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Effects of curing regimes and cement fineness on the compressive strength of ordinary Portland cement mortars

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ABSTRACT

Curing techniques and curing duration have crucial effects on the strength and other mechanical properties of mortars. Proper curing can protect against moisture loss from fresh mixes. The objective of this experimental work is to examine the compressive strength of ordinary Portland cement mortars (OMs) under various curing regimes and cement fineness. Six different curing methods including water, air, water heated, oven heated, air–water, and water–air were applied to the specimens and also six groups of mortars were used. The results showed that the highest and lowest compressive strengths are attributed to the specimens of OPC mortar water cured using grounded OPC for duration of 6 h (OM–G6–wc) and OPC mortar air cured under room temperature with oven heated after demoulding of the specimens at 60 °C for duration of 20 h (OM–OH–ac), respectively. The maximum levels obtained of compressive strengths at 7, 28, and 90 days are 57.5, 70.3, and 76.0 MPa, respectively.

1. Introduction

The compressive strength of cement mortar and concrete plays a fundamental role in the design and construction of the concrete structures [1]. The objective of curing is to keep concrete saturated or as nearly wet to assist the hydration of cement.

The rate and degree of hydration, and the resulting strength of concrete and other properties, depend on the curing process that follows placing and consolidation of the plastic concrete. Hydration of cement continues for years at a decreasing rate as long as the mixture contains water and the temperature conditions are favorable. Once the water is lost, hydration ceases. Curing of mortar and concrete is very essential for their strengths gain durability. Concrete is generally cured by water ponding [2]. In general, curing ensures that the mix water is available for cement hydration.

Curing is used to provide an appropriate environmental condition within a concrete structure, i.e. relative humidity and temperature to ensure the progress of hydration reactions causing the filling and segmentation of capillary voids by hydrated compounds. In a specific condition, curing duration to achieve an adequate hydration of Portland cement mortars and concretes depends mainly on the chemical and mineralogical compositions and also the fineness of cement. ACI 308 recommended practice [3] suggests 7 days of moist curing for most structural concretes. However, the period of curing should be extended to 14 days when the cement contains supplementary cementitious materials, such as slag and fly ash, owing to the slow hydration reactions between supplementary cementitious materials and the calcium hydroxide. The process of this reaction requires the presence of water to produce the cementing compounds to contribute for filling the capillary voids.

According to Powers [4] a minimum of 80% humidity is required for hydration of cement. Moreover, he suggested that the permeability of the surface concrete may increase 5–10-folds if concrete is insufficiently cured. The most effective method of curing is to keep the exposed concrete surface continuously moist by ponding and spraying with water. In this method, the concrete kept fully saturated during the period, the ideal condition for strength development and hydration of cement.

If the potential of mortar and concrete with regards to strength and durability is to be fully realized, it is most essential that they be cured adequately. The curing becomes even more important if they contain supplementary cementing materials such as ggbfs, fly ash, and silica fume and are subjected to dry and hot environments immediately after casting [5].

The necessity for curing arises from the fact that hydration of cement can take place only in water-filled capillaries so in order to obtain a good mortar or concrete, the placing of an appropriate mix must be followed by curing in a suitable environment during the early stages of hardening and a loss of water by evaporation from capillaries must be prevented [6,7].

Curing techniques and curing duration significantly affect the strength and other properties of mortar and concrete. The development of mortar properties such as strength depends on the hydration of cement. After placement, the only factors that influence

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Nomenclature

Acronym	Original expression
OM	OPC mortar
WH	water bath heated curing
G6	ground OPC for duration of 6 h
OH	oven heated curing
aw/c	curing in air under room temperature for the first week after casting and after that water cured up to 90 days
wa/c	water cured for the first week after casting and after that curing in air under room temperature up to 90 days
ac	curing in air under room temperature
wc	water cured
SSA	specific surface area
PSA	particle size analysis
FM	fineness modulus
SP	super plasticizer
W/B	water–binder ratio
S/B	sand–binder ratio
OPC	ordinary Portland cement
XRF	X-ray fluorescence
LOI	loss on ignition
f	compressive strength of the specimens in MPa

cement hydration of a particular mortar are the availability of moisture and temperature. Proper curing can maintain a satisfactory moisture content and temperature in mortar and concrete during their early ages so that the desired properties may develop [8,9].

One of the major determinants of cement quality is its fineness. It is well known that the compressive strength of cement increases with fineness, and that cement with a narrow size distribution has higher strength than those with a wide one. In this sight, grinding of cement, especially blended cements, has attracted interests of many researchers [10].

