Construction and Building Materials 36 (2012) 549–556

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Effect of curing regime and temperature on the compressive strength of cement-slag mortars

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HIGHLIGHTS

- ▶ WH/ac is the optimum curing regime for all groups of mortars in duration of 3–7 days.
- ▶ The optimum curing regime is not the same for all groups of mortars in duration of 28–90 days.
- ▶ Higher strengths achieved for OPC and OPC-slag mortars using lower binder content and curing regime wc.
- ▶ The strength of OSM380-wc at 90 days was obtained as 80 MPa.
- ▶ The highest strength for slag mortars could be only achieved using more slag content and curing regime wc.

ARTICLE INFO

Article history:
Received 10 July 2011
Received in revised form 16 May 2012
Accepted 4 June 2012

Keywords:
Curing
Temperature
Compressive strength
Cement
Slag
Mortars

ABSTRACT

In this experimental work 24 mixes were prepared. Each mix was made using binder contents 380 and 500 kg/m^3. All the made mixes are classified into three groups as OPC, OPC-slag and slag mortars. Each group includes eight mixes and the specimens were cured in different curing regimes after casting and demoulding, i.e. under room temperature (ac), in water without heating (wc), room temperature after heating 60 °C for duration 20 h (WH/ac) and in water after heating like as mentioned (WH/wc). The results showed that the highest strength is related to the OPC-slag mortars as 80 MPa for OSM380-wc. For all groups of mortars, there could rarely be strength loss at later ages. The results proved that WH/ac is the optimum curing regime for all groups of mortars in duration of 3–7 days, whereas the optimum curing regime is not the same in duration of 28–90 days. It was proved that higher strength could be achieved for OPC and OPC-slag mortars using lower binder content provided the specimens are cured in water without heating. This reality is reversed for slag mortars; namely for slag mortars the highest strengths could be only achieved using more slag content and water curing without heating. For SM500-wc the strengths obtained at 28 and 90 days were as 18 and 26 MPa, respectively.

1. Introduction

Cement, mortar and concrete are the most widely used construction materials all over the world. It is difficult to find out alternate material of construction which is suitable as that of such construction material from durability and economic viewpoints. The expanded uses of concrete have increased the interest of researchers for its use in aggressive environments such as marine environment [1].

Ground granulated blast-furnace slag (GGBFS) is a by-product of the iron making process and is produced by water quenching molten blast furnace slag. For its use in mortars, concretes and blended cements, it must be ground to improve its reactivity during cement hydration. The main constituents of GGBFS are CaO, SiO_2, Al_2O_3 and MgO. Slag shows primarily cementitious behaviour but may also show some pozzolanic character (reaction with lime). Use of GGBFS as a cement replacement in mortar and concrete is a common practice due to technological and environmental benefits. GGBFS as a waste material, rich in SiO_2, and Al_2O_3 is produced in large quantities. A lower cost and lower environmental impact, per unit volume, its application can perform similar properties of concrete as compared to ones with pure Portland cements [2].

Alternative materials for partial replacement of ordinary Portland cement in concrete are widely used around the world, and are being more and more common. The reasons for using alternative materials are environmental, economic, or technical benefits. Common alternative materials include GGBFS, fly ash and limestone filler. The kind of alternative material that is used often depends on the availability and on the field of application [3].

Replacement of clinker by slag not only offers energy savings and cost reduction compared to OPC, but also other advantages

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0950-0618/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2012.06.036

such as low heat of hydration, high sulphate and acid resistance, better workability, and good ultimate strength and durability. Attempts have been made to overcome the problem of slow strength development in cement-slag mortars and concretes using temperature and suitable curing regimes [4]. Using thermal activation method with curing mortar and concrete under elevated temperature is normally limited to precast concrete plants [5].

Temperature is a key variable affecting the curing of cement-based materials, because it influences both the early hydration kinetics and the properties of the hardened cement paste or concrete. The hydration temperature has a significant impact on the hydration of cement paste and concrete [6]. Therefore, consideration of the effects of high curing temperatures and of heat treatment should not be limited to precast steam-cured materials, which are generally cured at anywhere from 40 °C to 100 °C [6].

The cement-slag mortars can generally be classified into three groups as OPC mortars (OMs), OPC-slag mortars (OSMs) and slag mortars (SMs) [7].

The main objective of this investigation is to study the effect of curing regime and temperature on the strength improvement of cement-slag mortars. Three groups of mortars were made in this experimental work. In the first group, only ordinary Portland cement (OPC) was used as binder. In the second group, both the OPC and GGBFS were used. Finally, in the third group, only GGBFS was used. The results obtained showed that the second group of mortar gave the highest strengths when the specimens were cured in water in duration up to 90 days.

2. Experimental procedure

2.1. Mix proportions and curing

Table 1 represents the mix proportions for different mortars. In all the mixes water-binder and sand-binder ratios are as 0.33 and 2.25, respectively. At first, based on grain size distribution, five grades of silica sands were mixed. 2 min after that, cement and replacement slag were put into the mixture, followed by 4 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 was added. Mixing was continued for 2 min before finally, filling the moulds with two layers of fresh mortar and compaction of each layer with 10 impacts by a rod of 16 mm diameter. 24 h after casting, the specimens were demoulded and cured in water with 23 ± 2 °C for the required time necessary to break the specimens.

2.2. Materials

2.2.1. Cement

The cement used in all the mixes was ASTM type I (OPC). ASTM C109–99 [8] was used for determination of the compressive strength of hydraulic cement mortars, by use of 50 mm sided cube specimens. The specific gravity of cement used is about 3.14. The particle size analysis diagram for the binders used in the study is shown in Fig. 1. The chemical compositions of OPC used in this research were determined by the testing method X-ray fluorescence spectrometry (XRF). Chemical properties of the cement used in this experimental work are given in Table 2.

