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Relationships between compressive strength of cement–slag mortars under air and water curing regimes

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ABSTRACT

In this investigation 12 mortar mixes including three groups were prepared using binder contents 380 and 500 kg/m^3. All the specimens were cured after casting and demoulding in curing regimes, i.e. at room temperature (ac) and in water (wc). The highest strength was obtained for cement–slag mortars 380-wc at later ages as 80 MPa. For all groups of mortars, there could rarely be strength loss at later ages. It was observed that in duration of 3–7 days, wc is the optimum for all groups of mortars with exception of cement mortar 500 and slag mortar 500. In duration of 28–90 days, wc is also the optimum for three groups of mortars with exception of cement mortar 500. It was revealed that an exponential relationship exists between the strengths obtained in air and water curing conditions for each group of mortar, i.e. with and without using ground granulated blast furnace slag. It was proved that higher strengths could be obtained using lower binders' contents for cement and cement–slag mortars provided the specimens were cured in water. This is a new finding having importance from economic and environmental viewpoints; meaning that for producing higher strengths it is not a necessity to use more binders. It was found that increase in level of cement and slag makes the mortars more sensitive to air curing conditions.

1. Introduction

Ground granulated blast-furnace slag (GGBFS) is commonly used in combination with Portland cement in concrete for many applications. Concrete made with GGBFS has many advantages, including improved durability, workability and economic benefits. The drawback in the use of GGBFS concrete is that its strength development is considerably slower under standard 20 °C curing conditions than that of Portland cement concrete, although the ultimate strength is higher for the same water–binder ratio. GGBFS is not therefore used in applications where high early age strength is required [1].

The use of GGBFS in mortar has increased in recent years. Records indicate that blast furnace cement was used for the mortar during the construction of the Empire State Building in the 1930s. These materials not only impart technical benefits to both the fresh and hardened properties of mortar they are also environmentally friendly. GGBFS is classified as a latent hydraulic material. This means that it has inherent cementitious properties, but these have to be activated. The normal means of achieving this is to combine the material with Portland cement [2].

Slag cement has been used in different concrete projects of the United States of America for the last several decades. Besides, earlier usage of slag cement in Europe and elsewhere demonstrate the long term performance of slag concrete in many ways. Use of slag is noticeably increasing for the last several years due to its characteristic properties like improved workability, restrained heat of hydration, easier finishability, higher compressive strength, lower permeability and superior resistance to alkali silica reaction due to penetration of chloride ions and sulfate ions. It has been observed that slag can be effectively used to reduce the pore sizes and cumulative pore volume considerably leading to more durable and impermeable concrete. Although the strength development is remarkably reduced at early ages of curing due to having low initial rate of hydration of slag, the structural benefit of low heat of hydration of slag in decreasing the thermal cracking of mass concrete is significant. The risk of thermal cracking in slag concrete is seen to be lower than ordinary Portland cement. In Europe, the production of 1 ton OPC generates about 1.2 ton CO$_2$ while the production of 1 ton slag generates only 0.45 ton of CO$_2$. In addition, concrete made with slag has a lower content of chromium, which is responsible for skin irritation of workers handling concrete materials without any skin protection [3].

From both environmental and economical points of view, blast furnace slag is a very attractive mineral admixture to use in concrete, particularly in low-heat concrete for massive structures or in high performance concrete. Apart from the low-heat application, the superior durability of GGBFS against aggressive environments

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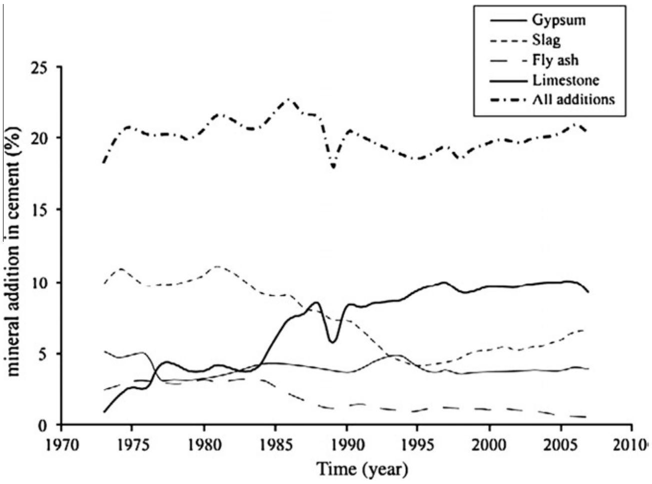


Fig. 1. Evolution of clinker substitution from 1973 to 2007 [14].

Table 1
Mix proportions of OPC–slag mortars having binder contents 380 and 500 kg/m^3 for 0%, 50% and 100% OPC replacement with slag.

Batch. No.	Batching name	OPC (kg)	GGBFS (kg)	SP (kg)	Free water (kg)	Silica sands (kg)	Granite gravels (kg)	Slump (mm)
1	OPC mortar 380 (OM380)	380	–	1.4	125.4	855	–	210
2	OPC mortar 500 (OM500)	500	–	1.5	165	1125	–	220
3	OPC–slag mortar 380 (OSM380)	190	190	1.8	125.4	855	–	220
4	OPC–slag mortar-500 (OSM500)	250	250	1.9	165	1125	–	230
5	Slag mortar 380 (SM380)	–	380	0.9	125.4	855	–	215
6	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 silica sands was used as 0.93%; all the specimens were cured in curing regimes ac and wc after casting and demoulding.
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 = air curing under room temperature, wc = water curing.