The most important property of cement is setting strength in concrete, and cement quality is assessed and controlled by measuring its strength under standard conditions. It is well known that the compressive strength of cement increases with fineness or specific surface area, and that for equal surface area, cements with a narrow particle size distribution have a higher strength than those with a wide size distribution. The chemical composition of the cement is a major determinant of its setting strength. In the cement industry, the fineness of the cement is usually expressed not as a size distribution but by surface area [11].

The hydration reactions in Portland cement is essential to improve the potential strength and durability of mortars and concretes. This contribution depends on the type and fineness of cement, the type and the amount of supplementary material present, the water/cement ratio and the curing conditions, especially at early ages [12].

This paper reports the results of an investigation about ordinary Portland cement mortars studied after six curing regimes. These included moist (water) curing (wc) as control, curing at room temperature (ac), curing at water bath heated (WH), curing at oven heated (OH), curing at room temperature for first week after casting and after that in the water up to 90 days (aw/c), and curing in water for first week after casting and after that at room temperature up to 90 days (wa/c). Six groups of mortars; OM air and water cured (first group), OM–WH air and water cured (second group), OM–G6 air and water cured (third group), OM–aw and OM–wa cured (fourth group), OM–OH air and water cured (fifth group), and OM–G6/WH air and water cured (sixth group) also were used. The objective of this study is to examine the compressive strength of ordinary Portland cement mortars under different curing regimes and cement fineness used in the investigation and also comparing the results obtained and determining the best and worst mixes for curing regime used.

2. Mix proportions, curing, and testing

Table 1 represents the mix proportions for different mixes. In all mixes W/B = 0.33, S/B = 2.25 and silica sands were used. At first, based on particle size analysis (PSA), five grades of silica sands were mixed. Two minutes after that, cement was put into the mixture, followed by 2 min of mixing. Firstly, the mixing water was added to the mix and mixing was continued for 2 extra 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 compacts each layer with ten impacts, by a rod of 16 mm diameter. Twenty-four hours after casting, the specimens were demoulded and cured in air under room temperature with 27 ± 3 °C and 65 ± 18% relative humidity or in water 23 ± 2 °C with time needed for breaking the specimens.

2.1. Materials

The properties of the materials that have been used in the study are described as follows.

2.1.1. Cement

The cement used in all mixes was ordinary Portland cement (OPC). ASTM C109-99 was used for 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 the PSA tests, the specific surface area (SSA) for OPC in use was determined to be 1.8939 m^2/g and 3.0987 m^2/g for grounded OPC in duration of 6 h. The PSA diagrams for the cement used in the study are shown in Fig. 1. The chemical compositions of OPC used in this research have been determined by X-ray fluorescence (XRF). Chemical properties of the cement are given in Table 2.

Table 1
Mix proportions of ordinary Portland cement mortars.

No.	Mix name	Curing regime	OPC (g)	Water (g)	Super plasticizer (g)	Flow (mm)
1	OM–wc-control	Water	1800	632.0	30	230
2	OM–ac	Air	1800	632.0	28	230
3	OM–WH–ac	Air	1800	632.0	26	225
4	OM–WH–wc	Water	1800	632.0	24	220
5	OM–G6–ac	Air	1800	632.0	21	235
6	OM–G6–wc	Water	1800	632.0	19	230
7	OM–aw/c	Air–water	1800	632.0	21	225
8	OM–wa/c	Water–Air	1800	632.0	20	220
9	OM–OH–ac	Air	1800	632.0	21	225
10	OM–OH–wc	Water	1800	632.0	19	220
11	OM–G6/WH–ac	Air	1800	632.0	25	225
12	OM–G6/WH–wc	Water	1800	632.0	22	220

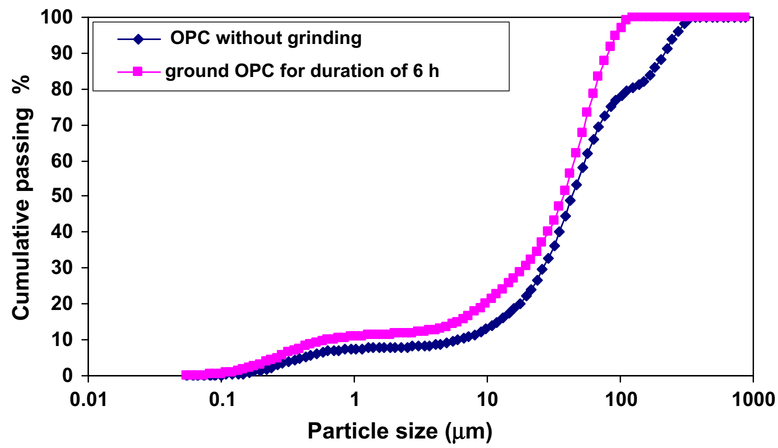

Fig. 1. Particle size analysis diagram for ordinary Portland cement.

