Materials and Design 31 (2010) 4522–4527

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Thermal activation of ordinary Portland cement–slag mortars

Fathollah Sajedi *, Hashim Abdul Razak

Civil Department of Faculty Eng. at University of Malaya, 50603 Kuala Lumpur, Malaysia

A R T I C L E I N F O

Article history:
Received 5 February 2010
Accepted 2 April 2010
Available online 13 April 2010

A B S T R A C T

Thirty one mix proportions of ordinary Portland cement (OPC)–slag mortars (OSM) used to study the effects of temperature on early and ultimate strengths. Three levels of slag (0%, 40%, and 50%) and different temperatures were used; it was found that 50% is the optimum level and 60 °C with 20 h duration is also optimum. The maximum strengths obtained of optimum mortar, at 3 and 7 days, for specimens cured in the air, are 55.00 and 62.00 MPa, respectively. These strength levels are 64.50% and 66.50% greater than those without heating. The results show for 0 and 2 h heating time, the strength of specimens cured in the water are greater than those cured in the air, but for 4–26 h, this statement is reversed. This is a novelty, is very important in the precast industry and has many advantages for arid regions to overcome curing of concrete structures.

1. Introduction

Temperature variation caused by the heat of hydration, in mass concrete or the change of external environment, has a large influence on the mechanical properties of early-age concrete. Mechanical properties, such as compressive strength, are factors to be considered in the design and construction of concrete structures. Therefore, effects of temperature and aging, on the mechanical properties, should be studied and quantified.

According to the experimental results, concrete subjected to high temperatures at early ages, attains a higher early-age compressive and splitting tensile strength but lower later age compressive and splitting tensile strength than concretes subjected to normal temperatures [1]. Mortar and concrete are the most important elements of infrastructures and, if well-designed, they can be durable construction materials. One effective way to reduce the environmental impact is to use mineral admixtures, as a partial cement replacement. This strategy has the potential to reduce costs, conserve energy, and reduce waste volumes. Mineral admixtures are silica-based materials, such as ground granulated blast furnace slag (GGBFS), fly ash and silica fume. Mineral admixtures have been used more and more for concrete because of their strength and durability [2]. The presence of some mineral admixtures, such as GGBFS in the cement, can modify the kinetics of hydration, reduce the heat evolution and produce additional calcium silicate hydrates (CSH) gel. These admixtures result in a noticeable performance increase to the concrete, in hot climates, in which the negative effect of the temperature is partly reduced by the pozzolanic reaction, their weak hydration heat and their great activation energies.

Several researchers reported that a high temperature improves strengths at early ages [1–3]. At a later age, the important number of formed hydrates had no time to arrange suitably, and this engendered a loss of ultimate strengths; this behavior had been called the crossover effect [4]. For ordinary Portland cement (OPC), it appears that the ultimate strength decreases, nearly linearly, with curing temperature [5]. Since GGBFS itself is nothing more than a latent hydraulic binder, it must be activated to react and provide the desirable mechanical properties. One of these activation methods is the thermal method [6]. The objective of this study is to produce a data inventory of the early-age behavior, of some mechanical properties, such as compressive strength of mortars with temperature. In addition, to investigate the relationship between compressive strength with temperature, and the relationship between the compressive strength of specimens, cured in air and water, at 3 and 7 days, for 40% and 50% levels of slag replacement.

2. Research significance

It is known that a lot of slag is produced in the steel–iron industry every year, throughout the entire world. If a means of consumption for these materials is found, it would help in terms of being environment friendly and also provide significant economic benefits. Moreover, several researches have shown that the use of the replacement materials in mortars and concretes has improved durability, which has vital significance for the structures built in aggressive environments, such as those in marine structures, big tunnels, and bridges with long life spans. However, there is a problem in using the materials; initial hydration is lower than that for OPC, and then the mortars and concretes have low

---

* Corresponding author. Tel.: +60 17 3293252.
E-mail address: f_sajedi@yahoo.com (F. Sajedi).

0261-3069/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2010.04.011

early-strengths. Hence, there are several ways of resolving this problem; one of the most common methods is using thermal activation, which is precisely the main purpose of this study.

