HIGH-TEMPERATURE CURING APPLICATION FOR CONCRETE COMPRISING FLY ASH AND GGBS

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Abstract

Fly ash (FA) and ground granulated blast-furnace slag (GGBS) are two promising supplementary cementitious materials (SCMs) that can be used in concrete applications. The early age strength development of such concrete is generally slow; however, the strength reduction can fairly be recovered with high-temperature curing implementation. In this study, the compressive strength behavior of binary and ternary concrete mixes those were subjected to 24 hours 50°C and 70°C curing conditions was explored. Two target compressive strengths levels of 30 MPa and 50 MPa were considered and the SCM blend level was 25 %. The results highlighted that, in terms of early strength achievement, the 50°C curing was favourable for the ordinary Portland cement (OPC) and OPC/GGBS mixes whereas the 70°C curing was attractive in the OPC/FA and in the ternary mixes. For the latter age strength, the high temperature curing detrimentally affected for the OPC and OPC/FA mixes whereas a considerable enhancement was noted for the GGBS blended mixes. The overall effectiveness of the high-temperature curing process was higher in the 30 MPa mixes than in the 50 MPa mixes. Meanwhile, the Arrhenious maturity function based strength predictions were identified to be more accurate than its prediction potential reported for past iso-thermal high-temperature curing applications.

Keywords: High-temperature curing; Maturity functions; Supplementary cementitious materials.

1. INTRODUCTION

Concrete is a leading material utilised in the construction industry, its popularity is ever consistent owing numerous attributes in strength and durability. However, the use of concrete possesses certain sustainability issues, because production of cement, which is the chief constituent of concrete, emits considerable amount of CO_2 to the environment. Consequently, the use of industrial by-products in the form of supplementary cementitious materials (SCMs) is highly promoted. Generally, SCMs are cheaper than cement. Such cement replacements could also be utilised to complement fresh and hardened concrete properties [1,2]. Two such popular SCMs are fly ash (FA) and ground granulated blast furnace slag (GGBS) [3,4].

FA is a found as a residual of coal-fired power plants and GGBS is a by-product of iron manufacturing [2]. The use of FA and GGBS introduces numerous attributes to the concrete quality and those include the improvements in: Workability, durability, and thermal properties [5]. FA is effective as a cementitious material up to about 30 % of cement replacement [3], and it of cause improves concrete workability [6]. Besides, Dhivakar *et al.* [7] studied the strength development of concrete mixes comprised of GGBS up to 50 %, and concluded that the optimum replacement level of GGBS in terms of strength was 30 %. Chandrakar, and Sing [8] experimented on high strength concrete (of 60 MPa compressive strength) that comprised ordinary Portland cement (OPC), FA and GGBS (OPC/FA/GGBS) ternary mixes at standard curing conditions. The results showed that the addition of 40 % FA and 30 % GGBS resulted in considerable 28 day compressive strength.

The partial replacement of cement with FA, and GGBS is thus identified to be impressive; however, particularly at early ages, reduction of compressive strength has been reported [9,10]. The strength decline is observed more seriously when GGBS is utilised at low temperature conditions [9,11]. Consequently, these SCMs are used reluctantly for applications where high early age strength is required, e.g. for precast concrete. It is meanwhile found that these SCMs (particularly GGBS) are considerably sensitive to high curing temperatures [9]. So, the strength reduction could potentially be overcome by the use of appropriate accelerated curing for such applications. It is also of note that the internal temperature of concrete structures significantly accumulates during early ages owing to the exothermic nature of cement hydration, particularly in mass concrete structures or insulated structures [9,12,13]. Hence, the temperature history of the concrete in a structure would be different from that of the control specimens which are under standard curing conditions. Interestingly, such unaccounted internal temperature risings in concrete structures simulate high-temperature curing conditions, so necessarily the strength of in-situ concrete (particularly SCM based concrete) would be better than what indicated by the control specimens. Because of these facts, comprehension of temperature sensitivity of cement/SCM hydration is useful.

As such, elevated temperature curing is a significant factor for the behavior of SCM based concrete and exploration into

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it is a vital research area. Such recent studies conducted on mortar/concrete that comprised of 30 % of FA and 50 % of GGBS are found in the literature [9,10]. In those investigations, two target compressive strength levels of 30/50 MPa and 10-50°C curing conditions were considered. Soutsos *et al.* [10] study was conducted on mortar subjected to iso-thermal high-temperature curing conditions. Whereas, the concrete specimens reported in Soutsos *et al.* [9] were subjected to curing temperatures which were matched with those of the internal temperature of real structures. It is meanwhile of interest how SCM blended concrete would react when it is subjected to the standard elevated-temperature curing practice, i.e. for 24 hours (ASTM C684-99 [14]). Also, explorations conduced at the conditions over 50°C temperature are seldom found. Another curiosity is how an OPC/FA/GGBS ternary blend would behave under high-temperature curing scenarios. To address these research gaps, the current study was formulated to explore the behavior of binary and ternary concrete mixes that comprised of 25 % of FA and GGBS each, and were subjected to 24 hours 50°C and 70°C high temperature curing cycles. To facilitate comparisons with the Soutsos *et al.* [9,10] studies, the target compressive strengths were selected to be 30 MPa and 50 MPa.