Table 2
Compositions of ordinary Portland cement (% by mass).

P_2O_5	SiO_2	Al_2O_3	MgO	Fe_2O_3	CaO
0.068	18.47	4.27	2.08	2.064	64.09
MnO	K_2O	TiO_2	SO_3	CO_2	LOI
0.045	0.281	0.103	4.25	4.20	1.53

2.1.2. Aggregates

The fine aggregates used in the mixes are graded silica sands with specific gravity, fineness modulus (FM) [7,13] and water absorption (BS812: Clause 21) 2.68%, 3.88% and 0.93%, respectively. The maximum size of aggregate is 4.75 mm. The PSA are given in Table 3 and the grain size distribution diagram is shown in Fig. 2.

2.1.3. Super plasticizer

In order to have appropriate consistency with low W/B ratio, super plasticizer (SP) is used. The SP used in this investigation is Rheobuild 1100. The specific gravity of SP is approximately 1.195 and brown in color, with a pH in the range of 6.0–9.0. The consumed amount of SP in the mortar depends on the level of cement and mortar building conditions.

2.1.4. Water

Potable water was used in all the mixes.

2.2. Testing procedure

2.2.1. Workability test of fresh mortar

In order to have appropriate workability and consistency for each mortar mix, after casting, a flow table test has been done. The range of flow amounts were

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

Sieve size (µm)	Sieve no.	$W_{SS} + W_S$ (g)	W_S (g)	W_{SS} (g)	Retained %	Cumulative ret. (%)	Cumulative 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 [7,13]; absorption % for silica sand is 0.93%.
Grain size distribution for silica sand used in the mixes is as: 12% mesh 50/100, 18% mesh 30/60, 30% mesh 16/30, 20% mesh 8/16, and 20% mesh 4/6.

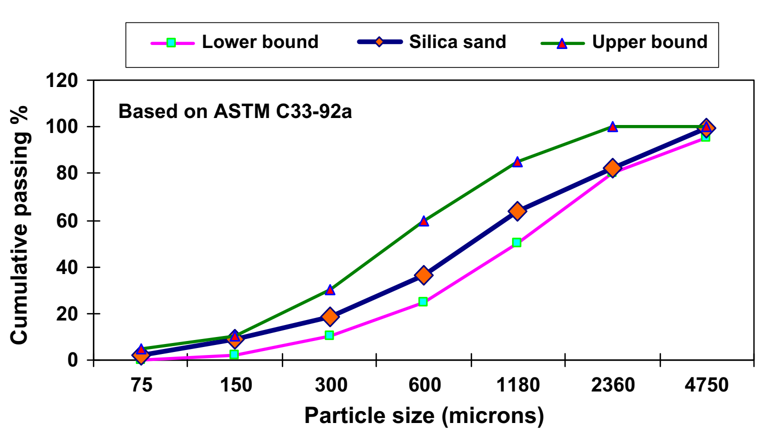

Fig. 2. Grain size distribution diagram for silica sands.

