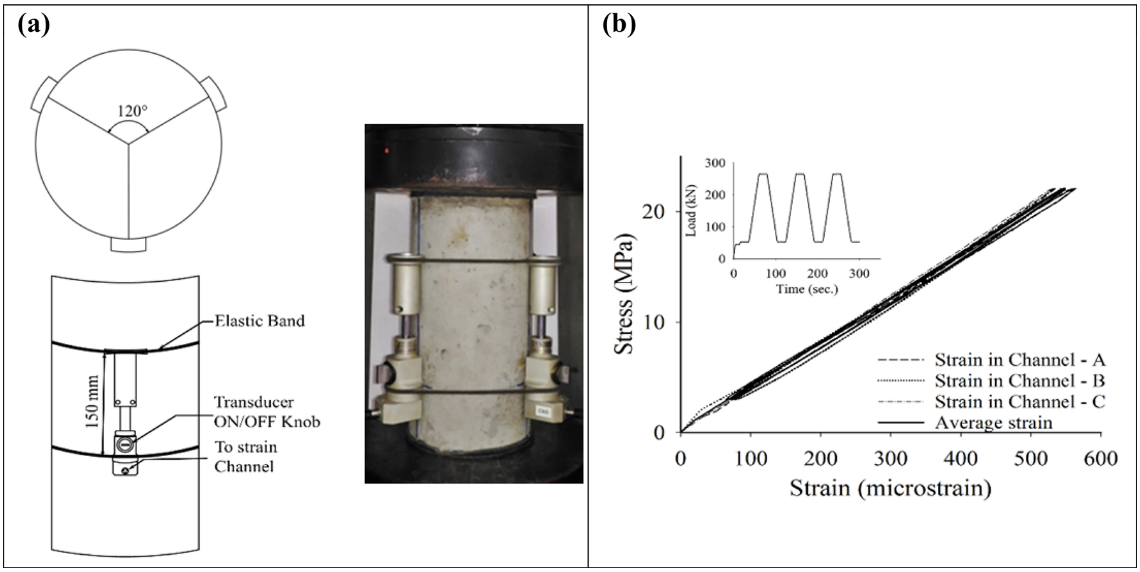

Fig. 2 **a** Test set-up and instrumentation and **b** typical stress–strain curve with loading history

Evolution of Compressive Strength

Table 3 shows the mean compressive strength obtained from at least three specimens, along with the corresponding standard deviation in parentheses. The cube compressive strength of concrete ranged from 20 to 55 MPa at 28 days and from 32 to 64 MPa at 1 year. On an average, the 7- to 28-day compressive strength ratio for the concretes was in the range of 0.51 to 0.92. The ratio for NoSCM concrete was in the range between 0.62 and 0.92, whereas in binary blended concretes with slags (SgA and SgB) and fly ashes (FaF and FaC) it was in the range of 0.56 to 0.87 and 0.51 to 0.82, respectively. In the case of ternary blended systems, the ratio was in the range of 0.68 to 0.86. This shows that the increase in the compressive strength from 7 to 28 days could be higher than the general value of 0.67 for OPC concretes used in practice [25]. Furthermore, the strength gain of some concretes was even double at the end of 1 year, in comparison with the 28-day compressive strength. For the concretes in this study, the cylinder-to-cube strength ratio was found to be 0.81; see Fig. 3.

As seen in the case of CmA mixes, the strength at lower w/b is lower for the blended binders at early ages though the strengths at later ages are similar. At higher water-to-binder ratios (*w/b* = 0.65), the strength development of the CmP-NoSCM and SgA-blended concrete is comparable. As expected, Class F fly ash concrete exhibits lower compressive strength at early ages. However, the long-term strength gain is more pronounced at 90 days and above. The results agree with those reported by other researchers [26, 27] that the early strength of slag and fly ash is lower when compared to the strength of non-blended concrete, due to the slow rate of hydration. It is evidently indicated in Table 3 that there is a significant increase in the strength of fly ash-blended concrete (both FaF and FaC) in the long term. Also, Class C fly ash concrete exhibits higher strength in comparison with that of Class F fly ash, which can be attributed to the higher calcium oxide content [28, 29]. As observed in Table 3, the strength of ternary blended concrete with CmP cement until 28 days is less than the NoSCM concrete, which confirms the results of [29]. Furthermore, only a marginal difference in the strength is observed between the SgB-FaF and SgB-FaC concretes. In the case of FaF-FaC-blended concrete, the 2-day strength was lower than the other mixes. However, there was a substantial increase in the strength later on, up to 90 days. In general, ternary blends provide a positive effect on the gain in compressive strength with age.