2.2.2. Slag

GGBFS was used as part of binder in this experimental work. Its specific gravity was approximately 2.87, with its bulk density varying in the range of 1180–1250 kg/m^3. The colour of GGBFS is normally whitish (off-white). Chemical compositions of the slag are given in Table 2. As with all cementing materials, slag reactivity is determined by its specific surface area (SSA). For better performance, the fineness of GGBFS should be greater than that of cement [10]. Based on the definition of slag activity index (SAI) in ASTM C989 [11], the slag used in the study is classified into Grade 120 and it is also a basic slag (K_b = 1.03 > 1.00). A result calculation is shown in the bottom of Table 2.

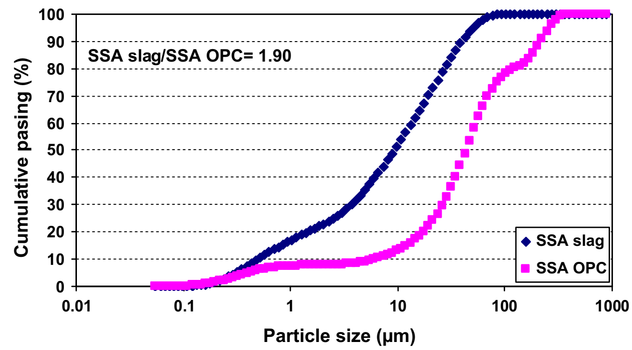

Fig. 1. The particle size analysis diagram for OPC and GGBFS.

2.2.3. Aggregates

The fine aggregates used in the mixes are graded silica sands with specific gravity, fineness modulus and water absorption (BS 812–103.1:1985 [12]) 2.68, 3.88 and 0.93%, respectively. The maximum size aggregate is 4.75 mm. Grain size distributions for silica sands are given in Table 3 and is also shown in Fig. 2.

2.2.4. Super plasticizer

In order to have a proper consistency with a low w/b ratio, super plasticizer is required. The specific gravity of super plasticizer is approximately 1.195, is dark brown in color, with a pH in the range of 6–9. The consumed amount of super plasticizer in the mortar depends on the replacement level of slag. It is a chloride-free product, meets ASTM C494 [15]. The basic components are synthetic polymers which allow mixing water to be reduced considered. The dosage of super plasticizer generally varies from 0.8 to 1.2 l/(100 kg) of cement. Other dosages may be recommended in special cases according to specific job conditions.

2.2.5. Water (mixing and curing)

Potable water was used in all the mixes and curing of the specimens.

2.3. Test and mixing procedures

2.3.1. Test for fresh mortar

In order to having appropriate workability for each mix, after casting a flow table test was performed as per ASTM C230 [16]. The range of flow amounts were 220–235 mm. In the test procedure, following casting, some mortar is put in the truncated brass cone in two layers. Each layer is compacted 10 times by a steel rod with 16 mm diameter. The cone is then lifted and mortar is collapsed on the flow table. Following that, both the table and the mortar are jolted 15 times in 60 s. The jolting of the flow table, allowed the mortar to consequently spread out the maximum spread to the two edges of the table was recorded. The average of both records is calculated as flow in mm.

2.3.2. Mortar mix method

Initially, five grades of silica sand are put in as a mixture and mixed for 2 min. Following that the cement and slag were added and mixing was done for 3–4 min.

Table 1
Mix proportions of cement-slag mortars for 0%, 50% and 100% OPC replacement with slag.

Batching name	OPC (kg)	GGBFS (kg)	SP (%)	Free water (kg)	Silica sand (kg)	Gravel (kg)	Slump (mm)
OPC mortar 380 (OM380)	380	–	1.4	125.4	855	–	210
OPC mortar 500 (OM500)	500	–	1.5	165	1125	–	220
OPC-slag mortar 380 (OSM380)	190	190	1.8	125.4	855	–	220
OPC-slag mortar 500 (OSM500)	250	250	1.9	165	1125	–	230
Slag mortar 380 (SM380)	–	380	0.9	125.4	855	–	215
Slag mortar 500 (SM500)	–	500	1.0	165	1125	–	225

In all the mixes s/b = 2.25 and w/b = 0.33 were used; total water = free water + absorbed water by fine aggregates; absorption content for sand and gravel were used as 0.93% and 0.40%, respectively; all the specimens were cured in curing regimes ac, wc, WH/ac and WH/wc.
Notes: GGBFS = ground granulated blast furnace slag, OPC = ordinary Portland cement, SP = super plasticizer, OM = OPC mortar, OSM = OPC-slag mortar, SM = slag mortar, ac = curing under room temperature, wc = water curing, WH = water bath heated at 60 °C for duration 20 h.

Table 2
Chemical compositions of cementitious materials (% by mass).

For OPC										
SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	MnO	K_2O	TiO_2	SO_3	CO_2	LOI
18.5	4.27	2.08	2.064	64.09	0.045	0.28	0.10	4.25	4.20	1.53
For GGBFS										
SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO	MnO	K_2O	TiO_2	SO_3	CO_2	Na_2O
31.2	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 [9]; 1.30 ⩽ CaO/SiO_2 = C/S = 1.33 for slag ⩽ 1.40 [9].

Table 3
GSD for silica sands based on BS 812-103.1:1985.

Sieve size (μm)	Sieve no.	$W_{SS} + W_S$ (g)	W_S (g)	W_{SS} (g)	Ret.%	Cumul.Ret.%	Cumul.pass.%
4750	No. 4	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 = fineness modulus = 388.31/100 = 3.88 [13,14]; GSD = grain size distribution.