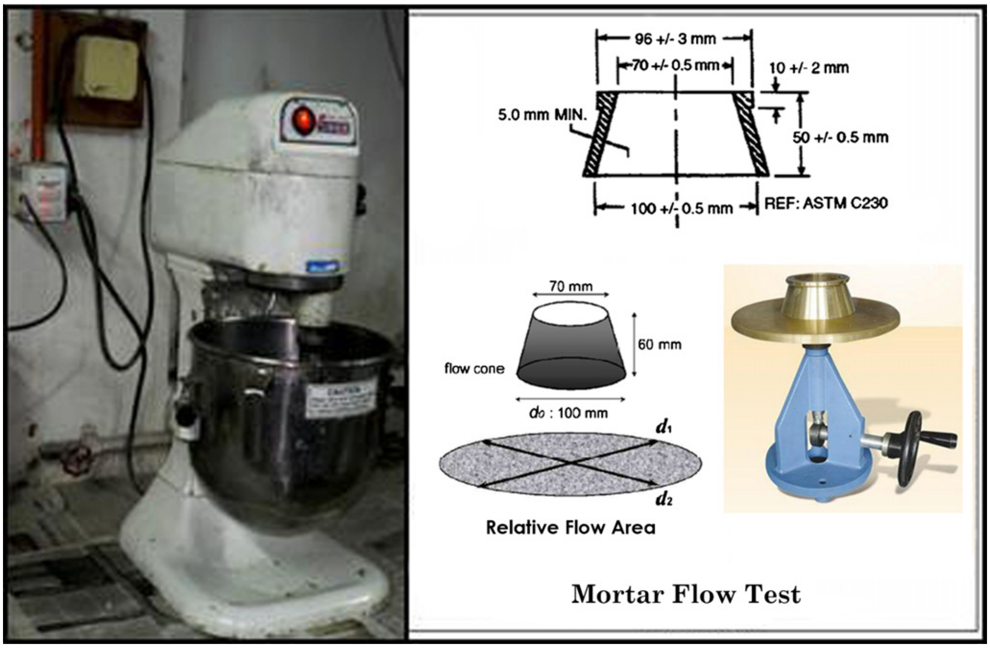

Fig. 3. Photographs for the mixer and flow table test.

between 220 and 235 mm. In the test procedure, after casting, some mortar is put in the truncated brass cone, in two layers. Each layer is compacted by a 16 mm diameter steel rod for 10 impacts, 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 60 s period. The jolting of the flow table enables the mortar to consequently spread out, with the maximum spread to the two edges of the table being recorded. The average record is calculated as flow in mm. The flow table tests were done according to ASTM C230/C230M-08 [14]. The photograph of the test equipment is shown in Fig. 3.

2.2.2. Compressive strength test of hardened mortar

Three cubic samples, with lengths of 50 mm, were used for each age. The specimens produced from fresh mortar were demoulded after 24 h, and were then cured in water with a temperature of 23 ± 2 °C, and in the air under room temperature with 27 ± 3 °C and 65 ± 18% relative humidity, until the specimens were then used for compressive strength tests at 3, 7, 28, 56, and 90 days. Compressive strength measurements were carried out using ELE testing machine press with a capacity of 2000 kN, and a pacing rate of 0.5 kN/s. Compressive tests have been done according to BS 1881, Part 116, 1983.

3. Results and discussion

First group of mortars (G1) is included two mixes OM–ac and OM–wc. Comparison of compressive strengths for the mixes shows that strength at 3 and 7 days for OM–ac are more than those of OM–wc, but after 7 days the strengths reduce up to 90 days. At 90 days the strength is minimized and there is strength loss about 7% compared to 56 days. Therefore curing in the air is not practically recommended. It can be seen that for OM–wc (control mix) the strengths are continuously increased at all ages and there is not any strength loss. For G1, variations of compressive strength vs. the age of specimens are shown in Fig. 4.

Second group of mortars (G2) includes two mixes OM–WH–ac and OM–WH–wc. Both mixes are heated in bath water heated in duration of 20 h with 60 °C after specimen demoulding. It is observed that for OM–WH–ac mix, strength at 3 and 7 days are more about 25% and 24% than those for control mix at the same ages, while for OM–WH–wc mix are more 9% and 4% than those for control mix. It is noted that for both mixes there are some strength loss at later ages. Strength loss contents are 5.5% at 90 days and 4.5% at 56 days for OM–WH–ac and OM–WH–wc, respectively. Comparing between the strengths for both mixes shows that it is better that the specimens are cured in air under room temperature after heating in the bath water. As a fact it can be said that this finding is a novelty and has a significant effect in precast concrete

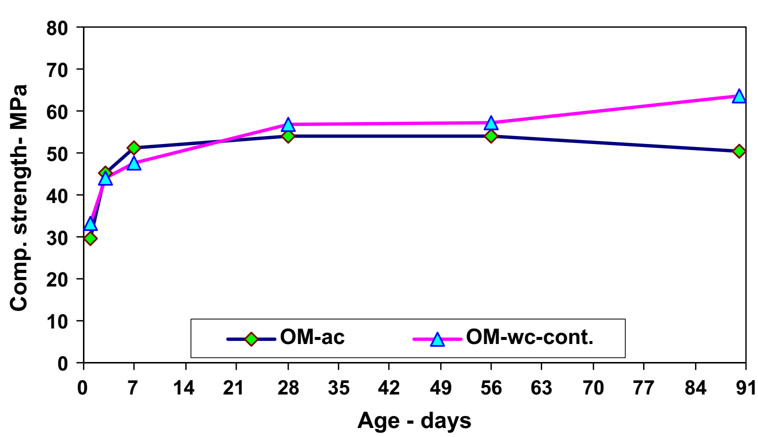

Fig. 4. Variations of compressive strength versus age of specimens for the first group of mortars.