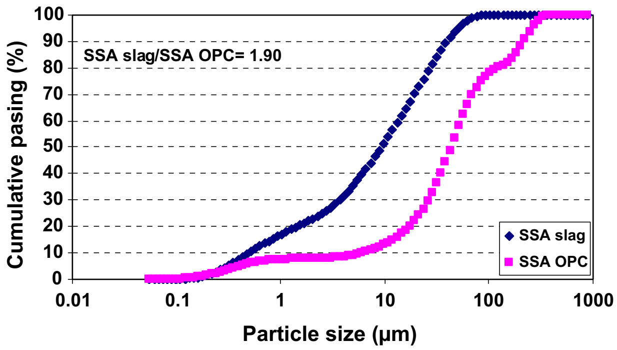


Fig. 2. The particle size analysis diagram for OPC and GGBFS.

makes this cement a suitable binder for concrete exposed to chloride, acid, and sulphate attacks. However, one of the disadvantages of GGBFS concrete is its poor resistance against carbonation. After carbonation attack, GGBFS concrete is vulnerable to scaling under the combined load of freezing-thawing and de-icing salt. Owing to surface disintegration, other attacks on the structure are more likely which can result in a dramatic decrease in durability [4].

Global cement production is expected to increase 2.5 times between 2005 and 2050 with the majority of this growth occurring in developing countries. The consolidated strategies to reduce CO_2 emissions resulting from the production of clinker are as: the substitution of clinker by mineral admixtures like blast-furnace slag, the use of alternative fuels such as bio-fuels and waste and increasing energy efficiency of the production process. Another strategy for reducing CO_2 emissions is to improve the efficiency of cement use [5–8]. Slag-based blended cements are now marketable worldwide and slag has been incorporated in quantities up to 85% by weight in different mix designs [9]. GGBFS is a by-product of the iron making process and is produced by water quenching molten blast furnace slag. Use of GGBFS as a cement replacement in mortar and concrete is a common practice due to technological and environmental benefits. 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 [10]. Replacement of clinker by slag not only offers energy savings and cost reduction compared to ordinary Portland cement (OPC), but also has other advantages such as low heat of hydration, high sulfate and acid resistance, better workability, and good ultimate strength and durability [11]. GGBFS is commonly used in combination with Portland cement in concrete for many applications [12,13].

Fig. 1 presents the evolution of mineral addition in cement from 1973 to 2007. It shows that the percentage has remained roughly constant at about 20% over the last 30 years, but its nature has changed with a diminution of GGBFS and an increase in limestone addition. This can be associated with the decline in French steel industry that began in the late 1970s, coupled with changes in standards that permitted higher level of limestone addition. It has to be noted that such substitutions are not made exclusively during cement production; they can also be made during concrete production [14].

Concrete made with GGBFS has many advantages, including improved durability, workability and economic benefits [12]. The drawback in the use of GGBFS concrete is that its strength development is considerably slower under standard 20 °C curing conditions than that of Portland cement concrete, although the ultimate strength is higher for the same water-binder ratio [15,16].

As reported in [17], the mortars used in this study can also be classified into three groups as OPC mortars (OMs), OPC–slag mortars (OSMs) and slag mortars (SMs). Three groups of mortars were made in this experimental work. In the first group, only OPC was used as binder. In the second group, both OPC and GGBFS were used. Finally, in the third group, GGBFS was only used. The results obtained showed that the second group of mortars gave the highest strengths when the specimens were cured in water in duration up to 90 days.

As reported by the researchers [18] "If the potential of concrete with regards to strength and durability is to be fully realized, it is mostly essential to be cured adequately. The curing becomes even more important if the concrete contains supplementary cementing materials such as fly ash or ground granulated blast-furnace slag or silica fume, and is subjected to hot and dry environments immediately after casting". Curing of concrete is maintaining satisfactory moisture content in concrete during its early stages in order to develop the desired properties. However, good curing is not always practical in many cases. Curing of concrete plays a major role in developing the concrete microstructure and pore structure, and hence improves its durability and performance, i.e. each 1 m^3 of concrete requires about 3 m^3 of water for construction most of which is for curing [19].

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 [26]; 1.30 $\leqslant$ CaO/SiO_2 = C/S = 1.33 for slag $\leqslant$ 1.40 [26].

Table 3
Grain size distributions for silica sands used in the study based on BS 812-103.1: 1985.

Sieve size (μm)	Sieve No.	$W_{SS} + W_S$ (g)	W_S (g)	W_{SS} (g)	Retained (%)	Cumulative retained (%)	Cumulative passing (%)
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	FM = 388.31/100 = 3.88			499.7	–	388.31	

W_S = weight of sieve, W_{SS} = weight of silica sands, FM = fineness modulus [33,34].

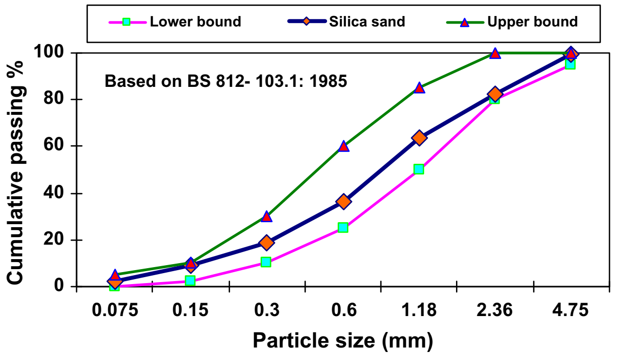


Fig. 3. Grain size distribution diagram for silica sands used in the study.