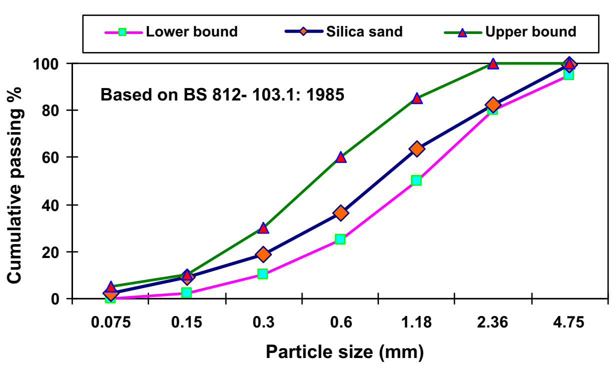

Fig. 2. Grain size distribution diagram for silica sands.

Next the calculated mixing water is poured into the mix and the mixing is extended for 2 additional min. Finally, super plasticizer is added and mixing continues for 2 min; immediately at the end of mixing, the flow table test was performed and the specimens were moulded. For each mix, the duration of mixing time is by about 10–11 min.

2.3.3. Test for hardened mortar

Three cubic specimens with 50 mm sides were used for each age. Specimens produced from fresh mortar were demoulded after 24 h, and were then cured in water with 23 ± 2 °C with 70 ± 10% relative humidity until they were used for compressive strength tests at 1, 3, 7, 28, 56, and 90 days. Compressive strength measurements were carried out using an ELE testing machine press with a capacity of 2000 kN, and a pacing rate of 0.5 kN/s. Compressive strength tests were done according to BS 1881, Part 116, 1983 [17].

3. Results and discussion

Totally, in this experimental work 24 mortar mixes were prepared. At early ages the use of a low level of replacement slag is neither economic nor durable. In this research, a 50% level of slag was selected as an optimum level [18]. All the made mixes are classified into three groups as OPC, OPC-slag and slag mortars. Each group includes eight mixes and the specimens were cured in different curing regimes after casting and demoulding, i.e. under room temperature without heating (ac), cured in water without heating (wc), under room temperature after heating 60 °C for duration 20 h (WH/ac) and in water after heating as above (WH/wc) [19,20]. It should be noted that each mix was made using binder contents 380 and 500 kg/m^3. The specimens of all groups of mortars for both binder contents 380 and 500 kg/m^3 and in different curing regimes ac, wc, WH/ac and WH/wc were analysed in duration up to 90 days. The results obtained are shown in Figs. 3–5. Variations of compressive strengths for all groups of mortars having binder

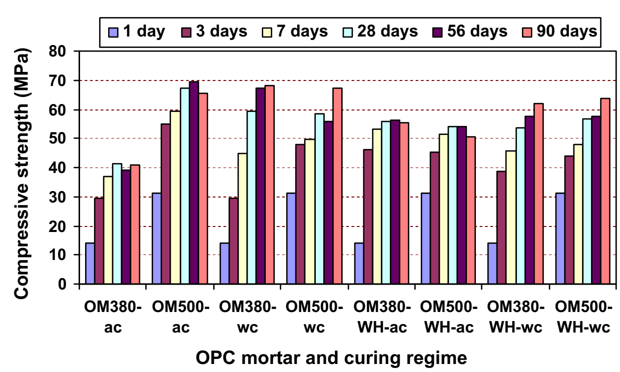

Fig. 3. Variations of compressive strength for OPC mortars having cement content 380 and 500 kg/m^3 in different curing regimes.

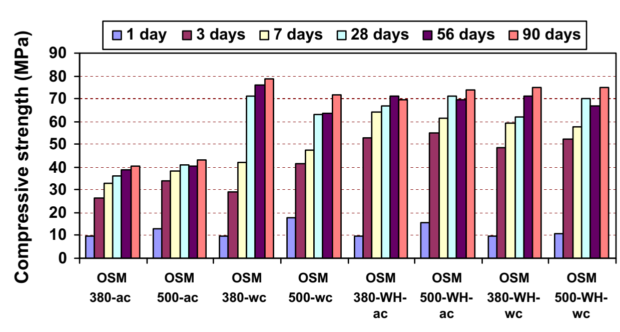

Fig. 4. Variations of compressive strength for OPC-slag mortars having cement content 380 and 500 kg/m^3 in different curing regimes.

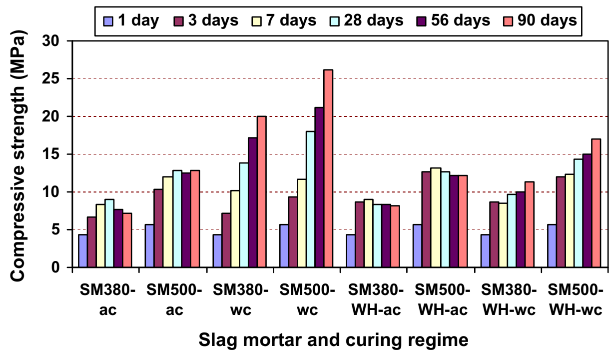

Fig. 5. Variations of compressive strength for slag mortars having cement content 380 and 500 kg/m^3 in different curing regimes.

contents 380 and 500 kg/m^3 are comparatively shown in Fig. 6. Using both slag and OPC, the highest compressive strength for OPC-slag mortars could be achieved. The strength of OSM380-wc was found about 80 MPa at 90 days with the use of only 190 kg/m^3 cement content in 1 m cube of mortar.