industry with notable advantages from viewpoint of economic. Moreover, at 28 days and above there is strength improvement for OM–WH–ac mix compared to control mix at the same ages. These strength improvements are more than those of OM–WH–wc mix. For G2, variations of compressive strength vs. the age of specimens are shown in Fig. 5.

As it is seen from Fig. 6, the third group of mortars (G3) includes two mixes OM–G6–ac and OM–G6–wc. Ground OPC in a period of 6 h is used in both mixes. After demoulding of the specimens for 24 h, the specimens were cured at room temperature for OM–G6–ac and in water for OM–G6–wc. Comparison of strengths for both mixes shows that for air cured mix the compressive strength at 3 days is maximized, but after 3 days the strengths are gradually reduced. At 90 days strength of the mix is about 71% strength at the same age of control mix. Therefore for G3, curing in the air is not recommended. It seems that whenever the OPC particles are ground, the specific surface area of the particles is increased and then it needs more water for hydration process. Hence, when the specimens are cured in the air, there is not enough water for hydration process, and then the strengths are reduced more and more at later ages. In contrary of air cured mix, there is continuous increasing in strength for water cured mix. It can be seen that there is 23.5% strength improvement compared to control mix at the same ages. Strength improvements at ages 3, 7, and 28 days are 14%, 20%, and 24% compared to control mix at the same ages, respectively. Although at 90 days there is some little strength loss compared to 56 days, but there also is about 19% strength improvement compared to control mix at the same age. For G3, variations of compressive strength vs. the age of specimens are shown in Fig. 6.

3.1. Effect of cement fineness

Since hydration starts at the surface of the cement particles, it is the total surface area of cement that represents the material available for hydration. Thus, the rate of hydration depends on the fineness of cement particles, and for a rapid development of strength a high fineness is necessary. However, the cost of grinding and the effect of fineness on other properties, e.g. gypsum requirement, workability of fresh concrete and long-term behaviour must be borne in mind [13].

Many results indicate that the early strength of a hardened cement paste is directly proportional to the fineness of the cement [15], but fineness cannot contribute to later-age strength. In contrast, excessively high fineness may increase the water requirement and cause a reduction in later strength gain.

Increasing the fineness of cement reduces the amount of bleeding in concrete. This is more pronounced for concrete containing no entrained-air.

Increasing the fineness of cement beyond an optimum limit increases the water requirement of concrete. The workability of non-air-entrained concrete is increased by the cement fineness.

In air-entrained concrete the effect of fineness of cement on workability is very much less pronounced. The 28-day compressive strength of concrete, with or without entrained-air, increases with

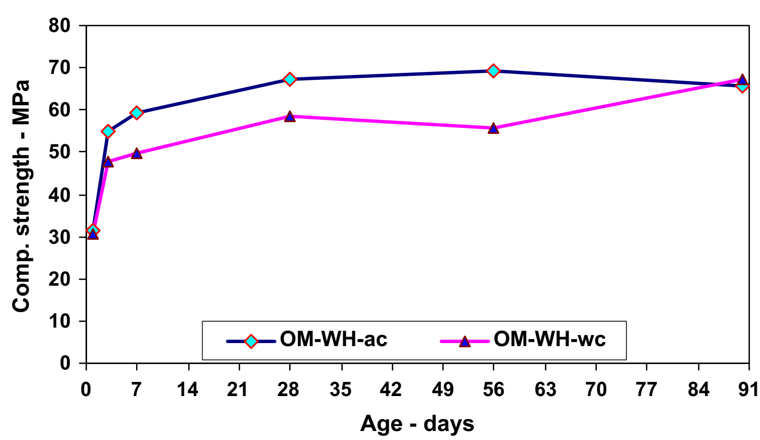

Fig. 5. Variations of compressive strength versus age of specimens for the second group of mortars.