The elastic modulus of FaF-blended concrete was lower than the CmP mix concrete at all replacement levels. The values for concrete with 15% and 30% replacement of fly ash were similar and much higher than that with 50% replacement. For Slag B there was a significant increase in the elastic modulus with slag replacement between 15 and 30%. However, with 50% replacement, the modulus did not increase further, indicating the filler effect on the elastic modulus.

ACI 209 [30] provides an empirical model to predict the compressive strength as a function of time, which is expressed as follows.

$$f'_c(t) = \frac{t}{\alpha + \beta t} f'_c(28) \quad (1)$$

where α and β are constants, $f'_c(28)$ is the mean cylinder compressive strength of concrete at 28 days and $f'_c(t)$ is the compressive strength of concrete at any age t. For 150-mm-

Table 3 Cube compressive strength and elastic modulus of concrete

Sl. no	Mix nomenclature	Mean cube compressive strength of concrete (MPa); (standard deviation)					Elastic modulus of concrete (GPa) (standard deviation)
		Age at testing (in days)					
		2	7	28	90	365	28
M1	CmP-NoSCM-0.65-280	9.61 (1.1)	19.61 (1.3)	30.21 (0.7)	32.10 (1.2)	33.91 (1.0)	29.73 (1.5)
M2	CmP-30SgA-0.65-280	11.08 (1.7)	19.09 (2.2)	31.14 (0.8)	31.96 (1.5)	34.17 (1.7)	31.45 (0.1)
M3	CmP-30SgB-0.65-280	13.44 (0.9)	24.93 (1.3)	33.27 (1.5)	38.63 (1.1)	39.22 (0.1)	34.47 (1.0)
M4	CmP-30FaF-0.65-280	5.96 (0.9)	13.16 (0.7)	22.33 (1.3)	36.33 (1.4)	39.00 (0.0)	29.39 (0.1)
M5	CmP-NoSCM-0.55-340	28.35 (0.8)	39.78 (1.7)	44.39 (2.2)	46.48 (0.4)	47.95 (1.0)	35.78 (0.4)
M6	CmP-15SgA-0.55-340	15.30 (0.5)	22.67 (1.0)	40.71 (1.2)	47.17 (1.8)	50.04 (1.9)	37.42 (1.2)
M7	CmP-15SgB-0.55-340	23.60 (1.2)	33.61 (0.9)	48.05 (1.0)	53.52 (0.8)	55.47 (0.4)	36.73 (0.5)
M8	CmP-15FaF-0.55-340	12.92 (0.5)	23.33 (1.2)	39.82 (1.4)	50.81 (0.9)	54.77 (1.8)	34.44 (0.1)
M9	CmP-15FaC-0.55-340	14.77 (1.2)	30.94 (1.5)	43.66 (0.7)	54.09 (1.1)	57.65 (0.4)	34.57 (0.9)
M10	CmP-NoSCM-0.50-310	32.18 (1.2)	40.26 (1.1)	45.65 (0.5)	48.60 (0.6)	49.33 (1.4)	33.42 (1.5)
M11	CmP-15SgA-0.50-310	15.61 (0.6)	38.32 (0.7)	52.48 (0.7)	59.51 (1.2)	62.17 (1.9)	40.10 (0.7)
M12	CmP-15SgB-0.50-310	24.87 (1.9)	38.20 (1.7)	52.59 (1.1)	55.96 (0.4)	58.13 (1.1)	35.89 (1.3)
M13	CmP-15FaF-0.50-310	18.12 (1.6)	23.86 (1.7)	35.62 (0.7)	57.13 (1.1)	62.93 (0.2)	30.12 (0.7)
M14	CmP-15FaC-0.50-310	19.59 (0.7)	27.00 (0.1)	42.03 (1.5)	58.75 (1.5)	61.07 (0.1)	36.77 (2.2)
M15	CmP-30SgB-0.50-310	24.48 (1.9)	39.86 (1.5)	52.15 (0.9)	62.91 (1.4)	63.38 (1.5)	37.50 (0.5)
M16	CmP-30FaF-0.50-310	11.71 (0.1)	20.48 (1.7)	37.00 (0.9)	50.03 (0.8)	55.31 (0.5)	32.83 (1.3)