3.1. Strength analysis

3.1.1. For OPC mortars

From Fig. 3 it can be seen that:

Comparison of compressive strengths for OPC mortars having cement content 380 kg/m^3 with and without heat treatment and cured under room temperature shows that the strengths without using heat are lower than those with the use of heat treatment. This reveals that there is an inner inside potential to increase the strengths using heat treatment, whereas air curing of the specimens was not able to improve the strengths. Strength comparison for OPC mortars having cement content 380 and 500 kg/m^3 and cured under room temperature, shows that the strengths of OPC mortar 500 are much higher than those of OPC mortar 380.

Strength comparison for OPC mortars 380 and 500 kg/m^3 water curing shows that in duration of 3–7 days the strengths of OPC mortar 500 are much higher than those of OPC mortar 380, but in duration of 28–90 days the strengths obtained for OPC mortars 380 and 500 kg/m^3 are approximately the same. Therefore it can be said that using OPC mortar 380 is preferable whenever high early age strengths are not needed. Strength loss was observed at 56 days for OPC mortar 500 but no strength loss was observed for OPC mortar 380 in duration up to 90 days.

Strength comparison for both OPC mortars 380 and 500 in both curing regimes WH/ac and WH/wc shows that it is preferable to cure the specimens in water after heating. In this curing regime no strength loss was observed. Strength loss was observed for the specimens at 90 days whenever they were cured under room temperature after heating. This statement is reversed for cement-slag mortars. Generally, strength comparison of OPC mortars 380 and 500 for the specimens cured in water and under room temperature using without and with the use of heat treatment shows that using OPC mortar 380 is preferable without using heating and only the specimens should be cured in water. In this curing regime the strength was obtained as 68 MPa at 90 days for OPC mortar 380. The strength obtained at 28 days was 60 MPa for OPC mortar 380 cured in water.

3.1.2. For OPC-slag mortars

From Fig. 4 it can be seen that:

For OPC-slag mortars cured under room temperature it is preferable that the specimens should be heated in water before they are cured under room temperature. It can be seen that the strength of specimens are increased about two times in heated water condition compared to without heat treatment. It should be noted that

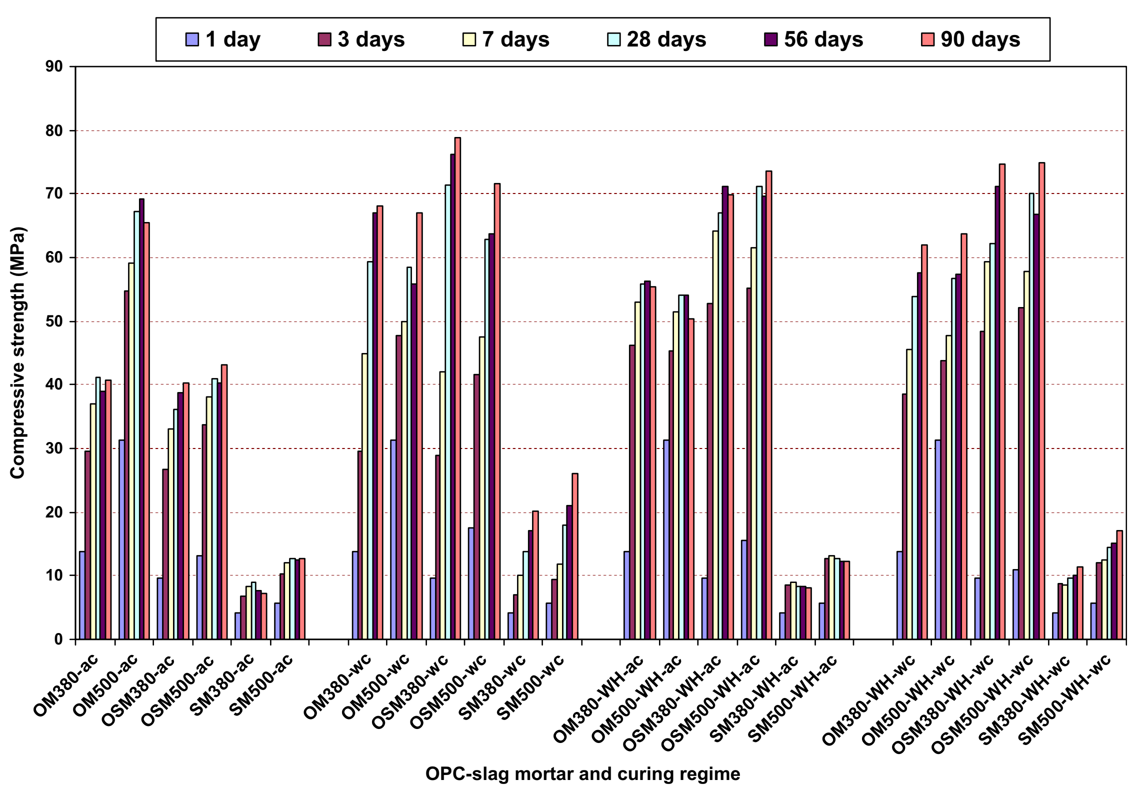

Fig. 6. Variations of compressive strength for OPC-slag mortars having binder content 380 and 500 kg/m^3 in different curing regimes.

not only the strengths were increased whenever the specimens cured in water after heating, but also strength loss was observed at some later ages. Therefore, it could generally be said that whenever OPC-slag mortars are heated, it is preferable the specimens are cured under room temperature after heating. Moreover, when the specimens are cured in water, there is no necessity to heat them in water before curing. Based on the results obtained, the compressive strength at 90 days for OPC-slag mortars 380 and 500 were observed as 80 and 70 MPa, respectively, whenever the specimens were cured in water without heating. It means that although the cement content used in OPC-slag mortar 500 is more than that of OPC-slag mortar 380 about 32%, but the strength obtained for OPC-slag mortar 380 is more about 14% compared to the strength of OPC-slag mortar 500 at 90 days. This is a new finding and needs to be studied more which has high significance from economic viewpoint.