3. Experimental procedure

3.1. Mix proportions and curing

Table 1 represents the mix designs for different mortars. In all mixes W/B = 0.33, S/B = 2.25. Silica sand was used in the mixes. At first, based on Particle size analysis (PSA), five groups of silica sands were mixed. One minute after that, cement and replacement–slag were put into the mixture, followed by 1 min of mixing.

Mixing water was then added to the mix, and mixing was continued for 2 min, after which the required amount of super plasticizer (SP) was added. Mixing was continued for 2 min before finally, filling the moulds with fresh mortar at two layers. Each layer was compacted with 10 impacts by a rod with 16 mm diameter. 24 h after casting, the specimens were demoulded and heated in water at 60 °C, for the required time, as mentioned in Table 1, and then cured in air room temperature (27 ± 3 °C) with 65 ± 18% relative humidity (RH) and water with 23 ± 3 °C until the test day.

3.2. Properties of materials

The properties of the materials have been used in the study are as follows:

Table 1
Mix proportions for thermal activation method of OM, OSM/40, and OSM/50.

No.	Mix name	OPC (g)	Slag (g)	Water (g)	SP (g)	Flow (mm)
For OM, air and water cured						
1	OM-air cure	1800	–	631.66	28	230
2	OM- water cure	1800	–	631.66	30	230
For OSM/40, air and water cured						
3	H0/0	720	480	421.11	28	225
4	H60/2	1440	960	842.22	82	230
5	H60/4,6	1440	960	842.22	90	230
6	H60/8,10	1440	960	842.22	79	230
7	H60/12,14	1440	960	842.22	79	230
8	H60/16	1440	960	842.22	82	230
9	H60/18,20	1440	960	842.22	73	230
10	H60/22,24,26	2160	1440	1263.33	70	220
For OSM/50, air and water cured						
11	H0/0	600	600	421.11	35	230
12	H60/2	1200	1200	842.22	76	235
13	H60/4,6	1200	1200	842.22	91	225
14	H60/8,10	1200	1200	842.22	90	235
15	H60/12,14	1200	1200	842.22	73	235
16	H60/16	1200	1200	842.22	76	235
17	H60/18,20	1200	1200	842.22	62	225
18	H60/22,24,26	1800	1800	1263.33	60	220
For optimum OSM/50 at 6 ages, only air cured						
19	H60/20	900	900	631.66	43	230

H60/*i*, *j*, *k* means 60 °C temperature with hearting time *i*, *j*, and *k* h.

3.2.1. Cement

The cement used in all mixing designs was OPC. ASTM C 109-99 was used for the determination of the compressive strength of hydraulic cement mortars by use of 50 mm side cubes specimens. The specific gravity of cement used is about 3.14. Based on PSA test, the specific surface area (SSA) for OPC was determined to be 1.8939 m^2/g. The chemical composition of OPC used in this research has been determined by the testing method X-ray fluorescence spectrometry (XRF). The compositions of OPC used in this experimental work are given in Table 2.

3.2.2. GGBFS

The specific gravity of the slag is approximately 2.87, with its bulk density varying in the range of 1180–1250 kg/m^3. The color of GGBFS is normally whitish (off-white). Based on PSA test, SSA for GGBFS has been determined at 3.5972 m^2/g. It can be seen that the SSA for slag = 1.90 $*$ SSA of OPC, which means that particles of slag are 90% finer than that of OPC. The compositions of slag are given in Table 2. As with all cementing materials, the reactivity of the slag is determined by its SSA. In general, increased fineness results in better strength development, but in practice, fineness is limited by economic and performance considerations, and factors such as setting time and shrinkage [7]. For better performance, the fineness of GGBFS must be greater than that of cement. Based on the definition of the slag activity index (SAI) in ASTM C 989, it can be seen that $SAI = (SP/P) * 100$; where, SP = average compressive strength of slag-reference cement mortar cubes (MPa); P = average compressive strength of reference cement mortar cubes (MPa). Based on this definition, the slag used in the tests is classified into Grade 120. A sample calculation is shown in bottom of Table 2.