2. HIGH TEMPERATURE CURING OF MORTAR/CONCRETE COMPRISING SCMS

Barnett *et al.* [11] explored the effects of iso-thermal curing on the strength development of mortars that contained GGBS at cement replacement levels of 0, 20, 35, 50, and 70 %. The investigation had three distinct target compressive strengths of 40, 70, and 100 MPa. The curing temperature varied so that 10, 20, 30, 40 and 50℃. The results demonstrate that the strength development of the GGBS mixes was much slower than that of OPC under the standard (20°C) curing conditions; whereas, high-temperature curing notably influenced the strength behavior of both OPC and GGBS mortars. For instance, at three days, the OPC mortar strength was found in the range of 15 to 24 MPa while the optimum curing temperature was 40°C. Also, the compressive strength of the 70 % GGBS mortar mix was 26 MPa at the 50°C curing condition; whereas, it was only 2 MPa when the curing temperature was 10°C. In fact, at 40/50°C curing conditions, the strength of GGBS mortars were fairly equivalent to that of the OPC mortar at early ages.

Soutsous *et al.* [10] explored the strength development of mortar that was proportioned with ASTM C1074-98 [15] to represent equivalent strength of 30 MPa and 50 MPa concrete. FA and GGBS were added as SCMs and the dosage levels were 30 and 50 % respectively. The mortar was subjected to isothermal curing regimes at temperatures of 10, 20, 30, 40 and 50°C. The study concluded that the high curing temperatures had a beneficial effect on the early age strength but a detrimental effect on the long term strength development. The GGBS mortars were more sensitive to the high-temperature than the OPC and FA mixes, and this observation complemented with the finding that the GGBS mixes possessed the highest activation energy amongst the experimented mixes. It is also reported that the strength development of 'equivalent' mortars appeared to be reasonably similar to the compressive strength of corresponding concretes.

Soutsos *et al.* [9] investigated the behavior concrete where the cement was blended with 30 % FA and 50 % GGBS. The 28 day target mean strength was 30 and 50 MPa. The highlight of this study was the implementation of temperature matched curing so that to have similar internal temperature conditions of selected real structures. For this exclusive simulation, a programmable computer controlled water tank was utilised. The compressive strength results of the cube specimens were compared with the strength of cores extracted from the structures, and the two types of results were found to be fairly similar. It was concluded that the early age temperature accumulation effectively contributed to enchase the strength of FA and GGBS blended concrete.

Jung and Choi [16] investigated the effect of high-temperature curing cycle on the compressive strength of concrete that contained high volume of GGBS (60 %) and had a constant water to binder ratio of 0.35. The peak temperature varied between 55°C - 75°C and the curing cycle parameters were: Delay period, temperature rise, peak period, peak temperature, temperature down, etc. The total high temperature curing duration was approximately 14 hours. The findings highlighted that the influence of the curing profile on the resulting compressive strength behavior was considerable. It was also shown that the higher the curing temperature, the higher was the very early age (1 day) strength, but the lower was the latter age strength.

3. STRENGTH PREDICTION OF CONCRETE/MORTAR SUBJECTED TO ELEVATED TEMPERATURE CURING

Several analytical prediction models are available to be used to estimate the compressive strength of concrete at a given curing temperature [9,11]. The following function proposed by Carino and Tank [17] is the relation that is recommended in the ASTM C1074-98 [15] procedure.

$$S = \frac{S_\infty k (t-t_0)}{1 + k (t-t_0)} \tag{1}$$

here, S is the compressive strength prediction (MPa) at age t (day), S_∞ is the ultimate strength (MPa), k is the rate constant (day^{-1}), and t_0 is age at which strength development is assumed to begin (day). If the compressive strength at different ages is known for a given mortar/concrete mix that is subjected to iso-thermal curing, the values of S_∞, k and t_0 pertaining to that particular curing temperature can be found via regression analysis[11]. Accordingly, Soutsos *et al.*[10] explored the strength vs. age behavior of mortar mixes comprised of: 100 % OPC, 70 % OPC/ 30 % FA, and 50 % OPC/ 50 % GGBS at two distinct strength levels of 30 MPa and 50 MPa (i.e. at two *w/b* ratios) and at five different curing temperatures (10°C - 50°C). Thereby the governing parameters in Equation 1 for each curing temperature were found. Similarly, Soutsos *et al.*[9] found these parameters pertaining to the concrete mixes which had identical composition of the Soutsos *et al.*[10] experimental series and were subjected to the standard curing conditions. Table 1 tabulates these findings.