3.1.3. For slag mortars

From Fig. 5 it can be seen that:

In two curing conditions of specimens as in water and under room temperature and without heating and with the use of heat treatment, using slag mortar 500 (SM500) gives higher strengths compared to slag mortar 380 (SM380) in duration up to 90 days. Strength comparison for the specimens of SM380 and SM500 in air and water curing regimes shows that the strengths are higher, whenever the specimens are cured in water. This result is true for both conditions, i.e. without and with the use of heating.

Strength comparison for both SM380 and SM500 with the use of heat treatment and curing under room temperature shows that not only the strengths were increased, but also strength loss was observed continuously in duration up to 90 days. It was reversely seen that the strengths were increased, whenever the specimens cured in water after heating and moreover, no strength loss was observed in duration up to 90 days.

General comparison of the strengths obtained for SM380 and SM500 in both curing regimes of air and water and for without and with the use of heat treatment, shows that the highest strength could be obtained whenever SM500 was used and the specimens were cured in water without heating. The highest strength for slag mortars was obtained as 26 MPa at 90 days.

From the results obtained it was observed that SM500 under room temperature gives higher strengths compared to SM380 in the same curing. Strength loss was similarly observed for both mortars at 56 days. Like air curing it was revealed that SM500 gave higher strengths at all ages compared to SM380 when both the specimens cured in water.

For both slag mortars SM380 and SM500 strength loss was observed continuously in duration of 7–90 days, whenever the specimens were heated after demoulding and then cured under room temperature. This fact proves that the specimens should not be cured under room temperature after heating; whereas no significant strength loss was observed for the specimens cured in water after heating. It seems that this is due to predominant effect of water curing compared to heating effect. In fact it can be said that water curing of the slag specimens gives higher effect than that of treatment effect.

Finally, it can be deduced that using heating for slag mortars is not efficient and useful; for obtaining the highest strength at later ages it recommends to use slag mortars with higher slag content; strength comparison of slag mortars in both curing regimes under room temperature and in water, without and with the use of heat treatment, showed that the highest strengths achieved are for the specimens cured in water and without heating.

3.1.4. General discussion

From Fig. 6 it can be seen that:

3.1.4.1. For ac curing. Generally from the results obtained it was observed that the strengths of OPC mortar 500 (OM500) cured under room temperature were higher than those of OPC mortar 380 (OM380), OPC-slag mortar 380 and 500 (OSM380 and OSM500), and slag mortars 380 and 500 (SM380 and SM500) in all the same ages. The results revealed that mortars OM500-ac and OSM500-ac showed strength loss about 5.4% and 1.3% at 90 and 56 days, respectively and no strength loss was observed for other mortars in duration up to 90 days. The results generally reveal that whenever the specimens of mortars are cured under room temperature the strengths increase with increasing of slag or cement content. This fact shows that binder plays a main role in strength improvement of the mortars, whereas for concrete this role is probably related to coarse aggregates.

Generally, strength comparison of three groups of mortars cured under room temperature showed that OPC mortars give the highest strengths; the lowest strengths are related to slag mortars and OPC-slag mortars have medium strengths, i.e. the strengths of OPC-slag mortars are lower and higher than those of OPC mortars and slag mortars, respectively.

3.1.4.2. For wc curing. It was cleared that OPC mortars gave higher strengths with using higher cement content whenever the specimens were cured in water in duration of 3–7 days. Higher strengths were seen for OM380 than OM500, and moreover strength loss of 4.4% was observed for OM500 at 56 days. OPC-slag mortars showed a similar behaviour as OPC mortars, but no strength loss was observed for OPC-slag mortars, and moreover the strength level of OPC-slag mortars at 90 days was higher than that of OPC mortars. It may be related to the presence of slag in OPC-slag mortars which can improve strengths near by water at later ages.

For slag mortars the strengths were improved at all ages in duration up to 90 days with increasing of slag content, and moreover no strength loss was observed. This fact can be attributed to high consistency of slag near by water. Strength comparison for both OM500 and SM500 showed that the strength of slag mortar at 90 days is about 39% of the strength of OPC mortar at the same age. This percentage is about 36.5% compared to OSM500. This reality once again shows that later ages strengths of OPC-slag mortars are higher than those of OPC mortars at the same ages whenever the specimens are cured in water.

3.1.4.3. For WH/ac curing. In this curing regime strength loss was observed for all three groups of mortars at beyond of 28 days. Strength loss was occurred for both mortars 380 and 500. The highest strength loss observed was related to slag mortar 380 as 8.2% at 28 days. Moreover, strength loss was observed for slag mortar 500 at 28 and 56 days as 4.5% and 3.5%, respectively.

Strength comparison for both OM380 and OM500 shows that OM380 gives higher strengths than OM500 whenever both specimens are heated in water before curing under room temperature. This fact may reveal that for mortars with higher cement content using heat treatment not only improves the strengths, but also it has a negative effect on strengths. Moreover, strength loss was observed especially at later ages. It may be related to high cement content because the hydration obtained from cement particles is enough to improve the strengths and then using heat treatment affects negatively on strengths.

Comparison of strengths between OSM380 and OSM500 shows that the mortar including higher binder gives higher strengths. This fact may be due to heating especially up to 3 days to release the latent potential of slag and then improves strength at short ages.