M17	CmP-30FaC-0.50-310	22.42 (1.4)	33.75 (1.5)	47.12 (0.9)	58.98 (1.4)	59.04 (0.8)	35.20 (0.8)
M18	CmP-50SgB-0.50-310	17.22 (0.8)	25.89 (1.0)	42.07 (1.7)	61.57(1.5)	62.79 (0.2)	36.95 (1.5)
M19	CmP-50FaF-0.50-310	4.38 (1.2)	10.82 (0.8)	21.24 (1.0)	43.11 (1.2)	44.00 (0.2)	22.85 (1.1)
M20	CmP-20SgB-20FaF-0.50-310	17.93 (1.0)	25.02 (0.2)	32.69 (1.3)	50.34 (1.1)	52.30 (1.0)	31.75 (1.7)
M21	CmP-20SgB-20FaC-0.50-310	19.41 (0.8)	28.15 (1.3)	39.63 (0.7)	53.49 (1.5)	55.01 (0.7)	39.38 (0.6)
M22	CmP-20FaF-20FaC-0.50-310	12.32 (1.2)	32.30 (1.0)	43.74 (1.7)	50.61 (0.7)	50.46 (0.7)	34.33 (1.6)
M23	CmP-NoSCM-0.60-310	12.92 (0.8)	20.14 (1.4)	32.36 (1.2)	34.53 (0.8)	37.06 (1.9)	36.61 (0.6)
M24	CmP-15SgA-0.60-310	13.10 (0.7)	27.98 (1.8)	43.77 (0.8)	45.34 (1.1)	46.11 (0.3)	32.87 (1.9)
M25	CmP-15SgB-0.60-310	11.96 (1.1)	19.49 (0.9)	32.53 (0.5)	40.16 (1.0)	42.93 (0.5)	29.33 (1.4)
M26	CmP-15FaF-0.60-310	9.35 (0.6)	23.73 (0.4)	31.27 (0.8)	41.47 (1.2)	44.81 (0.2)	34.31 (0.9)
M27	CmP-15FaC-0.60-310	16.56 (0.9)	23.59 (0.8)	34.73 (1.1)	42.12 (1.1)	44.29 (1.6)	39.96 (0.9)
M28	CmA-NoSCM-0.65-280	15.63 (0.9)	24.30 (1.1)	26.30 (0.6)	31.94 (0.8)	34.34 (2.3)	Data not available
M29	CmA-30SgA-0.65-280	15.94 (0.9)	20.83 (0.6)	24.07 (1.5)	31.00 (1.2)	31.72 (1.0)	
M30	CmA-30SgB-0.65-280	11.45 (0.8)	21.56 (2.0)	26.03 (0.3)	29.25 (1.4)	35.96 (1.9)	
M31	CmA-30FaF-0.65-280	12.60 (0.5)	15.89 (0.8)	19.48 (0.6)	28.33 (0.5)	32.00 (1.9)	
M32	CmA-NoSCM-0.55-340	28.11 (1.6)	35.66 (0.9)	43.66 (0.6)	44.44 (2.2)	45.17 (0.9)	
M33	CmA-15SgA-0.55-340	21.05 (0.8)	29.27 (0.8)	39.49 (1.5)	40.55 (1.4)	40.89 (2.8)	
M34	CmA-15SgB-0.55-340	29.72 (0.7)	37.19 (0.7)	44.60 (1.4)	46.94 (1.2)	50.40 (0.5)	
M35	CmA-15FaF-0.55-340	20.31 (0.9)	33.00 (0.9)	40.23 (2.3)	44.40 (0.7)	49.43 (1.1)	
M36	CmA-15FaC-0.55-340	15.24 (0.2)	23.26 (0.5)	42.45 (2.0)	45.33 (1.0)	45.12 (2.7)	
M37	CmA-NoSCM-0.50-310	30.72 (0.3)	34.22 (0.9)	43.17 (1.2)	54.40 (0.8)	54.65 (1.5)	
M38	CmA-15SgA-0.50-310	16.22 (0.5)	24.74 (1.5)	43.82 (0.4)	54.20 (1.7)	56.11 (1.4)	
M39	CmA-15SgB-0.50-310	27.66 (0.9)	35.65 (0.9)	48.09 (1.8)	49.10 (1.0)	54.97 (1.7)	
M40	CmA-15FaF-0.50-310	26.23 (1.6)	33.10 (0.6)	46.57 (2.7)	51.09 (2.2)	54.54 (1.9)	
M41	CmA-15FaC-0.50-310	21.50 (1.4)	23.46 (0.9)	43.95 (1.2)	46.04 (1.8)	45.63 (0.6)	
M42	CmA-30SgB-0.50-310	26.53 (0.7)	35.63 (1.0)	44.28 (1.1)	52.87 (1.0)	55.78 (0.6)	
M43	CmA-30FaF-0.50-310	10.82 (0.9)	19.46 (0.9)	35.71 (0.9)	39.12 (1.0)	40.85 (1.9)	
M44	CmA-30FaC-0.50-310	15.99 (0.9)	25.05 (1.2)	40.34 (1.0)	47.27 (2.5)	46.80 (0.5)	
M45	CmA-50SgB-0.50-310	30.46 (1.1)	37.04 (0.6)	45.87 (0.5)	57.15 (2.8)	61.73 (1.0)	