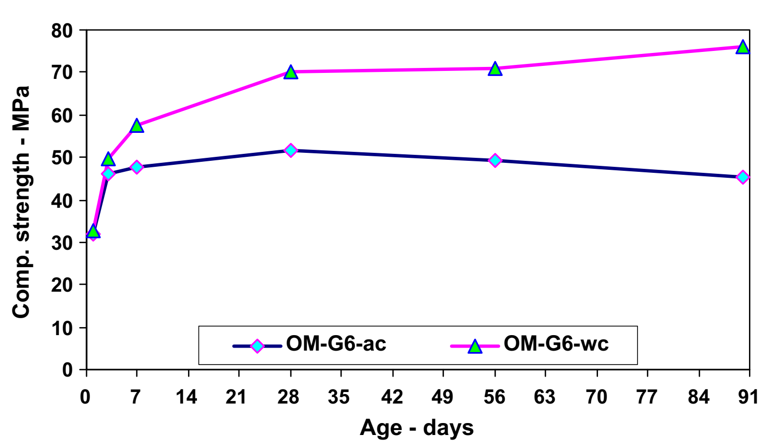

Fig. 6. Variations of compressive strength versus age of specimens for the third group of mortars.

an increase in cement fineness. The difference in compressive strength due to difference in fineness of cement is considerably less at 1 year's age.

The fineness of cement influences the drying shrinkage of concrete when the water content is increased because of fineness, the drying shrinkage is increased.

As it is seen from Fig. 7, fourth group of mortars (G4) includes two mixes OM–aw/c and OM–wa/c. Comparison of strength results shows that general trend for both mixes at all ages are approximately the same. For duration 3–56 days the strength improves for the specimens of both mixes. There is strength loss about 8% at 90 days compared to 56 days for the specimens of OM–aw/c mix only. At 90 days there is not only strength loss for the specimens of OM–wa/c mix but also the strength improves about 6% compared to control mix at the same age. For OPC mortars it can be said that the effect of first week water cured of the specimens after casting is equal or even more than that for later 12 weeks (from eighth day to 90 days). Hence, as a good constructional point, it can be said that in arid areas for curing of concrete structures it is very significant to cure them at least for duration of first week after casting. This is a new finding and can be recommended for building contractors in arid areas. Like of this point has recommended by ACI 308 Committee. ACI 308 recommended practice [3] suggests 7 days of moist curing for most structural concretes.

Moreover, it can be seen that whenever it is desired to gain the same strength results for OM–aw/c mix, it needs to cure the specimens for duration of 12 weeks in the water after first week of casting. For G4, variations of compressive strength vs. the age of specimens are shown in Fig. 7.

As it is seen from Fig. 8, fifth group of mortars (G5) includes two mixes OM–OH–ac and OM–OH–wc. For OM–OH–ac there is only strength improvement up to 3 days, although strength at 3 days is less than that of control mix at the same age. It is observed that at 7 days and above there is strength loss at all ages. The strength at 90 days is minimized and is about 72% of strength of control mix at the same age. It is seen that the foresaid statement is reversed for OM–OH–wc mix. For this mix the strengths at all ages except 90 days are improved. At 90 days there is strength loss about 7% compared to 56 days. There is strength improvement at 7, 28, and 56 days compared to control mix at the same ages about 2%, 6%, and 11%, respectively. Comparison of strength results shows that heated water curing has better strength results and also it is more practical and feasible than that of oven heated whenever the specimens are cured in bath water heater at 60 °C for duration of 20 h and also oven heated at 60 °C for duration of 20 h. When the specimens are heated in the water and then cured in air under room temperature, the higher strengths can be gained compared to those cured in water. It is observed that heating of the specimens in the water and curing in the air and also heating of the specimens in the oven and curing in the water have higher strengths than water heated with curing in the water and oven heated with curing in the air, respectively. For G5, variations of compressive strength vs. the age of specimens are shown in Fig. 8.

As it is seen from Fig. 9, sixth group of mortars (G6) includes two mixes OM–G6/WH–ac and OM–G6/WH–wc. For both mixes,

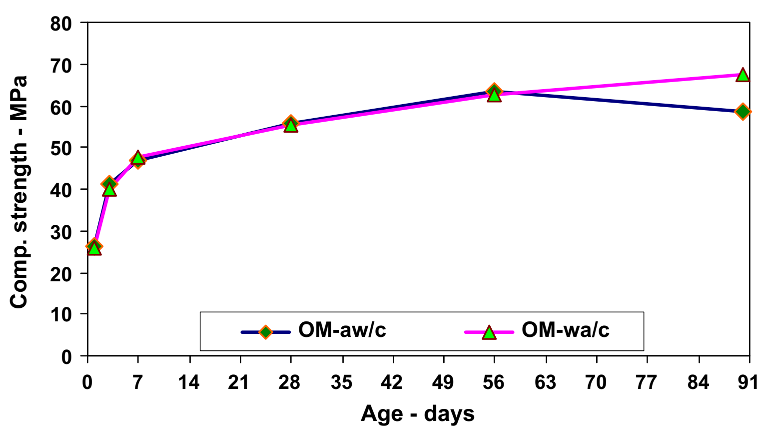

Fig. 7. Variations of compressive strength versus age of specimens for the fourth group of mortars.