Strength comparison of both SM380 and SM500 shows that the SM500 gives higher strengths compared to SM380 at all ages. For both mentioned mortars strength loss was observed at both 28 and 56 days.

Generally, strength comparison of three groups of mortars in curing regime WH/ac showed that OSM500 gave the highest strengths compared to other mortars as OM380 and OM500, OSM380 and OSM500, and SM380 and SM500 at all ages.

3.1.4.4. For WH/wc curing. In this curing regime it was observed that mortars SM380 and OSM500 showed strength loss at the ages 7 and 56 days as 2.6% and 4.7%, respectively. Unlike all other cases, strength loss was observed for SM380 at 7 days. It seems that this is due to SM380 which achieved strength increase about 105% at 3 days compared to the strength at 1 day. The strength obtained at 3 days after heating showed twice increasing which is high; whereas the slag content in SM380 is lower than that of SM500 and also heating has the highest effect on strength improvement up to 3 days [21,22]. It can be deduced that strength improvement is impossible in duration of 3–7 days, because the slag content is low and heating is not affecting after 3 days. Therefore, it can be expected that strength loss is occurred at 7 days.

Strength comparison for both OM380 and OM500 in curing regime WH/wc showed that OM500, i.e. with higher cement content, gives higher strengths at the same ages compared to OSM380, i.e. with lower cement content. It seems that this is due to water curing. Moreover, it can be deduced that water curing caused no strength loss for both mentioned mortars.

Strength comparison for both OSM380 and OSM500 in curing regime WH/wc showed higher strengths for OSM500 than OSM380. It is noted that for OSM500, strength loss was observed at 56 days as 4.7% which probably is due to heating effect. It should be noted that strength loss was observed as 2.2% for the mortar at the same age when it was cured under room temperature after heating.

Strength comparison for both SM380 and SM500 in curing regime WH/wc gave higher strengths for mortar including higher slag content, i.e. SM500, at all ages in duration up to 90 days. It seems that this is due to water curing effect. This is probably due to the slag particles releasing their latent pozzolanic potential near by water. Higher slag content gives higher pozzolanic potential and, then results in higher strengths. Moreover, no strength loss was observed for SM500 in curing regime WH/wc, although strength loss was observed as 2.6% for SM380 at 7 days.

Finally, strength comparison of all three groups as OMs, OSMs, and SMs in curing regime WH/wc showed that OSM500 gives the highest strength compared to all other groups of mortars at all ages.

3.2. Optimum curing regime

Based on the results given in Table 4 the optimum curing regimes can be suggested for three groups of mortars as below:

In duration of 3–7 days, i.e. short term, curing regime WH/ac is the optimum for all groups of mortars including OPC, OPC-slag and slag mortars.

In duration of 28–90 days, i.e. long term, curing regimes wc and ac are the optimum for OPC mortars having cement contents 380 and 500 kg/m^3, respectively. For OPC-slag mortars having cement contents 380 and 500 kg/m^3 curing regimes wc and WH/ac are the optimum, respectively.

The curing regime wc is the optimum for both the slag mortars having cement contents 380 and 500 kg/m^3. This reality once again shows the highly importance of water curing to release the latent pozzolanic potential of slag particles.

3.3. Strength relationships for curing in ac and wc

Regarding the highly importance of curing regimes ac and wc for all groups of mortars and based on the results obtained in the research, the relationships between strengths in the curing regimes as above were determined and given in Table 5. The results

Table 4
Curing regime ranking at early and later ages for cement-slag mortars.

No.	Batching no.	Mix name	Early ages (days)		Later ages (days)		
			3	7	28	56	90
1		OM-ac	WH/ac>	WH/ac>	wc>	wc>	wc>
2	OPC mortars (OM)-380	OM-wc	WH/wc>	WH/wc>	WH/ac>	WH/wc>	WH/wc>
3		OM-WH/ac	wc>	wc>	WH/wc>	WH/ac>	WH/ac>
4		OM-WH/wc	ac	ac	ac	ac	ac
5		OM-ac	WH/ac>	WH/ac>	ac>	ac>	wc>
6	OPC mortars (OM)-500	OM-wc	WH/wc>	ac>	wc>	WH/wc>	ac>
7		OM-WH/ac	ac>	WH/wc>	WH/wc>	wc>	WH/wc>
8		OM-WH/wc	wc	wc	WH/ac	WH/ac	WH/ac
9		OSM-ac	WH/ac>	WH/ac>	wc>	wc>	wc>
10	OPC-slag mortars (OSM)- 380	OSM-wc	WH/wc>	WH/wc>	WH/ac>	WH/ac>	WH/wc>
11		OSM-WH/ac	wc>	wc>	WH/wc>	WH/wc>	WH/ac>
12		OSM-WH/wc	ac	ac	ac	ac	ac
13		OSM-ac	WH/ac>	WH/ac>	WH/ac>	WH/ac>	WH/wc>
14	OPC-slag mortars (OSM)-500	OSM-wc	WH/wc>	WH/wc>	WH/wc>	WH/wc>	WH/ac>
15		OSM-WH/ac	wc>	wc>	wc>	wc>	wc>
16		OSM-WH/wc	ac	ac	ac	ac	ac
17		SM-ac	WH/ac>	wc>	wc>	wc>	wc>
18	Slag mortars (SM)-380	SM-wc	WH/wc>	WH/ac>	WH/wc>	WH/wc>	WH/wc>
19		SM-WH/ac	wc>	WH/wc>	WH/ac>	WH/ac>	WH/ac>
20		SM-WH/wc	ac	ac	ac	ac	ac
21		SM-ac	WH/ac>	WH/ac>	wc>	wc>	wc>
22	Slag mortars (SM)-500	SM-wc	WH/wc>	WH/wc>	WH/wc>	WH/wc>	WH/wc>
23		SM-WH/ac	ac>	ac>	WH/ac>	ac>	ac>
24		SM-WH/wc	wc	wc	ac	WH/ac	WH/ac

wc = Water curing, ac = air curing under room temperature, WH = water bath heated at 60 °C and duration 20 h, for making of cement-slag mortars the binders were used as 50% cement and 50% slag content.