Maturity functions can be utilised to estimate the strength of concrete corresponding on its temperature history. Two such popular maturity functions are the Nurse-Saul function and the Arrhenious function[10,11]. Fundamentally, both these tools convert the age of concrete which has a (curing) temperature history to a representative maturity age. The former forecasts the age conversion to vary linearly with curing temperature; whereas, the latter function appreciates that the age conversion varies exponentially against the curing temperature. The study conducted by Soutsos *et al.*[10] showed that the estimation of compressive strength for the GGBS/FA mortars ash was more accurate with the Arrhenious function than with the Nurse-saul function. Therefore, the Arrhenious function was selected as the prediction tool of the current study, and further details of this maturity function is explained in the following sections.

Table 1: Prediction model parameters[9]

MIX	PROPERTY		REMARKS
OPC (30 MPa)	t_0 (days)	0.245	for 20°C curing
	k (day^{-1})	0.37	
	S_∞ (MPa)	33.36	
	E_a (kJ/mol)	37.4	-
OPC/FA (30 MPa)	t_0 (days)	7.5E-09	for 20°C curing
	k (day^{-1})	0.151	
	S_∞ (MPa)	46.35	
	E_a (kJ/mol)	22.5	-
OPC/GGBS (30 MPa)	t_0 (days)	0.199	for 20°C curing
	k (day^{-1})	0.077	
	S_∞ (MPa)	36.9	
	E_a (kJ/mol)	52.8	-
OPC (50 MPa)	t_0 (days)	2.5E-09	for 20°C curing
	k (day^{-1})	0.556	
	S_∞ (MPa)	55.5	
	E_a (kJ/mol)	29.7	-
OPC/FA (50 MPa)	t_0 (days)	6.33E-09	for 20°C curing
	k (day^{-1})	0.22	
	S_∞ (MPa)	63.9	
	E_a (kJ/mol)	27.3	-
OPC/GGBS (50 MPa)	t_0 (days)	1.3E-09	for 20°C curing
	k (day^{-1})	0.113	
	S_∞ (MPa)	55.7	
	E_a (kJ/mol)	41.6	-

The Arrhenious function defines the equivalent age (t_e) of a concrete subjected to a known temperature history to be in the form of,

$$t_e = \sum e - \frac{E_a}{R}\left(\frac{1}{T_a} - \frac{1}{T_s}\right). \Delta t \qquad (2)$$

where, T_a is the average temperature of concrete during time interval Δt (in K), T_s is the specified reference temperature (in K), E_a is the apparent activation energy (J/mol), R is the universal gas constant (J/K.mol).

The age conversion factor (β) is therefore,

$$\beta = e - \frac{E_a}{R}\left(\frac{1}{T_a} - \frac{1}{T_s}\right) \qquad (3)$$

note that apparent activation energy E_a is a governing parameter in this function. Soutsos *et al.*[10] estimated E_a for their mortar mixes via plotting ln k against the reciprocal of absolute temperature, which is in fact the method proposed in ASTM 1074-98[15]. Note that these particular E_a values are indicated in Table 1. Furthermore, Soutsos *et al.*[10] extensively reviewed the apparent activation energies reported in the literature for GGBS (dosage up to 70 %) and FA (dosage up to 30 %) mixes. They found that E_a for GGBS increased with the increasing dosage; whereas, E_a for FA had the opposite behavior. Similarly, Barnett *et al.*[11] explored into E_a for GGBS via experiments comprised of three distinct *w/b* ratio and of GGBS dosages up to 70 %. They showed that E_a increased linearly with the increasing GGBS amount irrespective of the *w/b* ratio.

The use of maturity functions coupled with the S curve (Equation 1) is thus a potential and non-complex approach to predict the compressive strength of concrete which has been subjected to diverse curing temperature histories. However, it is mostly observed that the predictions are inconsistent and the investigators recommend the functions be tuned up. For instance, Arrhenious function based compressive strength predictions obtained for the experiments in[10] were considerable over estimations irrespective of the age and composition of the mixes. The discrepancy was more prominent for the high temperatures of 40°C and 50°C.

Table 2: Concrete mix proportions

SAMPLE	SCM COMPOSITION		TARGET STRENGTH (MPa)	CEMENT (kg/m³)	WATER (kg/m³)	GGBS (kg/m³)	FA (kg/m³)	COARSE AGGREGATE (kg/m³)	FINE AGGREGATE (kg/m³)
	FA	GGBS							
M1	-	-	30	405.9	205.0	0	0	1024.0	665.6
M2	25 %	-		304.5		0	101.5	1024.0	665.6
M3	-	25 %		304.5		101.5	0	1024.0	665.6
M4	25 %	25 %		203.0		101.5	101.5	1024.0	665.6
M5	-	-	50	431.1	169.0	0	0	1164.3	599.1
M6	25 %	-		323.4		0	107.8	1164.3	599.1
M7	-	25 %		323.4		107.8	0	1164.3	599.1
M8	25 %	25 %		215.6		107.8	107.8	1164.3	599.1

4. EXPERIMENTAL INVESTIGATION

An experimental series was conducted to explore the strength development of concrete comprised of OPC, FA and GGBS blends under high-temperature curing conditions. The cement replacement levels were 25 % FA, 25 % GGBS, and 25 % GGBS/FA. The target compressive strengths were 30 MPa and 50 MPa. High-temperature curing at 50°C and 70°C was implemented over the first 24 hours, and thereafter, the curing was switched to the ambient conditions where the mean temperature was 26°C.