3.2.3. Aggregates

The fine aggregates used in the mixes are graded silica sands with specific gravity, fineness modulus (FM) and water absorption (A) (BS812: Clause 21) 2.68%, 3.88% and 0.93%, respectively. The maximum aggregate size (MSA) is 4.75 mm. The PSA of the fine aggregates is given in Table 3 and the grain size distribution diagram is drawn in Fig. 1.

3.2.4. Super plasticizer

In order to have an appropriate consistency with a low W/ B ratio, super plasticizer (SP) is required. The SP used in this investigation is Rheobuild 1100. The specific gravity of SP is approximately 1.195, is brown in color, with a pH in the range of 7.0–9.0. The consumed amount of SP in the mortar depends on the replacement level of slag.

3.2.5. Water

The water used in all mixes was potable water in pipeline of the lab. It is assumed that the specific gravity of the used water is about 1 g/cm^3.

Table 2
Composition of cementitious materials (% by mass).

P_2O_5	SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	MnO	K_2O	TiO_2	SO_3	CO_2	Cl
For OPC											
0.068	18.47	4.27	2.08	2.064	64.09	0.045	0.281	0.103	4.25	4.20	0.015
SrO	SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	MnO	K_2O	TiO_2	SO_3	CO_2	Na_2O
For slag											
0.047	31.21	12.96	4.27	0.868	41.47	0.207	0.31	0.49	2.04	6.00	0.11

For 7 days; SAI = 47.57/47.76 = 1.00 > 0.95; For 28 days; SAI = 62.83/50.26 = 1.25 > 1.15; K_b (basicity index) for slag = (41.47 + 4.27)/(31.21 + 12.96) = 1.03 > 1.00 [8]; $1.30 \leqslant CaO/SiO_2 = C/S = 1.33$ for slag $\leqslant 1.40$ [8].

Table 3
PSA for silica sand (SS) based on BS 822: Clause 11.

Sieve size (μm)	Sieve No.	WSS + WS (g)	WS (g)	WSS (g)	Ret.%	Cum. Ret.%	Pass %
4750	3/16 in	409.9	408.3	1.6	0.32	0.32	99.68
2360	NO.7	462.3	375.7	86.6	17.33	17.65	82.35
1180	NO.14	437.2	343.0	94.2	18.85	36.5	63.50
600	NO.25	450.7	316.2	134.5	26.93	63.42	36.58
300	NO.52	379.1	288.7	90.4	18.09	81.51	18.49
150	NO.100	322.1	274.8	47.3	9.47	90.99	9.02
75	NO.200	309.9	275.2	34.7	6.94	97.92	2.08
Pan	–	250.8	240.4	10.4	2.08	–	0.00
Total				499.7	–	388.31	

FM = 388.31/100 = 3.88 [9,10] A for SS is 0.93%; PSA for SS is: 12%, 18%, 30%, 20%, and 20%.

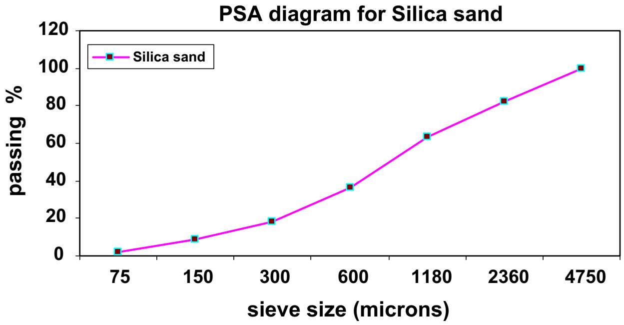

Fig. 1. PSA diagram for silica sand.

3.3. Test and mixing procedures

3.3.1. Test for fresh mortar

In order to have appropriate consistency for each mortar mix, after casting, a flow table test has been done. The range of flow amounts were between 220 and 235 mm. The process of the test procedure is that after casting, some mortar is put in the truncated brass cone, in two layers, and each layer is compacted 10 times by a steel rod with a 16 mm diameter. The cone is then lifted and the mortar is collapsed on the flow table. Following that, both the table and mortar are jolted 15 times in a period of 60 s. The jolting of the table, allowed the mortar to consequently spread out and the maximum spread to the two edges of the table was recorded. The average of both records is calculated as flow (mm). The photograph for the mixture and flow table test is shown in Fig. 2.