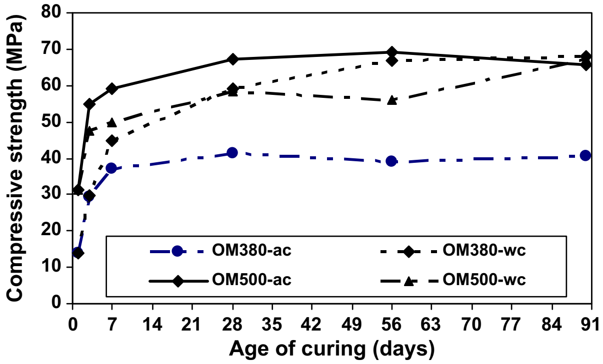


Fig. 4. Variations of strengths versus age of curing for the OPC mortars' specimens having cement contents 380 and 500 kg/m^3 and cured in ac and wc.

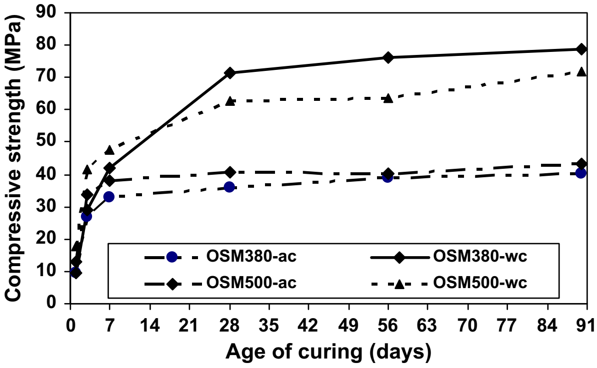


Fig. 5. Variations of strengths versus age of curing for the OPC–slag mortars' specimens having cement contents 380 and 500 kg/m^3 and cured in ac and wc.

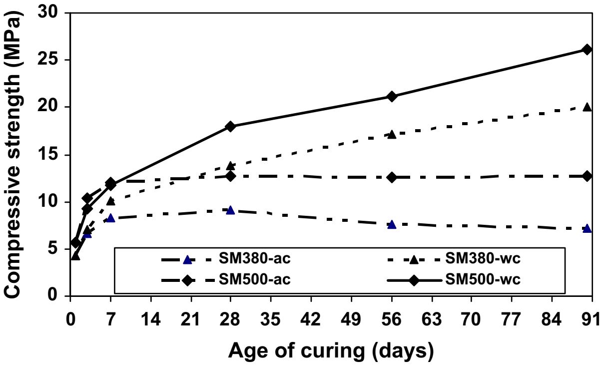


Fig. 6. Variations of strengths versus age of curing for the slag mortars' specimens having cement contents 380 and 500 kg/m^3 and cured in ac and wc.

Proper curing of concrete structures is important to ensure they meet their intended performance and durability requirements. In conventional construction, this is achieved through external curing, applied after mixing, placing and finishing [20]. Proper curing is one of essential means to get a durable concrete. It consists of the length of moist curing and the temperature of curing. The hydration of cement can take place only when the vapor pressure in the capillaries is sufficiently high, about 0.8 of saturation pressure [21]. Therefore early drying of concrete may stop the cement hydration before the pores are blocked by hydration products and thus a more continuous pore structures may be formed. The cover concrete is more sensitive to drying since it is more prone to lose water. The formation of a continuous pore structure in cover concrete may provide an easy passage for the intrusion of aggressive species and therefore the deteriorating of the concrete structure. Early drying can also lead to more shrinkage and cracking and this would aggravate the deterioration process of concrete. Usually the concretes with lower w/c are less sensitive to the curing [21].

In practice, structural concrete is seldom moist-cured for more than 7 days. Experimental studies are applied in determining the influence of a mineral admixture on the microstructure, capillary and porosity of concrete. The use of additional cementitious materials due to economic, technical, and environmental considerations has become very common in modern concrete construction. Most of the studies on the strength development, pore size distribution, and durability of concrete systems have been performed thus, far under standard curing conditions [22]. During the 20th century, there has been an increase in the consumption of mineral admixtures by the cement and concrete industries. This rate is expected to increase. The increasing demand for cement and concrete is met by partial cement replacement of different materials [23].

By far the most common test carried out on concrete is the compressive strength test. The main reason to understand this fact is that this kind of test is easy and relatively inexpensive to carry out [24,25].

Literature shows that very little data is available on the strength development of mortar and concrete containing ggbfs [27]. For this purpose, experimental investigation is carried out on the compressive strength development of cement–slag mortars with time and for three different percent replacements of ggbfs. The aim of this study is to determine the strength development equations versus age of curing in log- scale in both curing regimes ac and wc for all three groups of mortars in duration up to 90 days. Moreover, the relationships between compressive strengths of the mortars in ac and wc are presented. Based on the relations determined, the strength of specimens can be obtained with high accuracy in water curing when they are given under room temperature and vice versa. Likewise, the optimum curing regimes are given in both durations of 3–7 and 28–90 days for three groups of mortars.

2. Experimental procedure

2.1. Mix proportions and curing

Totally, in this experimental work 12 mixes of mortars were prepared. Table 1 represents the mix proportions for 12 mixes of mortars. In all the mixes water-binder and sand-binder ratios were as 0.33 and 2.25, respectively. At first, based on grain size distributions, 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 using a rod of 16 mm diameter; using a rod to compact mortar specimens is standard as confirmed in [17,28]. 24 h after casting, the specimens were demoulded and cured in air under room temperature with 27 ± 3 °C and 65 ± 18% RH or in water 23 ± 2 °C with time needed for breaking the specimens.