4.1 Materials

CEM I 42.5N [3] Ordinary Portland cement, crushed coarse aggregate (maximum size of 20 mm), and river sand were used as primary ingredients for concrete. The specific gravities of these material were 3.15, 2.64, and 2.58 respectively and the fineness modulus of the sand was 2.60. The specific gravities of FA and GGBS were 2.20 and 2.82 respectively. In addition, a Naphthalene Sulphonate based high range water reducing admixture was added to the 50 MPa mixes to achieve the desired workability.

4.2 Concrete mix proportioning

Mix portioning of the OPC mixes was carried out as per ACI 211.1-91 [18]. The specific gravities of OPC, fly ash, GGBS, fine aggregate and coarse aggregate were 3.15, 2.3, 2.9, 2.7, and 2.6 respectively. The major constituents of the SCMs were fly ash: SiO_2 - 56 % and GGBS: CaO - 41 %, SiO_2 - 35 %. In addition, fineness modulus of the fine aggregate was 2.8 and the dry rodded bulk density of the coarse aggregate was 1600 kg/m³. The target workability was 100 mm slump and the w/c ratio for 30 MPa and 50 MPa mixes was maintained at 0.5 and 0.4 respectively. For the SCM blended mixes, simply the OPC content (in the control mix) was partially replaced with the desired level of FA and/or GGBS amount. The resulting eight mix proportions are shown in Table 2. Note that a notation of M1 to M8 is used where M1 to M4 mixes represent the 30 MPa compressive strength range and M5 to M8 mixes represent the 50 MPa compressive strength range.

4.3 Experimental procedure

The materials were added to a pan concrete mixer in the order of coarse aggregate, OPC, GGBS and/or FA, sand, and water. For the 50 MPa mixes, the superplasticiser was mixed with the water and added. The materials were mixed for 5 minutes and then the resulting concrete was cast into 150 mm standard steel cube moulds, see Figure 1. The specimens were compacted on a vibrating table and the surface was levelled. For the high temperature curing application, the specimens together with the mould were wrapped by polythene sheets and transferred to the curing tank, see Figure 2. Those specimens were kept in the curing tank for the first 24 hours., and subsequently, were demoulded and moved to the room temperature curing tank.

Figure 1: Cube casting

Figure 2: Polythene wrapping

For each mix combination, 18 of 150 × 150 × 150 mm cubes were cast so that to test three samples each for compressive strength at 7 days and 28 days at each curing regime. There were 144 cubes cast altogether.

5. RESULTS AND DISCUSSION

The compressive strength results for 30 MPa mixes and 50 MPa mixes are shown in Figures 1 and 2 respectively. The results are also tabulated in Table 3. Overall, except for the ternary combinations (M4 and M8), the target strength was reached reasonably in both strength category mixes at 28 days. Another highlight is that the high-temperature curing application could increase the 7 days/28 days strength ratio (so that early hardening rate) generally by 20-30 % in the 30 MPa mixes and by 10-20 % in the 50 MPa mixes (see Table 3).

Table 3: Compressive (cube) strength results

MIX	HIGH TEMPERATURE CURING (°C) (FIRST 24 HOURS)	7 DAY RESULT		28 DAY RESULT		7 DAYS/28 DAYS STRENGTH RATIO
		AVERAGE COMPRESSIVE STRENGTH (MPa)	STRENGTH INCREASE	AVERAGE COMPRESSIVE STRENGTH (MPa)	STRENGTH INCREASE	
M1	-	28.7	-	52.6	-	54.5 %
	50	44.3	55 %	51.4	-2 %	86.3 %
	70	40.4	41 %	46.2	-12 %	87.5 %
M2	-	23.9	-	45.6	-	52.3 %
	50	26.1	9 %	39.3	-14 %	66.3 %
	70	37.3	56 %	51.3	13 %	72.6 %
M3	-	18.1	-	29.3	-	62.0 %
	50	32.1	77 %	40.1	37 %	80.1 %
	70	28.1	55 %	32.7	12 %	85.8 %
M4	-	8.8	-	17.8	-	49.6 %
	50	17.8	101 %	23.3	31 %	76.3 %
	70	20.1	127 %	25.1	41 %	80.0 %
M5	-	49.6	-	65.5	-	75.7 %
	50	59.5	20 %	58.1	-11 %	102.4 %
	70	57.4	16 %	60.6	-7 %	94.7 %
M6	-	33.0	-	49.0	-	67.3 %
	50	32.7	-1 %	42.8	-13 %	76.4 %
	70	43.8	33 %	51.9	6 %	84.3 %
M7	-	35.9	-	48.4	-	74.1 %
	50	41.6	16 %	49.1	1 %	84.7 %
	70	30.9	-14 %	36.1	-25 %	85.6 %
M8	-	17.5	-	33.0	-	52.9 %
	50	25.4	45 %	36.1	10 %	70.2 %
	70	39.4	126 %	38.3	16 %	10.3 %