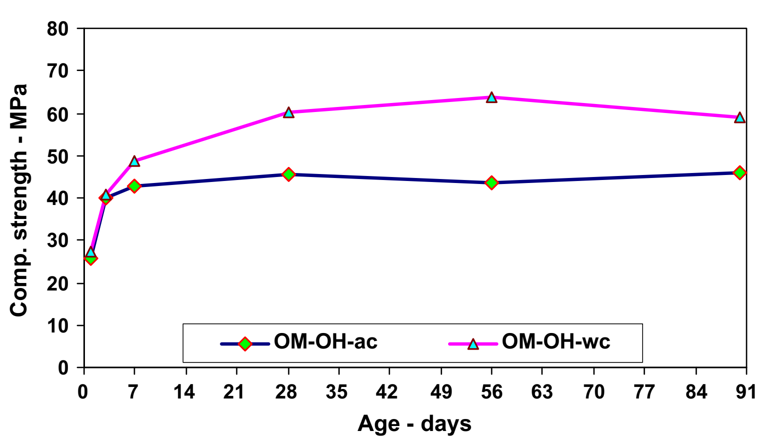

Fig. 8. Variations of compressive strength versus age of specimens for the fifth group of mortars.

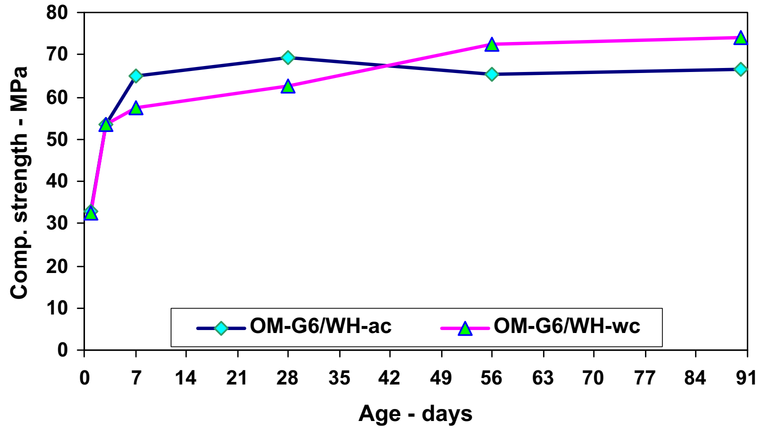

Fig. 9. Variations of compressive strength versus age of specimens for the sixth group of mortars.

cement particles are first ground in a period of 6 h and after that the mixes are made; after specimens demoulding they are heated in bath water heated for duration of 20 h at 60 °C. In fact, in G6 the effects of both cement fineness and curing regimes are studied, simultaneously.

Air curing of the specimens shows strength improvement at 3, 7, and 28 days compared to control mix at the same ages about 22%, 36%, and 22%, respectively. At 56 days there is strength loss about 6% compared to 28 days. Grind of OPC particles has increased surface area, and then it needs more water for hydration process. It seems for air cured the inside water of the specimens is enough for hydration process up to 28 days, and hence there is gain strength until 28 days. After 28 days the inside water of specimens is not enough for hydration process, and then the hydration is slowed or may be stopped; finally, strength loss is occurred. For water cured regime, the above statement is reversed and the hydration process can be completed adjacent with water, and hence the gain of strengths is continued. Water curing of the specimens' shows that strength improves at all ages and there is no strength loss. For G6, variations of compressive strength vs. the age of specimens are shown in Fig. 9.