3.3.2. Test for hardened mortar

Three cubic samples, with lengths of 50 mm, were used for each age. Samples produced from fresh mortar were demoulded after 24 h, and were then cured in air with a temperature of 27 ± 3 °C and 65 ± 18%RH, and in the water with a temperature of 23 ± 3 °C, until the samples were then used for compressive strength tests at 3 and 7 days. Compressive strength measurements were carried out using an ELE testing machine press with a capacity of 2000 kN, and a loading rate of 0.5 kN/s. Compressive tests have been done according to BS 1881, Part 116, 1983.

3.3.3. Mortar mix method

At first, five groups of silica sand are put in as a mixture and mixed for 2 min. After that, the cement and slag are added and mixing is done for 3–4 min. Then the calculated water added is poured into the mix and the mixing is extended for 2 min, finally the SP is added and mixing continued for 2 min. Immediately after the end of mixing, the flow table test is done and the specimens are moulded. For each mix, the duration of mixing time takes about 8–10 min.

4. Results and discussion

In this experimental work, 29 mix designs of OSM have been used and two mixes as a control. For each mix, two points are important. Firstly, using a higher percentage of slag is desirable because it has some economic and environmental benefits, and also helps to improve the durability of the mortars. Secondly, it improves early strength. It is clear that by increasing the level of replacement–slag causes early strength to be reduced, since the slag has lower initial hydration heat than that OPC. Moreover, for short-term purposes, the use of a lower level of replacement–slag is neither economic nor durable. In this research, it is desirable to know the optimum temperature and its duration, which will give the highest early strength at 3 and 7 days.

In this investigation the effects of 50 °C, 60 °C, and 70 °C temperatures were studied on the early strengths at 3 and 7 days of OSM/50. The results are shown in Fig. 3. It is clear that 60 °C has

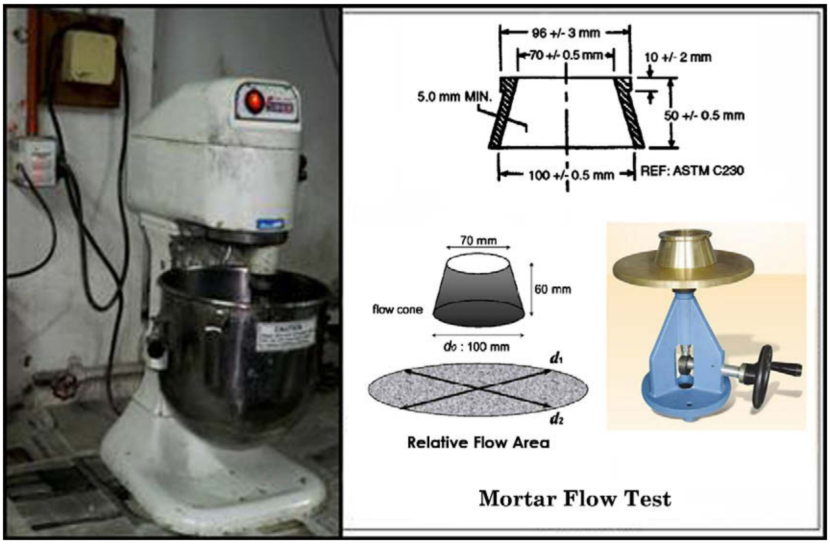

Fig. 2. Photograph for mixture and flow table test.

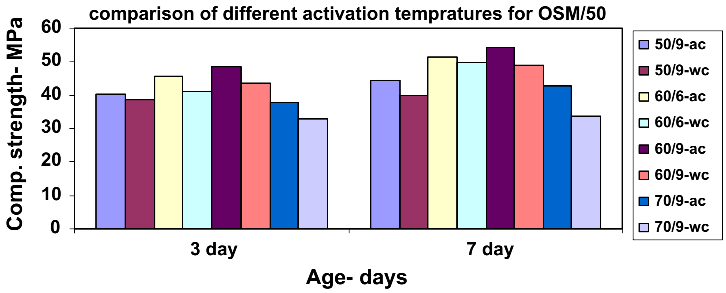

Fig. 3. The effects of different temperatures on early-age strengths of OSM/50.

the most enhancing effect on early-age strengths, so it is selected as the optimum temperature.