Table 3 continued

Sl. no	Mix nomenclature	Mean cube compressive strength of concrete (MPa); (standard deviation)					Elastic modulus of concrete (GPa) (standard deviation)
		Age at testing (in days)					
		2	7	28	90	365	28
M46	CmA-50FaF-0.50-310	4.84 (0.3)	13.00 (0.0)	25.72 (0.6)	28.40 (1.0)	32.34 (1.9)	
M47	CmA-20SgB-20FaF-0.50-310	21.29 (1.3)	36.57 (1.1)	42.40 (0.9)	50.59 (0.6)	55.09 (0.3)	
M48	CmA-20SgB-20FaF-0.50-310	21.11 (1.5)	29.60 (1.1)	43.44 (0.7)	44.56 (2.2)	43.92 (1.5)	
M49	CmA-20SgB-20FaC-0.50-310	14.86 (0.8)	18.42 (1.8)	27.29 (1.4)	40.29 (1.1)	49.30 (1.7)	
M50	CmA-NoSCM-0.60-310	17.47 (1.1)	25.69 (1.2)	31.36 (1.2)	36.68 (1.5)	42.68 (2.6)	
M51	CmA-15SgA-0.60-310	16.11 (0.5)	25.39 (1.3)	32.77(2.5)	39.84 (1.1)	43.90 (2.4)	
M52	CmA-15SgB-0.60-310	16.48 (0.5)	24.02 (1.0)	39.41 (1.2)	42.70 (1.6)	42.65 (0.4)	
M53	CmA-15FaF-0.60-310	20.91 (0.2)	25.65 (1.4)	35.89 (1.2)	43.11 (0.4)	44.66 (1.6)	
M54	CmA-15FaC-0.60-310	15.24 (0.2)	20.21 (0.5)	26.59 (1.6)	30.67 (0.1)	35.49 (1.2)	

diameter and 300-mm-long cylinders and for Type I cement and moist curing, ACI 209 suggests the constants α and β to be taken as 4 and 0.85, respectively. Considering the parameters to be valid for the specimens and concretes considered here, the ratio of compressive strength of concrete at time t to the mean compressive strength at 28 days can be expressed as follows.