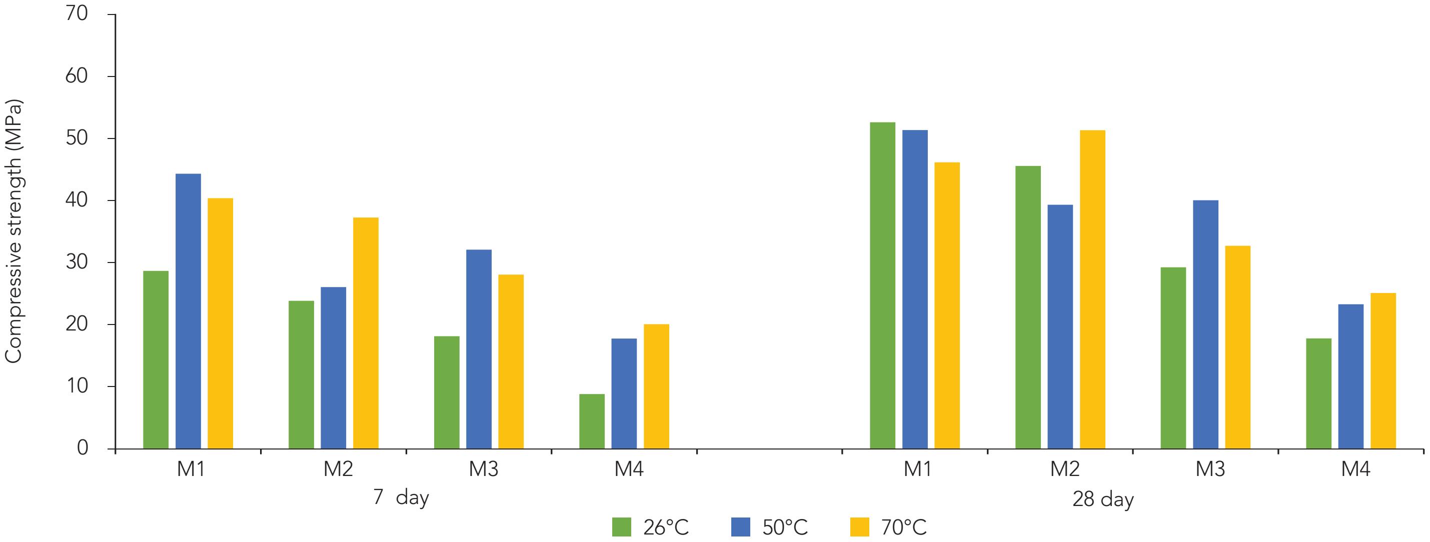

Figure 3: Compressive strength comparisons for 30 MPa series

Figure 3 shows that the applied accelerated curing was fairly effective to enhance the early strength development of the 30 MPa OPC mixes. The 7 day compressive strength was escalated for 50°C and 70°C curing cycles by 55 and 41 % respectively, so the former provided better strength augmentation. However, the influence of the high temperature curing detrimentally affected on the 28 strength where strength reduction up to 12 % was noticed. It is an expectable outcome, because with high early age temperature, un-hydrated particles densifies around the hydrated elements and hinders the effectiveness of latter age hydration [2,11]. Meanwhile, in terms of early age compressive strength, the manipulation of the 70°C curing temperature on the OPC/FA blends was impressive. The pertaining 7 day compressive strength was enhanced by 56 %. Also, the 28 day compressive strength of this mix was slightly above the ambient temperature curing mix. However, 50°C curing did not indicate such significance at 7 days and was detrimental for the 28 day strength. Meanwhile, in the OPC/GGBS mixes, significant strength enhancements with 50°C curing were noticed in the range of 77 and 37 % at 7 and 28 days respectively. In contrast, the 70°C curing provided a lesser influence than the 50°C curing, however it was still useful. Similarly, the high-temperature curing was favourable with the ternary mixes for both 7 and 28 day strengths. The 70°C option was more impressive in terms of strength enhancement. For instance, the 7 day compressive strength had almost doubled due to the application of the high-temperature curing. However, the target strength achievement is noticed to be unsatisfactory in these ternary mixes, so, mix design revision is vital for such applications.

Figure 4 depicts that the compressive strength development pattern for the 50 MPa OPC mixes under the applied curing scenarios was reasonably similar to that of the 30 MPa series.