The results obtained in the study for compressive strengths, based on heating time, are given in Table 4. Based on the results, it can be seen that for the specimens of 3 and 7 day strengths, without heating and with 2 h heating time, being cured in water produced a better outcome than when cured in air. This reality has been proven for both OSM/50 and OSM/40. However, as soon as the heating time is increased to 4 h and more, the aforesaid statement is reversed. Conversely, when the heating time is increased to 4 h and more, the strength of specimens cured in air is improved, compared to the strength of specimens cured in the water. It seems this is due to air temperature and a high relative humidity of the air. This reality is shown in Fig. 4. An elevated curing temperature accelerates the chemical reactions of hydration, and increases the early-age strength, but during the initial period of hydration, an open and unfilled pore structure of cement paste forms and therefore negatively affects the properties of hardened concrete, especially at later ages [9,11]. Hardened mortars and concretes can reach their maximum strength within several hours through elevated temperature curing. However, the ultimate strength of hardened mortars and concretes has been shown to decrease with curing temperature [5].

It was found that by increasing the curing temperature from 20 °C to 60 °C and the heating time to 48 h causes a continuous increase in compressive strength [12]. Studies [13–15] have shown that there is a threshold maximum, heat curing temperature value, in the range of 60–70 °C, beyond which heat treatment is of little or no benefit to the engineering properties of concrete.

From data in Table 4 it can be seen that maximum strengths at 3 and 7 days, for OSM/40 and OSM/50, are attributed to the specimens cured in the air and are as: For OSM/40, F3 = 55.23 MPa, and F7 = 61.11 MPa for 18 h and 20 h, respectively. For OSM/50, F3 = 55.29 MPa, and F7 = 61.63 MPa for 20 h each.

The 3 and 7 days strengths for OPCs specimens, cured in air and water are as follows:

$$\begin{aligned} &\text{Cured in air,} \quad F1 = 29.55\ \text{MPa},\ F3 = 45.40\ \text{MPa}, \\ &\qquad\qquad\quad \text{and } F7 = 51.36\ \text{MPa}. \\ &\text{Cured in water,} \quad F1 = 33.33\ \text{MPa},\ F3 = 43.84\ \text{MPa}, \\ &\qquad\qquad\quad \text{and } F7 = 47.76\ \text{MPa}. \end{aligned}$$

It is noted that the maximum 3 and 7 days strengths of OSM/40's and OSM/50's specimens are 21.65%, 18.98% and 21.78%, 20.00% more than that of OPCs specimens cured in the air, respectively. It can be observed in Table 4 that at 56 days there is strength loss, compared to 28 days strength at about 2.2%. This has been previously reported by other researchers [16]. Whereas the main objective of elevated temperature curing is to achieve early strength development, and it is generally acknowledged that there is also strength loss as a result of heat curing [9]. Another mix of OSM/50 has been designed for an optimum temperature and heating time of 20 h (H60 °C – 20 h) at ages 1, 3, 7, 28, 56, and 90 days. The results of compressive strength vs. age of the specimens cured in the air are shown in Fig. 5. The best curve fitting is a logarithmic relationship:

$$\text{CS—T—C} = 5.2039 * \text{Ln}(t) + 50.664; \ \text{with } R^2 = 0.9311$$

Table 4
Compressive strength (MPa) vs. heating time (h) for OSM/40 and OSM/50 at 60 °C.