2.2. Materials

2.2.1. Binders including cement and slag

The cement used in all the mixes was OPC. Its specific gravity was about 3.14. The particle size analysis (PSA) diagram for the binders used in the study is shown in Fig. 2. The chemical compositions of OPC used in this research were determined by the testing method X-ray fluorescence spectrometry (XRF). Chemical properties of OPC used in this experimental work are given in Table 2. ASTM C109-99 [29] was used for determination of the compressive strength of hydraulic cement mortars by using 50 mm side cubes as specimens. Based on particle size analysis tests, the specific surface area of OPC was determined to be 1893.9 m^2/kg (based on BET). It should be noted that standard deviations of compressive strengths for all specimens were within an acceptable range as less than 7.00. Maximum and minimum amounts of standard deviation were as 5.20 and 0.25, respectively.

GGBFS is not therefore used in applications when high early-age strength is required. Attempts have been made to overcome the problem of slow strength development in mortars and concretes containing GGBFS using suitable curing regimes [11]. 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 [30]. Based on the definition of slag activity index (SAI) in ASTM C989 [31], 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.

2.2.2. Fine aggregates

The fine aggregates used in the concrete mixes were graded silica sands with specific gravity, fineness modulus (FM) and water absorption (BS 812-103.1:1985 [32]) 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. 3.

2.2.3. Water and super plasticizer

Potable water was used in all the mixes for casting and in curing of the specimens. 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 colour, 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 [35]. 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.

2.3. Test and mixing procedures

2.3.1. Mortar mix method

Initially, five grades of silica sands were 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. 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 for mortars and the specimens were moulded. For each mix of mortar, the duration of mixing time is by about 10–11 min.

2.3.2. Flow table test for fresh mortars

In order to have appropriate workability for each mix, after casting a flow table test was performed as per ASTM C230 [36]. 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.

2.3.3. Compressive strength test for hardened mortars

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 60 ± 10% RH 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 [37].

3. Results and discussion

In this research, a 50% level of slag was selected as an optimum level [38]. All the mixes are classified into three groups including OPC, OPC-slag and slag mortars. Each group includes 4 mixes and the specimens were cured in different curing regimes after casting and demoulding, i.e. under room temperature (ac) and in water (wc) [39,40]. It should be noted that the mixes were made using binder contents 380 and 500 kg/m^3. The specimens of all three

Table 4
Curing regime ranking at early and later ages for mortars having binder contents 380 and 500 kg/m^3.

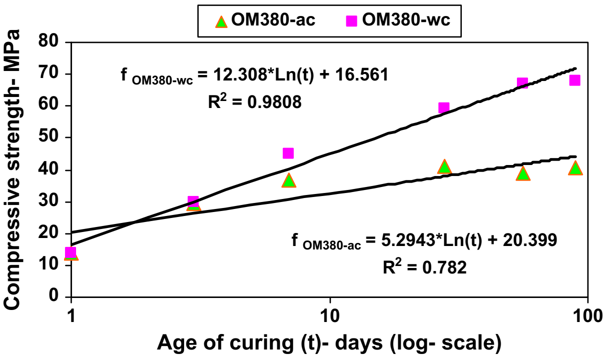
No.	Batching no.	Mix name	Strength at early ages (days)		Strength at later ages (days)		
			3	7	28	56	90
1	OPC mortars 380-(OM380)	OM-ac	wc>	wc>	wc>	wc>	wc>
2		OM-wc	ac	ac	ac	ac	ac
3	OPC mortars 500-(OM500)	OM-ac	ac>	ac>	ac>	ac>	wc>
4		OM-wc	wc	wc	wc>	wc>	ac>
5	OPC–slag mortars 380-(OSM380)	OSM-ac	wc>	wc>	wc>	wc>	wc>
6		OSM-c	ac	ac	ac	ac	ac
7	OPC–slag mortars 500-(OSM500)	OSM-ac	wc>	wc>	wc>	wc>	wc>
8		OSM-wc	ac	ac	ac	ac	ac
9	Slag mortars 380-(SM380)	SM-ac	wc>	wc>	wc>	wc>	wc>
10		SM-wc	ac	ac	ac	ac	ac
11	Slag mortars 500-(SM500)	SM-ac	ac>	ac>	wc>	wc>	wc>
12		SM-wc	wc	wc	ac	ac>	ac>

wc = Water curing, ac = air curing under room temperature, for making of OPC–slag mortars the binders were used as 50% cement and 50% slag content.

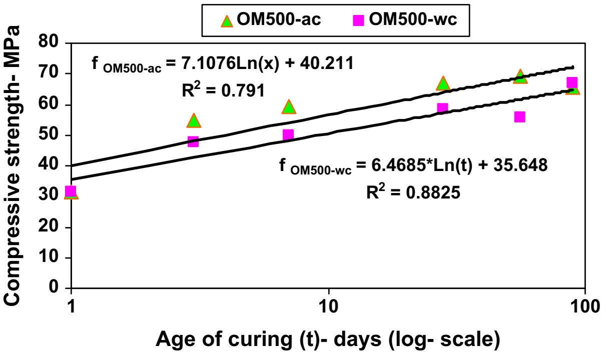
Table 5
Strength development relationships of mortars having binder contents 380 and 500 kg/m^3 cured in ac and wc.