$$\frac{f_c'(t)}{f_c'(28)} = \frac{t}{4 + 0.85t}. \qquad (2)$$

Figure 4 shows the variation of the $\frac{f_c'(t)}{f_c'(28)}$ ratio (denoted as strength ratio, fc_{ratio}, herein) as a function of time, for various concretes, where the experimental data are indicated by the markers, and the solid curve gives the trend estimated by Eq. 2. The dashed curves give the 95% confidence intervals (CI), which were calculated by assuming a normal distribution, as follows:

$$\mathrm{CI} = fc_{\text{ratio}} \pm 1.96 \times \mathrm{CoV}_{\text{experiment}} \times fc_{\text{ratio}}. \qquad (3)$$

where $\mathrm{CoV}_{\text{experiment}}$ is the coefficient of variation of the experimentally observed fc_{ratio} at the corresponding age.

As seen in Fig. 4a, the OPC concretes with high w/b, CmP cement and without any SCMs (M1 and M23) follow the trend predicted by ACI 209. The early-age strength of other OPC concretes is relatively higher than that predicted by the ACI equation. Also, almost all the concretes with CmA cement exhibit higher fc_{ratio} than predicted, especially when cured for more than 28 days. This may be because of the higher amount of CaO in this cement than in CmP cement. As shown in Fig. 4b, c, respectively, all SgB-blended concretes had higher strength than expected, while the SgA-blended concretes followed the expected trend. This can be attributed to the higher fineness of SgB in comparison with SgA. Figure 4d, e shows the effects of FaF and FaC, respectively, with FaC concretes having higher strength than the expected strength. However, in FaF concretes, the long-term strength ratios at 90 and 365 days are much higher than other blended concretes. This may be because the Class F fly ash exhibits retarded pozzolanic action [31].

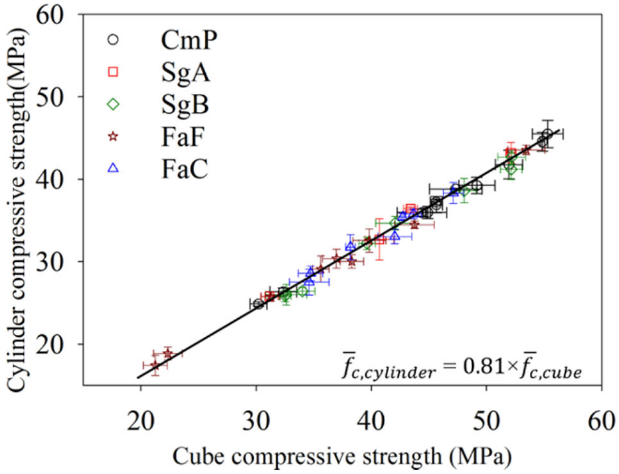

Fig. 3 Comparison of cube–cylinder compressive strength

Elastic Modulus of Concrete

The average 28-day elastic modulus of concrete, obtained from three specimens in each case, ranges between 22 and 40 GPa, with a standard deviation ranging between 0.05 and 2.2 GPa, as shown in Table 3. As expected, the elastic modulus of concrete increases with its compressive strength. A comparison of the measured mean elastic