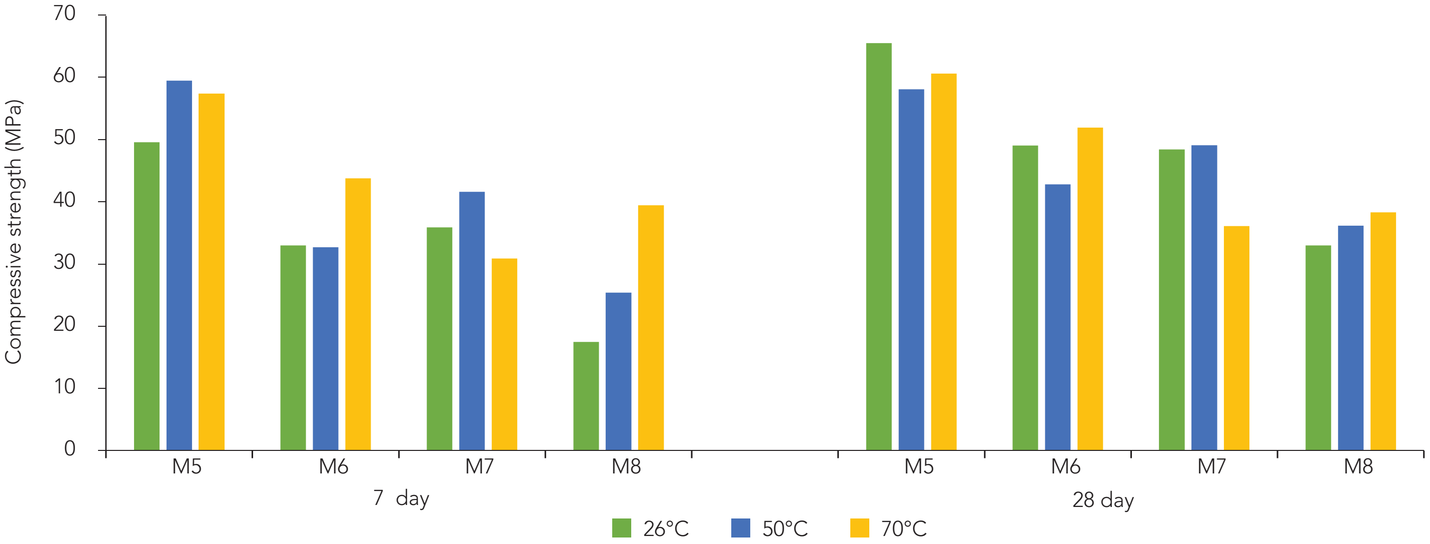

Figure 4: Compressive strength comparisons for 50 MPa series

The 50°C curing condition was slightly more favourable than 70°C towards the 7 day compressive strength. Of note is that the effectiveness of the curing process in this context was lower than that for the 30 MPa mixes. Similar to the previous situation, the high-temperature curing was detrimental for the 28 day strength of the OPC mixes. Meanwhile the behavior of the 50 MPa OPC/FA mixes is identified to be fairly similar to the 30 MPa behavior. The 70°C curing was more effective than 50°C towards the 7 day strength whereas no significant strength benefit from the high-temperature is noted at 28 days. Also, the effectiveness of the high-temperature curing noticed in the 30 MPa OPC/GGBS series was not observed in the 50 MPa series. The 50°C curing provided marginal 7 day strength enhancement while the 70°C application had a negative impact. Besides, the ternary mixes again showed considerable sensitivity on the curing temperature at 7 days. The influence towards the 28 day strength was not much highlighted. However, as pointed up previously, mix design revision is recommendable in order to reach the target strength of such ternary concrete mixes.

As a summary, for both 30 MPa and 50 MPa mixes, the high temperature curing application was useful to escalate the 7 day compressive strength of the OPC and OPC/FA mixes. For the OPC mixes, the 50°C curing was better whilst the 70°C curing was better for the OPC/FA mixes. However, the latter age strength was negatively affected. Meanwhile, in the presence of GGBS, the accelerated curing generally supported both the early and latter age compressive strengths. In the OPC/GGBS blends, the 50°C curing was more impressive whereas in the ternary blends, the 70°C curing was more effective towards compressive strength. In the latter context, strength enhancements over 125 % were observed. It is interesting to note that the overall effectiveness of the high temperature curing was higher in 30 MPa mixes than in the 50 MPa mixes. That outcome agrees with the findings in [11] where those highlighted that higher the *w/c* ratio, the higher was the effectiveness of high temperature curing.

6. PREDICTION OF COMPRESSIVE STRENGTH DEVELOPMENT

The compressive strength of the cube specimens were predicted via the Arrhenious maturity function. It is of note that Soutsos *et al.* [10] made a similar attempt for mortar cubes that were subjected to iso-thermal curing up to 50°C, and Soutsos *et al.* [9] made such predictions for temperature match cured concrete samples where the maximum temperature was about 60°C. Certain level of over prediction disparity was observed at both these attempts, particularly at high-temperature curing regimes. It is therefore interesting to see the prediction model potential to deal with first 24 hours curing conditions and with 70°C temperature curing.