No.	Regression relationship
1	$f_{OM380\text{-}ac} = 5.2943 * \mathrm{Ln}\,(t) + 20.399$; $R^2 = 0.7820$
2	$f_{OM380\text{-}wc} = 12.308 * \mathrm{Ln}\,(t) + 16.561$; $R^2 = 0.9808$
3	$f_{OM500\text{-}ac} = 7.1076 * \mathrm{Ln}\,(t) + 40.211$; $R^2 = 0.7910$
4	$f_{OM500\text{-}wc} = 6.4685 * \mathrm{Ln}\,(t) + 35.648$; $R^2 = 0.8825$
5	$f_{OSM380\text{-}ac} = 6.0005 * \mathrm{Ln}\,(t) + 15.862$; $R^2 = 0.8573$
6	$f_{OSM380\text{-}wc} = 16.109 * \mathrm{Ln}\,(t) + 11.151$; $R^2 = 0.9833$
7	$f_{OSM500\text{-}ac} = 5.4105 * \mathrm{Ln}\,(t) + 21.457$; $R^2 = 0.7372$
8	$f_{OSM500\text{-}wc} = 10.911 * \mathrm{Ln}\,(t) + 23.731$; $R^2 = 0.9472$
9	$f_{SM380\text{-}ac} = 0.6205 * \mathrm{Ln}\,(t) + 5.6504$; $R^2 = 0.4346$
10	$f_{SM380\text{-}wc} = 3.3895 * \mathrm{Ln}\,(t) + 3.6617$; $R^2 = 0.9824$
11	$f_{SM500\text{-}ac} = 1.347 * \mathrm{Ln}\,(t) + 7.6745$; $R^2 = 0.7421$
12	$f_{SM500\text{-}wc} = 4.3201 * \mathrm{Ln}\,(t) + 4.6004$; $R^2 = 0.9691$

f and t are compressive strength of mortar and age of curing, respectively; R^2 is coefficient of determination in regression relationships.
Note 1: SM = slag mortar, OSM = OPC–slag mortar for 50% OPC replacement with slag, OM = OPC mortar, ac = air curing under room temperature, wc = water curing.
Note 2: It should be noted that a logarithmic equation as $f = a * \mathrm{Ln}\,(t) + b$ is the best to describe the relationship between compressive strength of OPC–slag mortars at the same age and curing regime.



(a) - for OM380



(b) - for OM500

Fig. 7. Strength development versus age of curing in log- scale for OPC mortars having cement contents 380 and 500 kg/m^3 and cured in ac and wc.

groups of mortars for binder contents 380 and 500 kg/m^3 in different curing regimes ac, wc were analyzed in duration up to 90 days. Variations of compressive strengths for all three groups of mortars having binder contents 380 and 500 kg/m^3 are shown in Figs. 3–5. One of the findings in this study is to use both slag and OPC to achieve the highest compressive strength for OPC–slag mortars. This was found OSM380-wc about 80 MPa at 90 days with use of only 190 kg/m^3 cement content in one meter cube of mortar.

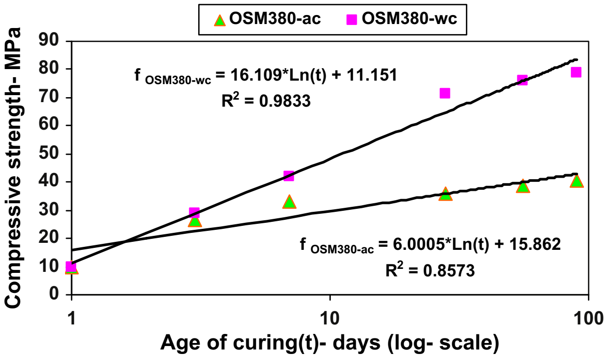
3.1. Strength analysis of the mixes

3.1.1. Mortars having binder contents 380 and 500 kg/m^3 cured in ac

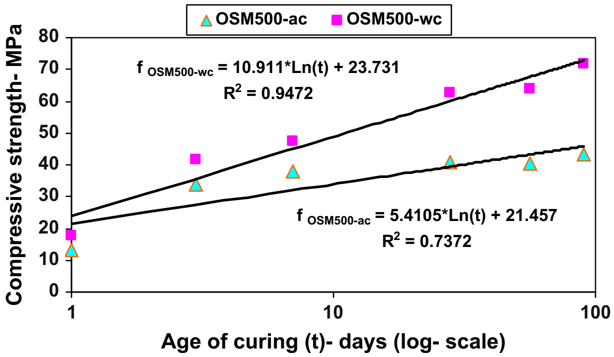
Variations of compressive strength for the specimens cured in water (wc) and under room temperature (ac) are shown in Figs. 4–6. From the Figures it is observed that the strengths of OPC mortar 500 (OM500) cured under room temperature are higher than those of OPC mortar 380 (OM380), OPC–slag mortar 380 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 major role in strength improvement of the mortars, whereas for concrete this role is probably related to porosity and aggregate interface. Overall, 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; 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.

3.1.2. Mortars having binder contents 380 and 500 kg/m^3 cured in wc

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 compared to OM500, and moreover strength loss of 4.4%



(a) - for OSM380



(b) - for OSM500

Fig. 8. Strength development versus age of curing in log-scale for OPC–slag mortars having binder contents 380 and 500 kg/m^3 and cured in ac and wc.

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 M500 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.