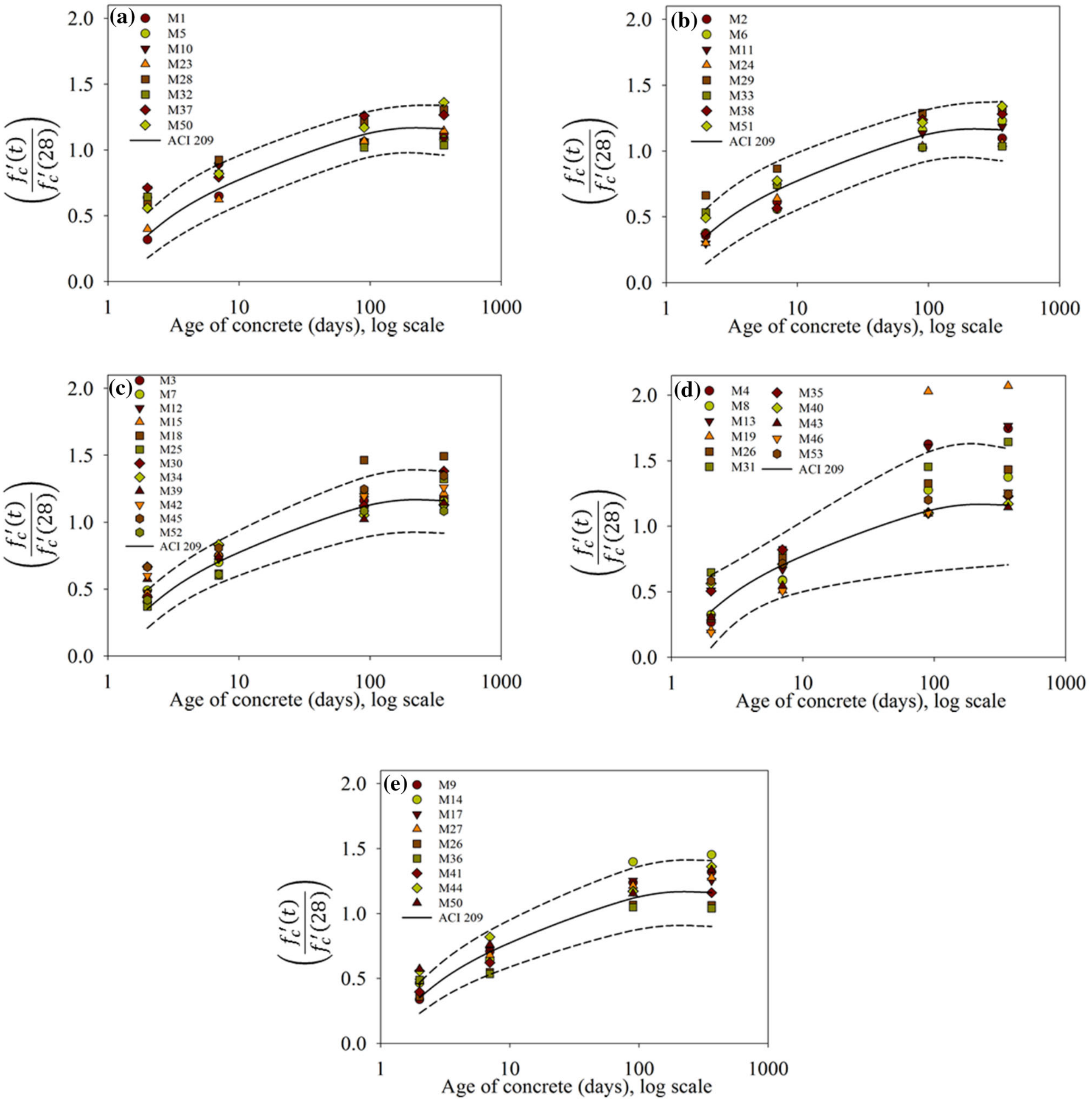

Fig. 4 Comparison of $\left(\frac{f_c'(t)}{f_c'(28)}\right)$ data for **a** OPC. **b** SgA, **c** SgB **d** FaF and **e** FaC concretes with the ACI prediction model and 95% confidence interval

modulus of concrete and the model predictions (say, IS 456:2000 [32], ACI 318:2008 [33], ACI 209:2005 [30], and *fib* Model Code 2010 [34]) as functions of the measured cube compressive strength is given in Fig. 5. The description and details of the code recommendations are discussed below.

IS 456 estimates the elastic modulus of concrete at 28 days, E_c, as follows:

$$E_c = 5000\sqrt{f_{ck}} \tag{4}$$

where f_{ck} is the characteristic 28-day cube compressive strength (MPa). The ACI 318 report recommends the following model for E_c.