As discussed previously, the essential parameters for this particular prediction model are: S_∞, k, t_0, and E_a. Table 1 tabulates these four parameters found by Soutsos *et al.* [9] for the compositions of: 100 % OPC (Composition A); 70 % OPC/30 % FA (Composition B); and 50 % OPC/50 % GGBS (Composition C) for each compressive strength category of 30 MPa and 50 MPa. It is considered reasonable to use the values of: Composition A for M1/M5 (100 % OPC) mixes; and Composition B for M2/M6 (75 % OPC/25 % FA) mixes. Besides, the composition of M3/M7 (75 % OPC/25 % GGBS) mixes represents an intermediate level of Composition A and Composition C. Via the observation of Barnett *et al.* [11] that for GGBS blended mixes were proportional to the GGBS composition, the average of each parameter for Composition A and Composition C was utilised to represent the conditions of M3/M7 mixes. Accordingly, S_∞, k, t_0, and E_a values were 35.1/55.6 MPa, 0.2235/0.3345 day^{-1}, 0.222/0.1895 day, and 45.3/35.7 kJmol^{-1} for M3 and M7 mixes respectively. It is of note that strength prediction for the ternary mixes was not attempted because of unavailability of the parameter values for such mixes, and such investigation is identified as a matter for future work.

Figure 5 compares the compressive strength predictions with the experimental results. In general, the predictions move from over prediction to under prediction as the strength increases. Of the OPC mixes (M1/M5), the predictions are conservative; whereas, some extreme underestimations (of about 40 %) are also observed for the 30 MPa mixes. In view of the OPC/FA blends (M2/M6), the predictions for the 30 MPa mixes are generally conservative; whereas, those for the 50 MPa mixes are overestimated. For the OPC/GGBS blends (M3/M7), both over and under predictions are noted for the 30 MPa category; whereas, overestimations are found for the 50 MPa category including a few severe discrepancies. Interestingly, recall that much overestimated predictions were reported when the