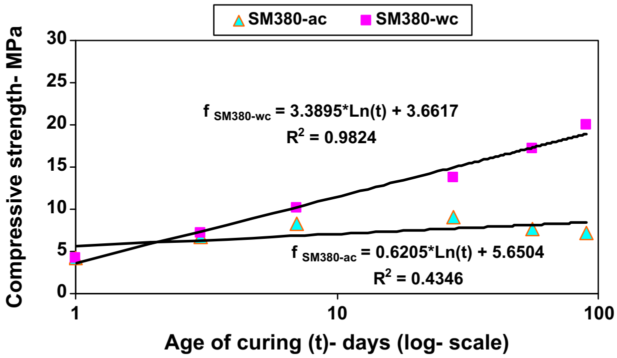
3.2. Optimum curing regimes and comparison

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

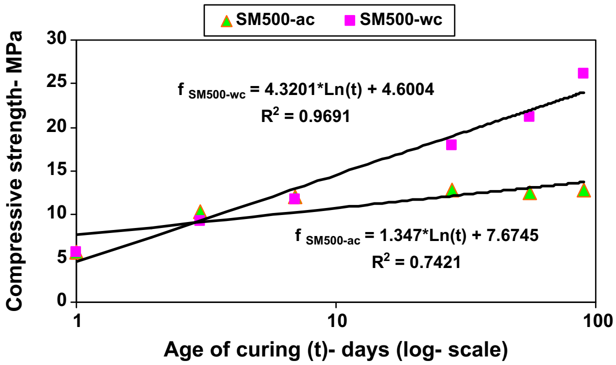
In duration of 3–7 days, i.e. short term, curing regime wc is the optimum for all three groups of mortars including OPC mortars, OPC–slag mortars and slag mortars with exception of OM500 and SM500.

In duration of 28–90 days, i.e. long term, curing regime wc is the optimum for all three groups of mortars with cement contents 380 and 500 kg/m^3 with exception of OM500. It can be seen that wc is the optimum for the OPC–slag mortars having binder contents 380 and 500 kg/m^3 in the whole duration up to 90 days.

The curing regime ac is the optimum for both OM500 and SM500 in duration of 3–90 and 3–7 days, respectively. This reality once again shows the highly importance of water curing to release the latent pozzolanic potential of slag particles. Probably, it can be said that ac is the optimum for both OM500 and SM500 in duration of 3–7 days due to in this duration the internal mixing water and higher contents of binders, i.e. cement and slag, are available enough, and then hydration process progression is well done.



(a) - for SM380



(b) - for SM500

Fig. 9. Strength development versus age of curing in log- scale for slag mortars having slag contents 380 and 500 kg/m^3 and cured in ac and wc.

3.3. Strength development of mortars' specimens cured in ac and wc

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 the later ages. In this research based on the results obtained for the 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.

As reported in [32,41], our results in this research also shows that the most appropriate form of equation to describe the variations of compressive strength versus age of curing is a logarithmic function in the form of $f = a * Ln(t) + b$; 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 5 and Figs. 7–9, can forecast the strength development of three groups of mixes including OPC, OPC-slag and slag mortars. The results of the best fitted curves are shown in the Figures for all the mixes having binder contents 380 and 500 kg/m^3.

Comparison of the relations given in Figs. 6–8 in both curing regimes ac and wc shows that given coefficient of determination R^2 from regression relationships in wc are significantly bigger than those of ac; for instance, the R^2 values for SM380 are as 0.9824 and 0.4346 in curing regimes wc and ac, respectively. This reality clearly reveals that more strength variations exist for all three

Table 6
Comparison of compressive strengths for the specimens of three groups of mortars having binder contents 380 and 500 kg/m^3 cured in ac and wc at 3 and 90 days.

Description Binder content (kg/m^3)	380				500			
Curing regime	ac		wc		ac		wc	
	OPC mortars							
Age of specimen (days)	3	90	3	90	3	90	3	90
Comp. strength (MPa)	29.49	40.77	29.63	68.05	54.81	65.52	47.71	67.08
Difference percentage	−0.47	−40.1	0.47	66.9	14.9	−2.3	−12.9	2.4
	OPC–slag mortars							
Age of specimen (days)	3	90	3	90	3	90	3	90
Comp. strength (MPa)	26.65	40.39	28.89	78.79	33.69	43.19	41.56	71.69
Difference percentage	−7.7	−48.7	8.4	95.1	−18.9	−39.7	23.4	66
	Slag mortars							
Age of specimen (days)	3	90	3	90	3	90	3	90
Comp. strength (MPa)	6.69	7.16	7.11	20.07	10.31	12.77	9.31	26.16
Difference percentage	−5.9	−64.3	6.3	180.3	10.7	−51.2	−9.7	104.8

ac = Air curing under room temperature, wc = water curing, + and − denote increase or decrease in strength of specimen cured in water or at air under room temperature, respectively.

Table 7
Relationships between compressive strengths of the mortars' specimens cured in ac and wc for three groups of mortars.

No.	Exponential regression relationships
1	$f_{OM380\text{-}wc} = 5.9448 * e^{0.0578\ fac}$; $R^2 = 0.9663$
2	$f_{OM500\text{-}wc} = 18.062 * e^{0.0177\ fac}$; $R^2 = 0.9023$
3	$f_{OSM380\text{-}wc} = 4.6884 * e^{0.0708\ fac}$; $R^2 = 0.9829$
4	$f_{OSM500\text{-}wc} = 9.2556 * e^{0.0462\ fac}$; $R^2 = 0.9802$
5	$f_{SM380\text{-}wc} = 1.6998 * e^{0.2551\ fac}$; $R^2 = 0.5278$
6	$f_{SM500\text{-}wc} = 1.7789 * e^{0.1842\ fac}$; $R^2 = 0.7990$
	Linear regression relationships
7	$f_{OM380\text{-}wc} = 1.9261 * f_{ac} - 17.486$, $R^2 = 0.8608$
8	$f_{OM500\text{-}wc} = 0.7872 * f_{ac} + 6.1622$, $R^2 = 0.8348$
9	$f_{OSM380\text{-}wc} = 2.3325 * f_{ac} - 20.598$, $R^2 = 0.8658$
10	$f_{OSM500\text{-}wc} = 1.6841 * f_{ac} - 7.9374$, $R^2 = 0.8961$
11	$f_{SM380\text{-}wc} = 2.0748 * f_{ac} - 2.8411$, $R^2 = 0.3262$
12	$f_{SM500\text{-}wc} = 2.2052 * f_{ac} - 8.9713$, $R^2 = 0.6174$