$$E_c = 4733\sqrt{f_c'} \tag{5}$$

where $f_c{}'$, is the specified cylinder compressive strength of

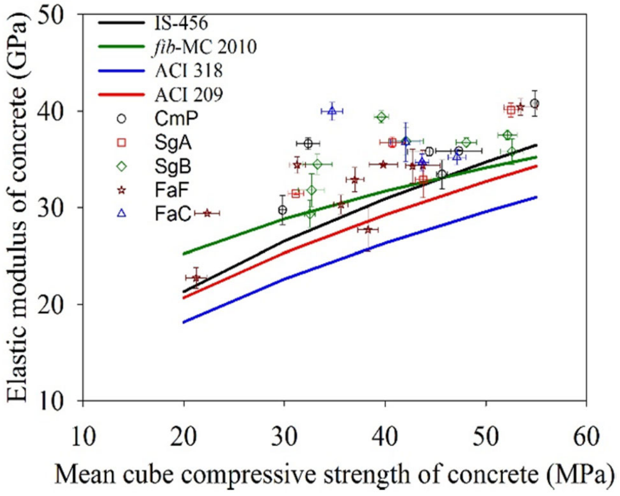

Fig. 5 Relation between the elastic modulus and compressive strength of concrete

concrete (MPa). However, ACI 209 suggests that the elastic modulus of concrete at time *t* (defined as E_{ct}) can be calculated as follows.

$$E_{ct} = g_{ct}[w^3(f'_c)t]^{1/2} \tag{6}$$

where g_{ct} is equal to 0.043; *w* is the unit weight of concrete (kg/m^3); and f'_{ct} is the cylinder compressive strength at any time *t* (MPa). The elastic modulus of concrete can also be predicted using the *fib* Model Code-2010 as follows:

$$E_{ci} = E_{c0} \times_E \times \left(\frac{f_{\mathrm{cm}}}{10}\right)^{0.3} \tag{7}$$

where E_{ci} is the modulus of elasticity of concrete at 28 days (MPa); f_{cm} is the mean cylinder compressive strength of concrete (MPa); E_{c0} is 21.5×10^3 MPa; and α_{E} is 1.0 and 1.2 for quartzite and basalt or dense limestone aggregates, respectively.

IS 456 and ACI 318 consider the characteristic compressive strength of cube (f_{ck}) and cylinder (f'_c), respectively, whereas *fib* MC-2010 and ACI 209 use the mean compressive strength of cylinders in the calculation of elastic modulus. For comparing the predictions, the mean cylinder compressive strength was converted to the mean cube compressive strength by multiplying with 1.23, taken from the average ratio obtained in this study. Also, for IS 456 and ACI 318 the characteristic/desired compressive strength was calculated considering $\sigma_{\mathrm{characteristic}} = \sigma_{\mathrm{mean}} - ks$, where "*k*" was taken as 1.65 and "*s*" was the standard deviation, taken as 1.12 from the measured cube compressive strength data in this study. The mean values are plotted with the predictions of elastic modulus in Fig. 5. It is clearly seen that the ACI 318 and ACI 209 model predictions are more conservative than the recommendations of IS 456 and *fib* MC 2010, as they are much lower than the band of data presented.

Conclusions

This work has evaluated the strength development and the elastic modulus of concrete with slag and fly ash-blended binders. The main conclusions drawn for the present study are as follows:

1. Slag-blended concrete shows higher strength gain at later ages in comparison with conventional concrete. Also, concrete with slag develops higher compressive strengths than the fly ash concrete.
2. Use of fly ash as a partial replacement for cement reduces the compressive strength at an early age. However, a significant increase in the strength is observed at the ages beyond 90 days, when the replacement dosage is up to 30%. Also, the relative strength gain of Class C fly ash concrete was higher than that of Class F fly ash. Nevertheless, prolonged curing is essential for fly ash-blended concrete to develop the higher strength.
3. At higher replacement dosages (i.e., 50%), the strength gain in slag- and fly ash-blended concrete is at slower rate than that of the control concrete initially; however, at age of 90 days and beyond, it attains comparable strength levels.
4. Concretes with ternary blended binders exhibit substantially higher compressive strength than the binary blends, at all ages of testing.
5. The time-dependent strength development, as given by the ACI 209 model, seems to better estimate the response of the concretes considered here beyond 28 days, while the estimates at 2 and 7 days seem to be conservative. The FaF concretes behave differently than the prediction with a higher increase in strength from 90 to 365 days.
6. The static elastic modulus of concrete increases with an increase in the compressive strength, in the same relation for both blended and non-blended concrete systems. It appears that the relations given by ACI 318 and ACI 209 are more conservative for the present concretes than those of IS 456 and *fib* MC 2010.

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