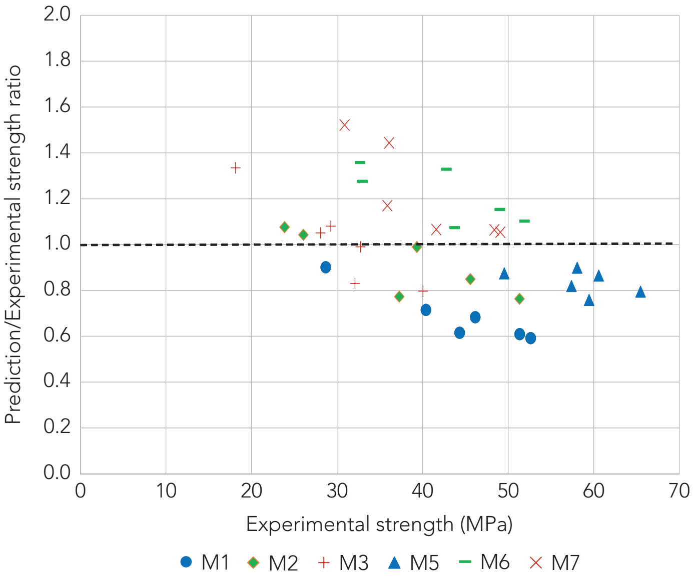

Figure 5: Predicted and experimental compressive strength ratios

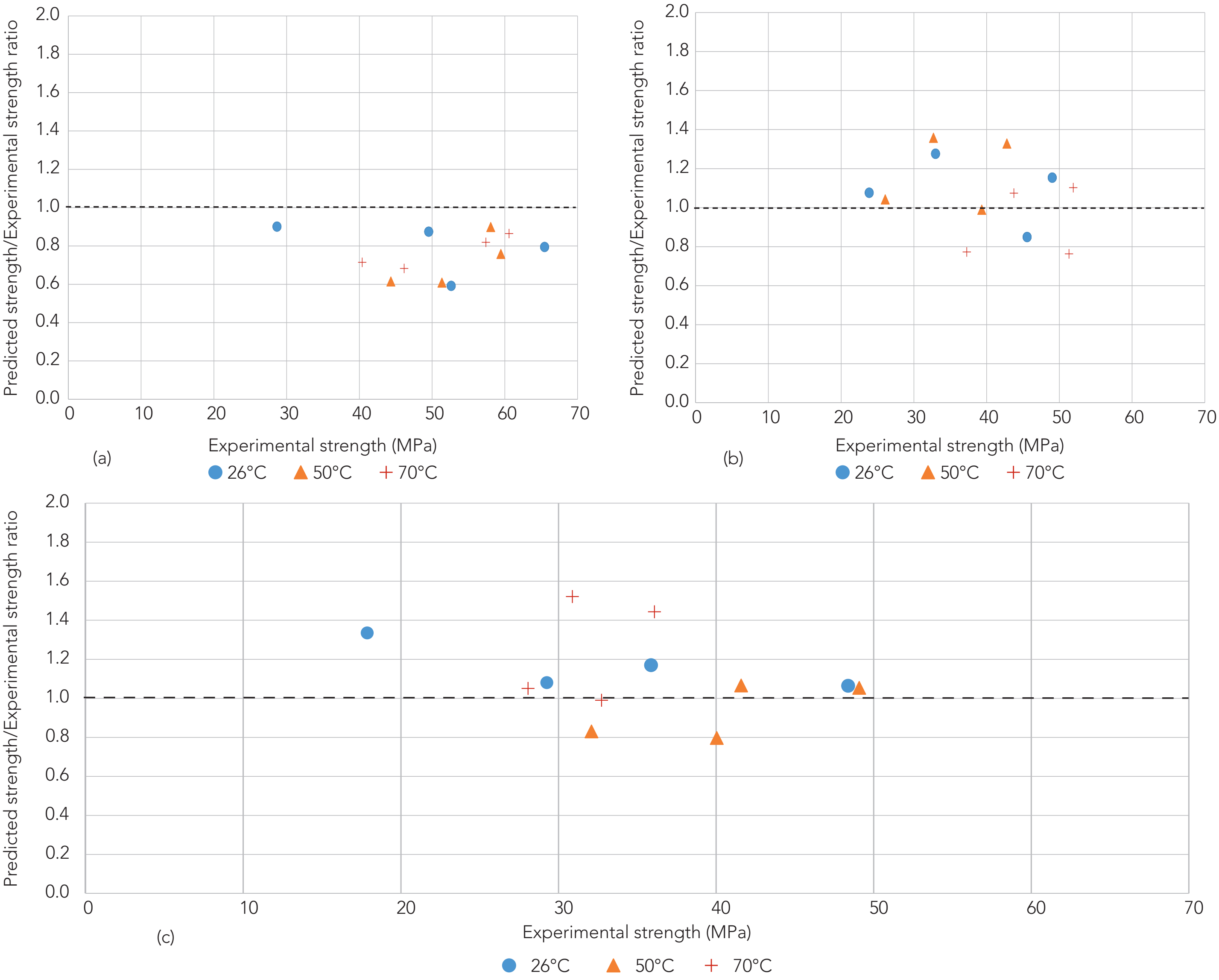

Figure 6: Influence of curing temperature on predictions: (a) M1/M5; (b) M2/M6; (c) M3/M7

prediction model was tested on Soutsos *et al.*'s [10] iso-thermal curing applications.

Figure 6 (a) - (c) illustrate the correlation of the analytical predictions with the experimental results for each high-temperature curing conditions. It is generally observed that the curing temperature does not show any notable manipulation on the predictions. In contrast, Soutsos *et al.* [10] reported the prediction discrepancy increased with the increased iso-thermal curing temperature.

Based on these observations, it is reasonable to claim that the prediction model capability to deal with 24 hours high-temperature curing conditions is more satisfactory than its potential reported in the literature on the iso-thermal high temperature curing applications. Also, the model does not show any notable vulnerability to deal with either 50°C or 70°C high-temperature level.

7. CONCLUSIONS

The compressive strength behavior of concrete mixes that comprised of OPC, OPC/25 % FA, OPC/25 % GGBS, and OPC/25 % FA/25 % GGBS under 24 hours 50°C and 70°C high-temperature curing applications was studied. The experiment had two target compressive strength levels of 30 MPa and 50 MPa. Based on the findings, the following conclusions could be drawn.

1. The application of high-temperature curing resulted in significant compressive strength escalations for the explored concrete mixes. Except for the OPC/FA/GGBS ternary mix, the target strength was reached reasonably in both 30 MPa and 50 MPa mixes.
2. The high-temperature curing application increased the 7 days/28 days strength ratio generally by 20-30 % and by

10-20 % for the 30 MPa and 50 MPa mixes respectively. Hence, the high-temperature application promoted the early age strength gain, particularly in the mixes with high *w/b* ratio.

3. The high temperature curing was helpful to escalate the 7 day compressive strength of the OPC and OPC/FA mixes of both strength (30/50 MPa) categories. For the OPC mixes, 50°C was the ideal curing temperature whilst the 70°C curing provided the best strength achievement for the OPC /FA mixes. However, the latter age strength was negatively affected in these mixes.

4. In the presence of GGBS, the high-temperature curing generally supported both the early and latter age compressive strengths of the concrete. For the OPC/GGBS blends, the 50°C curing was more useful; whereas, for the OPC/FA/GGBS ternary blends, the 70°C curing was more effective. Also, compressive strength enhancement over 125 % were observed in the ternary blends, but those mixes were deficient in achieving the target strength.

5. The overall effectiveness of the high temperature curing process was higher in the 30 MPa series than in the 50 MPa series.

6. The Arrhenious maturity function based strength predictions were found to be more satisfactory than its reported prediction accuracy for the iso-thermal high-temperature curing applications. Hence, it is apparent that the prediction model could associate the 24 hours high-temperature curing condition and the two exclusive high-temperature curing levels reasonably. However, further tuning up of the prediction model and its parameters is essential, and it is identified as a matter for future work.

7. FA and particularly GGBS can be used to replace OPC more than that used in this study (25 %), and hence, the exploration of scenarios carrying such high SCM levels under high-temperature curing is a recommendable future study. In addition, since it was observed that the effectiveness of the high-temperature curing is sensitive to the level of compressive strength and the use of high-strength concrete is wide spreading, it could be worthwhile to extend the current study towards high-strength applications.

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