Heating time (h)	For OSM/40				For OSM/50			
	3 days		7 days		3 days		7 days	
	AC	WC	AC	WC	AC	WC	AC	WC
0	33.21	34.48	40.29	47.43	33.61	35.59	37.03	49.61
2	36.64	38.40	44.84	49.83	36.37	37.56	42.47	50.05
4	39.71	35.39	46.17	43.22	42.60	37.71	47.49	47.31
6	45.0	41.17	47.24	43.96	45.51	40.92	51.48	49.85
8	49.61	41.61	52.33	44.85	46.36	43.37	53.13	49.04
10	47.27	40.41	55.56	50.88	50.41	43.96	55.04	48.40
12	48.97	42.49	50.93	46.41	52.63	41.84	57.65	48.27
14	52.65	47.03	56.40	48.51	48.28	41.17	60.00	52.47
16	51.73	45.92	58.99	54.83	51.23	48.36	61.25	53.44
18	55.23	46.07	59.68	50.24	53.51	48.37	59.95	52.41
20	53.08	49.01	61.11	51.20	55.29	49.95	61.63	55.31
22	50.67	43.73	58.77	56	50.49	48.45	60.96	56.05
24	54.64	50.12	60.37	56.76	51.55	48.48	62.28	55.59
26	52.48	48.97	57.12	53.75	53.04	46.63	61.25	54.77
For optimum OSM/50 at six ages-air cured								
F1 = 15.55	F3 = 55.09	F7 = 61.44	F28 = 71.16		F56 = 69.61		F90 = 73.57	

AC = air cured; WC = water cured.

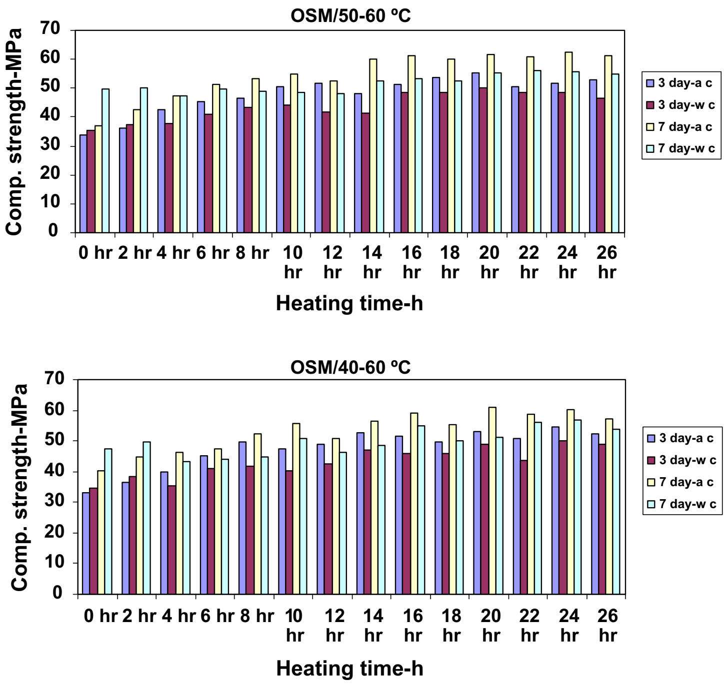

Fig. 4. Comp. strength vs. heating time for OSM/50 and OSM/40 cured in air and water.

where CS is compressive strength in MPa and *t* is age of specimen in day.

The relationships between compressive strength and heating time for air and water cured of OSM/40 and OSM/50 are shown in Table 5. It can be seen that the best relations are binomial and attributed to air cured specimens.

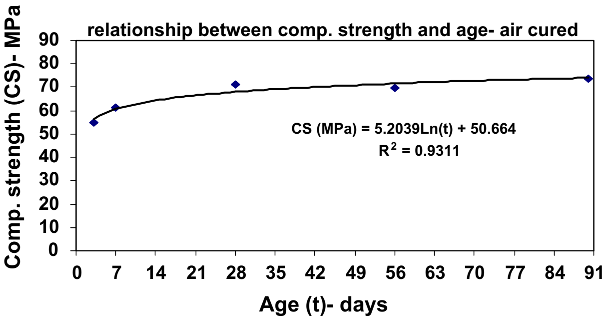

Fig. 5. Relationship between comp. strength vs. age for optimum OSM/50 cured in air.

It is seen that the best curve fitting for 3 and 7 days strengths are power relations.