Table 5
Relationships between compressive strength of cement-slag mortars cured in water and under room temperature without heating.

No.	Regression relationship
1	$f_{SM380\text{-}wc} = 1.6998 * e^{0.2551x}$; $R^2 = 0.5278$
2	$f_{SM500\text{-}wc} = 1.7789 * e^{0.1842x}$; $R^2 = 0.7990$
3	$f_{OSM380\text{-}wc} = 4.6884 * e^{0.0708x}$; $R^2 = 0.9829$
4	$f_{OSM500\text{-}wc} = 9.2556 * e^{0.0462x}$; $R^2 = 0.9802$
5	$f_{OM380\text{-}wc} = 5.9448 * e^{0.0578x}$; $R^2 = 0.9663$
6	$f_{OM500\text{-}wc} = 18.062 * e^{0.0177x}$; $R^2 = 0.9023$

x is Compressive strength of cement-slag mortar cured under room temperature;
R^2 is coefficient of determination in regression relationships.
Notes: SM = slag mortar, OSM = OPC-slag mortar for 50% OPC replacement with slag, OM = OPC mortar, ac = curing under room temperature, wc = water curing.

evaluation showed that the best regression equation to describe this relationships is a exponential function as $f_{M\text{-}wc} = a * e^{b*x}$; where $f_{M\text{-}wc}$ is compressive strength of mortar mix cured in water in MPa, *a* and *b* are the constant factors for each mix, *x* is compressive strength of mortar mix under room temperature in MPa, and R^2 is coefficient of determination in regression relationships.

3.4. Strength development of the mortars

Customarily, whenever we want to understand the behaviour of a phenomenon, it is accepted to model its behaviour by the use of a diagram or mathematical relationship. Using the relationships can approximately forecast the behaviour of the phenomenon at later ages. Based on the results obtained in the research for OPC mortars, OPC-slag mortars with 50% OPC replacement with slag and slag mortars in different curing regimes having binder contents 380 and 500 kg/m^3, mathematical equations have been determined to forecast the variations of compressive strengths versus age of curing.

Table 6
Curve fitting relationships for strength of cement-slag mortars in different curing regimes.

No	Mix name	Relationship formula	R^2
1	OM380-ac	$5.2943 * \mathrm{Ln}(t) + 20.399$	0.7820
2	OM500-ac	$7.1076 * \mathrm{Ln}(t) + 40.211$	0.7910
3	OSM380-ac	$6.0005 * \mathrm{Ln}(t) + 15.862$	0.8573
4	OSM500-ac	$5.4105 * \mathrm{Ln}(t) + 21.457$	0.7372
5	SM380-ac	$0.6205 * \mathrm{Ln}(t) + 5.6504$	0.4346
6	SM500-ac	$1.347 * \mathrm{Ln}(t) + 7.6745$	0.7421
7	OM380-wc	$12.308 * \mathrm{Ln}(t) + 16.561$	0.9808
8	OM500-wc	$6.4685 * \mathrm{Ln}(t) + 35.648$	0.8825
9	OSM380-wc	$16.109 * \mathrm{Ln}(t) + 11.151$	0.9833
10	OSM500-wc	$10.911 * \mathrm{Ln}(t) + 23.731$	0.9472
11	SM380-wc	$3.3895 * \mathrm{Ln}(t) + 3.6617$	0.9824
12	SM500-wc	$4.3201 * \mathrm{Ln}(t) + 4.6004$	0.9691
13	OM380-WH/ac	$2.5631 * \mathrm{Ln}(t) + 45.707$	0.7568
14	OM500-WH/ac	$1.6613 * \mathrm{Ln}(t) + 46.099$	0.4463
15	OSM380-WH/ac	$4.706 * \mathrm{Ln}(t) + 50.988$	0.8393
16	OSM500-WH/ac	$5.2039 * \mathrm{Ln}(t) + 50.664$	0.9311
17	SM380-WH/ac	$-0.1996 * \mathrm{Ln}(t) + 9.0747$	0.6076
18	SM500-WH/ac	$-0.2374 * \mathrm{Ln}(t) + 13.3$	0.6328
19	OM380-WH/wc	$6.5844 * \mathrm{Ln}(t) + 31.878$	0.9945
20	OM500-WH/wc	$5.5041 * \mathrm{Ln}(t) + 37.48$	0.9671
21	OSM380-WH/wc	$7.0705 * \mathrm{Ln}(t) + 42.043$	0.9353
22	OSM500-WH/wc	$6.1857 * \mathrm{Ln}(t) + 45.888$	0.9107
23	SM380-WH/wc	$0.7319 * \mathrm{Ln}(t) + 7.4866$	0.8127
24	SM500-WH/wc	$1.3877 * \mathrm{Ln}(t) + 10.028$	0.9291

Notes: SM = slag mortar, OSM = OPC-slag mortar for 50% OPC replacement with slag, OM = OPC mortar, ac = curing under room temperature, wc = water curing, WH = water bath heated at 60 °C and duration 20 h, *t* is age of specimens in days, R^2 is coefficient of determination in regression relationships.