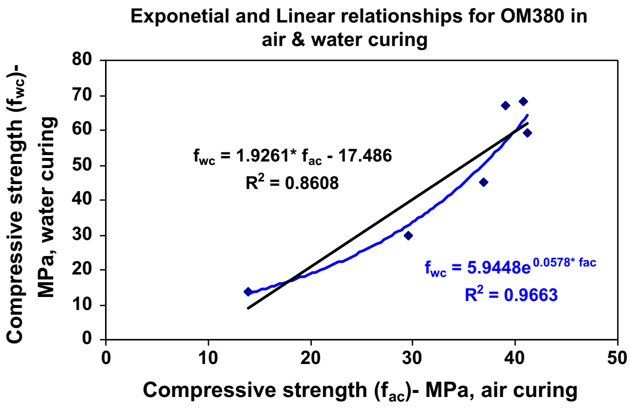
f_{ac} *and* f_{wc} are the compressive strength of mortars' specimens cured in ac and wc, respectively; R^2 is coefficient of determination in regression relationships.
Note 1: SM = slag mortar, OSM = OPC–slag mortar for 50% OPC replacement with slag, OM = OPC mortar, ac = curing under room temperature, wc = water curing.
Note 2: It should be noted that an exponential equation as $f_{wc} = a * e^{(b*fac)}$ is the best to describe the relationship between compressive strengths for OPC–slag mortars cured in ac and wc; f_{wc} and f_{ac} are the strengths of specimens cured in wc and ac, respectively.

groups of mortars in curing regime ac compared to water curing regime. This result once again shows the highly importance of water curing for all groups of mortars compared to air curing regime.

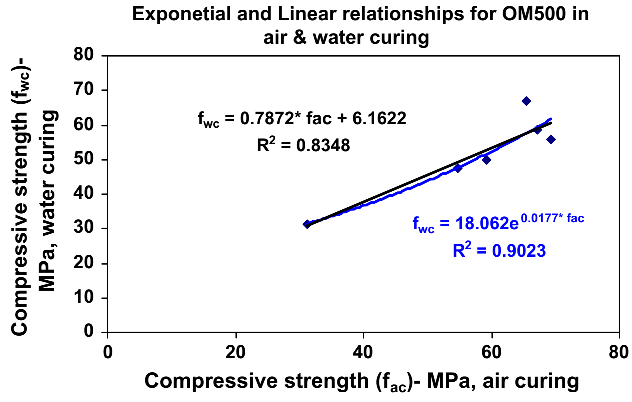
Generally, comparison of the strengths given in Table 6 in both curing regimes ac and wc shows that the strengths are more sensitive whenever supplementary materials are used in mortars. The results obtained revealed that the strength of specimens at the specified age and cured in ac are lower than those of wc; especially, differences of percentage will be increased with increase in age of specimens [42–44].

Strength comparison of the specimens for OPC mortars cured in ac and wc shows that the strengths of OM380 and OM500 cured in water at 90 days are higher about 67% and 2.4% than those of the specimens cured in air.

For the specimens of OPC–slag mortars 380 it was observed that the strength of specimens at 3 and 90 days when cured in air were lower about 7.7% and 48.7% than those of the specimens cured in water; in other words, the strength of specimens cured in water are more about 8.4% and 95.1% than those of the specimens cured in air at 3 and 90 days, respectively.



(a)- for OM380

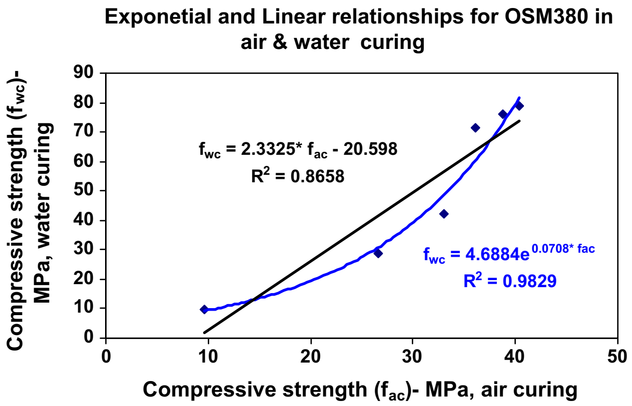


(b)- for OM500

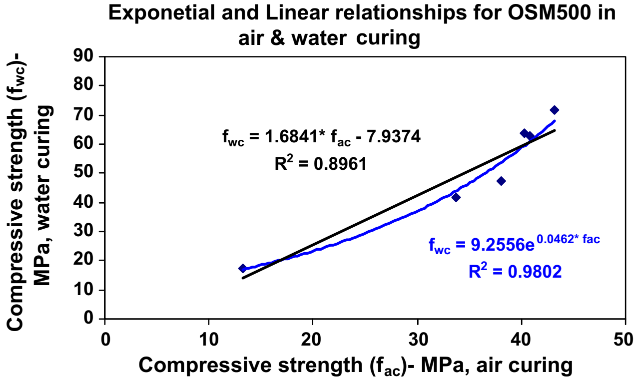
Fig. 10. Relationships between the compressive strength of OPC mortars' specimens cured in wc and ac having cement contents 380 and 500 kg/m^3.