According to the results obtained in the study, it can be said that thermal activation is one of the best methods for the activation of OSM. From the results obtained, presented in Table 6, it is seen that there is an acceptable power relationship for 3 and 7 days strengths between OSM/50 and OSM/40 air cured specimens. These relationships are determined by regression technique. Based on the results presented in Table 4, it can be seen that for 60 °C temperature and a heating time of 20 h, the maximum early strength is attributed to OSM/50 at 61.63 MPa. It can be seen that the increment percentage of 61.63 MPa is about 0.62%, when com-

Table 6
Relationship between compressive strengths (CS) of OSM/50 and OSM/40.

No.	Age (days)	Power regression relation	Curing regime
1	3	CS OSM/50 = $1.3991*x^{0.9147}$, $R^2 = 0.8857$	Air
2	7	CS OSM/50 = $0.4548*x^{1.2047}$, $R^2 = 0.9334$	Air
3	3	CS OSM/50 = $2.098*x^{0.8064}$, $R^2 = 0.7349$	Water
4	7	CS OSM/50 = $5.9897*x^{0.5511}$, $R^2 = 0.6897$	Water

x = CS of OSM/40 (MPa); R^2 = correlation coefficient.

Table 5
Relationship between compressive strength (MPa) vs. heating time (h) for air and water cured of OSM/40 and OSM/50.

No.	Age (days)	Binomial relation	Linear relation	Curing type
For OSM/40				
1	3	$-0.0455x^2 + 1.865x + 32.921$, $R^2 = 0.9261$	$0.6825x + 38.651$, $R^2 = 0.7545$	Air
2	3	$-0.0131x^2 + 0.8806x + 34.825$, $R^2 = 0.8502$	$0.5391x + 36.191$, $R^2 = 0.8252$	Water
3	7	$-0.0347x^2 + 1.5959x + 40.621$, $R^2 = 0.9107$	$0.6927x + 44.234$, $R^2 = 0.8068$	Air
4	7	$0.0163x^2–0.0222x + 46.327$, $R^2 = 0.6305$	$0.4011x + 44.634$, $R^2 = 0.5815$	Water
For OSM/50				
5	3	$-0.0487x^2 + 1.9196x + 34.298$, $R^2 = 0.9271$	$0.6526x = 39.366$, $R^2 = 0.7212$	Air
6	3	$-0.0184x^2 + 0.9857x + 35.234$, $R^2 = 0.8492$	$0.5066V + 37.154$, $R^2 = 0.7954$	Water
7	7	$-0.0479x^2 + 2.1079x + 38.56$, $R^2 = 0.9598$	$0.8628x + 43.54$, $R^2 = 0.8291$	Air
8	7	$0.0115x^2 + 0.0108x + 48.789$, $R^2 = 0.7742$	$0.3089x + 47.597$, $R^2 = 0.7232$	Water

x = heating time (h), R^2 = correlation coefficient.

pared to a heating time of 16 h. This shows that if the heating time is increased to more than 20 h, an increase of the 7 day strength is not noticeable. Hence, it can be said that 60 °C, with duration of 20 h, is the optimum temperature and heating time.

Based on the relationship in Table 6, it is shown that the correlation coefficient (R^2), in regression relations, for relationship between strengths, at 3 and 7 days of OSM/50 and OSM/40 water cured, is small. This shows that there is not an acceptable relationship between water cured strengths of the specimens, but reversely, there is a proper relationship between the strengths of specimens air cured at 3 and 7 days.

5. Conclusions

The results obtained from this research allow us to draw the following conclusions:

1. Based on obtained experimental results in the study, for each specified material, there is an optimum temperature to obtain high early strength. It is determined that 60 °C is the optimum temperature. Duration of heating time is also very important for obtaining high early strength. For the slag used in this study, 20 h heating time is optimum. Usually, as heating time increases towards the optimum, the compressive strength will be increased.
2. Maximum strengths at 3 and 7 days, for OSM/50 cured in the air, are 55.29 MPa and 61.63 MPa, respectively. It can be seen that these strength levels are 21.78% and 20.00% more than that for OPC's specimens cured in the air, and 26.12% and 29.04% more than that for OPC's specimens cured in water, respectively.
3. If the mortar is heated more than the optimum heating time, it is specified that this will not lead to an increase in the early strength of mortar.
4. According to the results of this study and other researches [17,18], it can always be reported that thermal activation is one of the best applicable methods for the activation of OSMs. It is well known that this method is usually used in precast concrete plants.
5. The results obtained show the best relationship of compressive strengths vs. heating time, for the specimens cured in air and water, between OSM/40 and OSM/50, are power relations.
6. There is a proper relationship between the compressive strength of the specimens cured in air and water, of OSM/40 and OSM/50 at 3 days, but not for 7 days.
7. It has been shown that the 3 and 7 days strengths of the specimens cured in water, of OSM/40 and OSM/50, without heating and for 2 h heating, are more than that cured in the air, but as soon as the heating time is increased to 4 h and more, this statement is reversed. This is a new finding with high importance in the precast industry, and has many advantages in arid regions for air curing of concrete structures.

References

[1] Jin-Keun Kim, Sang Hun Han, Young Chul Song. Effect of temperature and aging on the mechanical properties of concrete, Part I. Experimental results. Cem Concr Res 2002;32(7):1087–94.

[2] Corina-Maria Aldea, Francis Young, Kejin Wang, Surendra P Shah. Effects of curing conditions on properties of concrete using slag replacements. Cem Concr Res 2000;30(3):465–72.

[3] Ezzian K, Bougara A, Kadri A, Khelafi H, Kadri E. Compressive strength of mortar containing natural pozzolan under various curing temperature. Cem Concr Compos 2007;29(8):587–93.

[4] Cakir O, Akoz F. Effect of curing conditions on the mortars with and without GGBFS. Constr Build Mater 2008;22(3):308–14.

[5] Carino NJ. The maturity method: theory and application. JCCA 1984;6(2):61–73.

[6] Vladimir Zivica. Effects of type and dosage of alkaline activator and temperature on the properties of alkali-activated slag mixtures. Constr Build Mater 2007;21(7):1463–9.

[7] Jin-Keun Kim, Sang Hun Han, Seok Kyun Park. Effect of temperature and aging on the mechanical properties of concrete, Part II. Prediction model. Cem Concr Res 2002;32(7):1095–100.

[8] Pal SC, Mukherjee A, Pathak SR. Investigation of hydraulic activity of ground granulated blast-furnace slag in concrete. Cem Concr Res 2003;33(9):1481–6.

[9] Neville AM. Properties of concrete. 4th and final ed. Malaysia: Prentice Hall; 2008.

[10] Neville AM, Brooks JJ. Concrete technology. Malaysia: Prentice Hall; 2008.

[11] Brooks JJ, AL-kaisi AF. Early strength development of Portland and slag cement concretes cured at elevated temperatures. ACI Mater J 1990;87(5):503–7.

[12] Shi C. Strength, pore structure and permeability of alkali-activated slag mortars. Cem Concr Res 1996;26(12):1789–99.

[13] Hanson JA. Optimum steam curing procedures in precasting plants, PCA research and development laboratories. Dev Dept Bull 1963;D62(1). Also in J Amer Concr Inst, 60(1) 1963. p. 75–99.

[14] Pfeifer DW, Marusin S. Energy efficient accelerated curing of concrete, a state-of-the-art review. Technical Report No. 1, Prestressed Concrete Institute; 1991.

[15] Kosmatka SH, Panarese WC, Allen GE, et al. Design and control of concrete mixtures. 5th ed. Ottawa: Canadian Portland Cement Association; 1991. p. 131.

[16] Bougara A, Lynsdale C, Ezziane K. Activation of Algerian slag in mortars. Constr Build Mater 2009;23(1):542–7.

[17] Barnet SJ, Soutsos MN, Millard SG, Bungey JH. Strength development of mortars containing ground granulated blast-furnace slag: effect of curing temperature and determination of apparent activation energies. Cem Concr Res 2006;36(3):434–40.

[18] Zain MFM, Radin SS. Physical properties of high-performance concrete with admixtures to a medium temperature range 20–50 °C. Cem Concr Res 2000;30(8):1283–7.