Comparison of all the relationships shows that the most appropriate form of equation to describe the variations of compressive strength versus age of curing is a logarithmic function as $f = a * Ln(t) + b$; where R^2 is the coefficient of determination, *a* and *b* are constants for the specified mortar, f is compressive strength in MPa and t is the age of specimens in days. Using the relationships given in Table 6 and Figs. 7–10, can forecast the strength development of three groups of mixes including OPC,

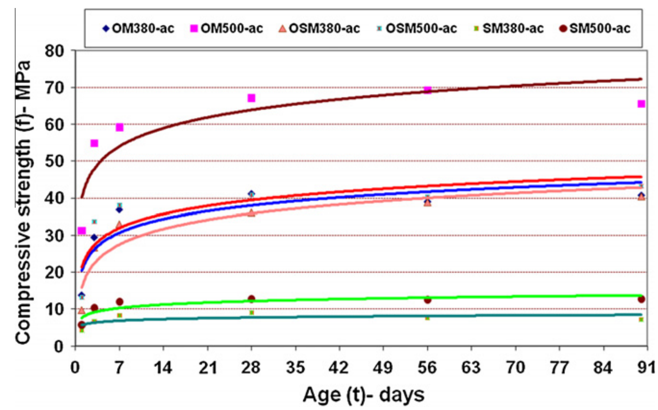

Fig. 7. Strength development curve fitting relationships for OPC-slag mortars under room temperature and without heating.

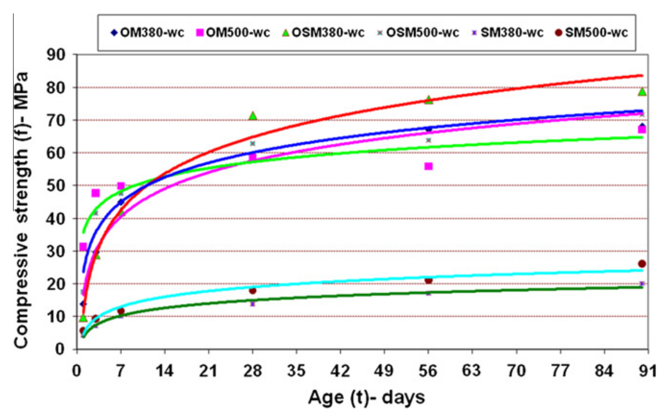

Fig. 8. Strength development curve fitting relationships for OPC-slag mortars cured in water without heating.

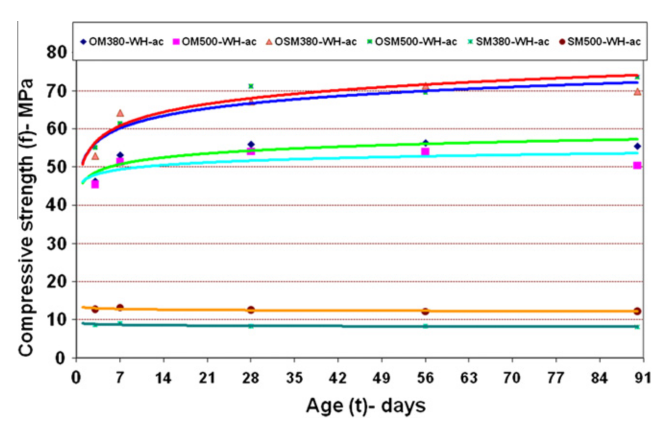

Fig. 9. Strength development curve fitting relationships for OPC-slag mortars under room temperature after heating 60 °C for duration 20 h of the specimens.

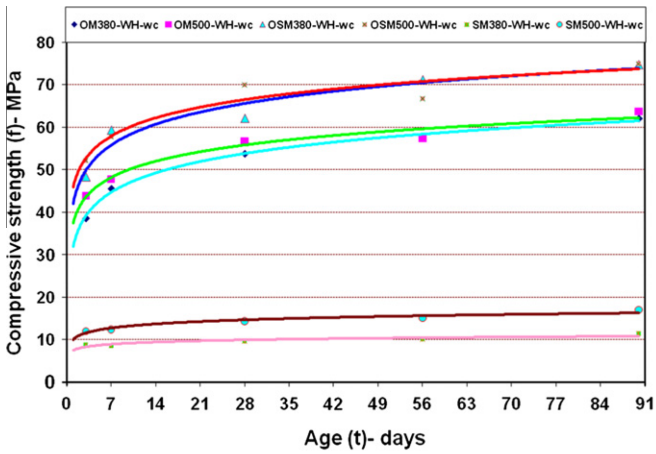

Fig. 10. Strength development curve fitting relationships for OPC-slag mortars cured in water after heating 60 °C for duration 20 h of the specimens.

OPC-slag and slag mortars. The results of the best fitted curves are shown in the Figures for all the mixes.

4. Conclusions

The results obtained in the research allow us to present as following:

1. The highest strength obtained is attributed to OSM380-wc as 80 MPa at 90 days.
2. For all three groups of mortars, there could rarely be strength loss at later ages.
3. The results showed that curing regime and its duration has a significant effect on strength improvement of all groups of mortars.
4. Based on the results obtained it was revealed that the most appropriate form of equation to describe the variations of compressive strength versus age of curing is a logarithmic function as $f = a * Ln(t) + b$.
5. It was proved that in duration of 3–7 days, curing regime WH/ac is the optimum for all groups of mortars, but in duration of 28–90 days, optimum curing regimes are different as wc and ac.
6. It was proved that higher strength could be obtained using lower binder contents for both OPC and OPC-slag mortars for water cured specimens. This is a new finding; means that for producing higher strengths it is not a necessity to use more binders in OPC and OPC-slag mortars.

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