Strength growth was observed for the specimens of slag mortars 380 and 500 at 90 days as 180% and 105%, respectively whenever they were cured in water compared to air curing.

Based on the results given in Table 6, it is seen that strength growth for the specimens of three groups of mortars having binder content 380 cured in water is more than that of mortars having binder content 500 at 90 days. This statement is true at 3 days only for OPC and slag mortars and not for OPC–slag mortars.

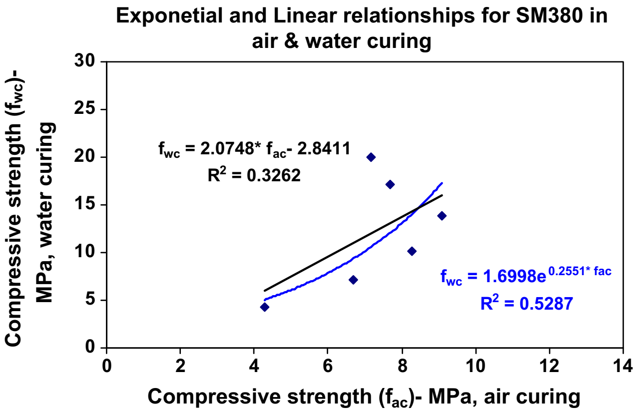


(a)- for OSM380

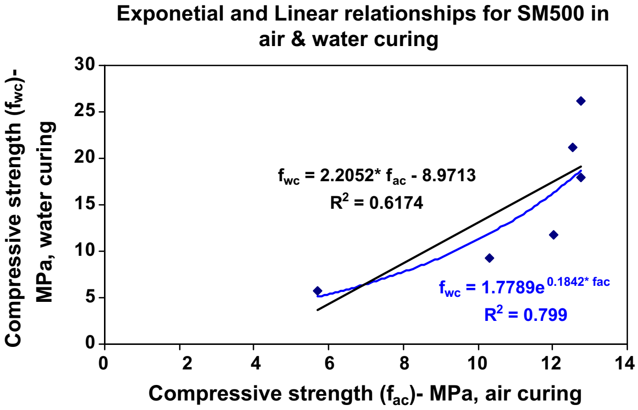


(b)- for OSM500

Fig. 11. Relationships between the compressive strength of OPC–slag mortars' specimens cured in wc and ac having binder contents 380 & 500 kg/m^3.



(a)- for SM380



(b)- for SM500

Fig. 12. Relationships between the compressive strength of slag mortars' specimens cured in wc and ac having slag contents 380 and 500 kg/m^3.

3.4. Relationships between the strength of specimens cured in ac and wc

Regarding the highly importance of curing regimes ac and wc for all three groups of mortars and based on the results obtained from this research, the relationships between strengths in the mentioned curing regimes were determined and given in Table 7. These relationships are shown in Figs. 10–12 using exponential and linear regression equations. The results comparison and evaluation showed that the best regression equation to describe this relationships is a exponential function as $f_{\text{M-wc}} = a * e^{(b * f_{\text{M-ac}})}$; where $f_{\text{M-wc}}$ and $f_{\text{M-ac}}$ are the compressive strength of mortar mixes cured in water and under room temperature, respectively in MPa, a and b are the constant factors for each mix. R^2 is coefficient of determination in regression relationships which given in Table 7.

As reported in [42] the best equation to relate the strengths in both curing regimes ac and wc is a linear equation. In this investigation a linear relationship can be accepted as the best only after exponential equation; there are clearly some errors in the results in this case.

4. Conclusions

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

1. An exponential relationship exists between the strengths obtained in air and water curing conditions for all groups of mortars; with and without GGBFS.
2. In this investigation it was proved that higher strengths could be obtained using lower binder contents for OPC and OPC–slag mortars provided the specimens are cured in water. This is a new finding having importance from economic and environmental viewpoints; it means that for producing higher strengths it is not a necessity to use more binders in OPC and OPC–slag mortars.
3. Air curing conditions influenced OPC and slag mortars more than OPC–slag mortars.
4. The highest strength obtained is attributed to the second group of mortars as 80 MPa at 90 days, when the specimens were cured in water. This is related to OSM380-wc.
5. The increase in the level of OPC and slag makes the mortars more sensitive to air curing conditions.
6. It was recognized that in duration of 3–7 days, wc is the optimum for all three groups of mortars with exception of OM500 and SM500; in duration of 28–90 days, wc is also the optimum for three groups with exception of OM500.
7. The results obtained showed rarely strength loss at later ages for the three groups of mortars.
8. The results showed that curing regime and its duration has a significant effect on the strength improvement of all three groups of mortars.
9. 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 in the form of $f = a * Ln\,(t) + b$. a and b are the specified constants.

10. The highest strengths obtained for OPC mortar 380 at 28 and 90 days were as 59 and 68 MPa, whenever the specimens were cured in water. Moreover, no strength loss was observed in duration up to 90 days.
11. The highest strengths obtained for OPC–slag mortars 380 at 28 and 90 days were as 71 and 80 MPa, whenever the specimens were cured in water. Moreover, no strength loss was observed in duration up to 90 days.
12. For slag mortars it was revealed that the highest strengths could be only achieved using more slag and with use of water curing. For this group of mortars using SM500-wc is preferable compared to SM380-wc. The strengths obtained at 28 and 90 days for SM500-wc and SM380-wc were as 18 & 26 and 13.8 & 20 MPa, respectively. It is seen that the strengths of SM500-wc are higher than those of SM380-wc at 28 and 90 days about 28.6% and 30.0%, respectively.

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