3.2. Comparison of OM–G6–wc and OM–G6/WH–wc mixes

Comparison of strength results of OM–G6/WH–wc mix and those of OM–G6–wc mix shows that ultimate strength results of OM–G6–wc mix are higher than those of OM–G6/WH–wc mix. Therefore it can be said that without use of heating in heated water method and only with use of more fineness of cement particles it can be achieved to higher strengths and this reveals notable effect of cement fineness on the strength improvement of mortars. Comparing between strength results of OM–G6–wc (sole effect of cement fineness) and OM–G6/WH–wc (both effects of cement fineness and water heated curing at 60 °C for duration of 20 h) mixes shows there is no strength loss for both mixes and the strengths at all ages are continuously increased. However, it is seen that ultimate strength of OM–G6–wc mix is higher than that of another mix about 2.6%. Hence, it can be said that the sole effect of cement fineness is more than that of combined effect of cement fineness and water heating. This shows that the higher strength is achieved only with use of more cement fineness and without use of water heating which also is more economic. Based on the strength results, it is seen that average strength gain at six ages for OM–G6–wc and OM–G6/WH–wc mixes compared to control mix is 16.3% and 15.4%, respectively. This indicates more strength gain for OM–G6–wc mix.

3.3. Determination of the best and worst mixes

Comparison of the results for six groups of mortars shows that the best and worst mixes are OM–G6–wc and OM–OH–ac, respectively. In fact, the highest strength results are attributed to OM–G6–wc mix. This means that the highest strengths can be achieved without strength loss whenever OPC particles are grounded in a period of 6 h and the specimens are cured in the water after demoulding. Based on PSA test results, it is seen that SSA ratio for OPC particles with 6 h grinding and without grinding is about 1.64. This means whenever the OPC particles are averagely grounded 64% more than those in use, the highest strengths can be achieved without strength loss provided that the specimens are moist cured.

For the best mix, the strength is continuously improved at all ages without strength loss.

The worst mortar is OM–OH–ac. In this mix, at first the specimens are heated in the oven in a period of 20 h at 60 °C after demoulding, and then were cured at room temperature. It is observed that at all ages the strengths are less than those of control mix at the same ages. The strength at 90 days is the lowest about 72% of strength of the control mix at same age. The highest strength of the mix is attributed to strength at 3 days and it is about 90% of strength of control mix at the same age. It seems that the oven temperature resonates the strength at early age, e.g. at 3 days, and results in the highest strength at 3 days. Oven temperature evaporates the inside water of the specimens, and then the remained inside water of the specimens is not enough for progression of hydration process. Due to there is no water for hydration process in curing regime of OM–OH–ac mix, therefore the strengths will be reduced after 3 days more and more, and then the strength is the lowest at 90 days, which is about 72% of the control mix strength at the same age. For the best and worst mixes, variations of compressive strength vs. the age of specimens are shown in Fig. 10.

The relationship between relative compressive strength vs. curing regimes is shown in Fig. 11 for all the mixes. It is clear that the highest and lowest compressive strengths are attributed to OM–G6–wc and OM–OH–ac mixes, respectively. It is seen that there is no strength loss for OM–G6–wc mix, whereas the specimens of OM–OH–ac mix have strength loss at 56 days. Additionally, it is observed that the strengths of OM–OH–ac mix will be reduced gradually after 3 days compared to the control mix at the same ages.

The variation of compressive strength based on age of specimens for all the mixes are shown in Fig. 12. It is observed that there is not any strength loss for the mixes OM–wc–cont., OM–G6–wc, OM–aw/c, and OM–G6/WH–wc. The other mixes have strength loss at some later ages. It is usually seen that strength loss is attributed to later ages, typically after 56 days.

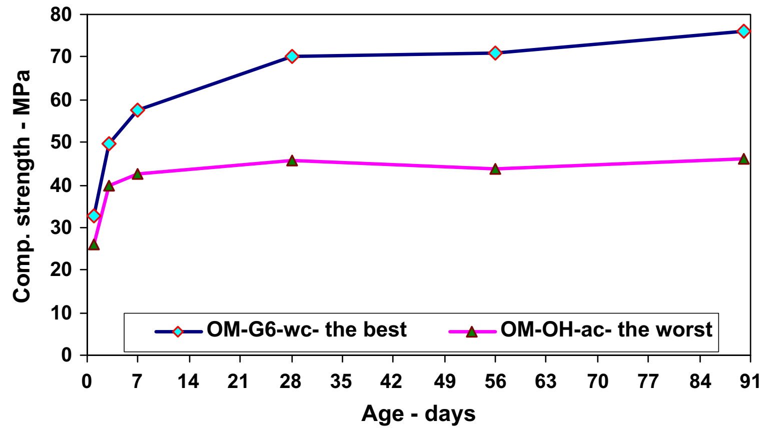

Fig. 10. Variations of compressive strength versus age of specimens for the best and worst mixes.

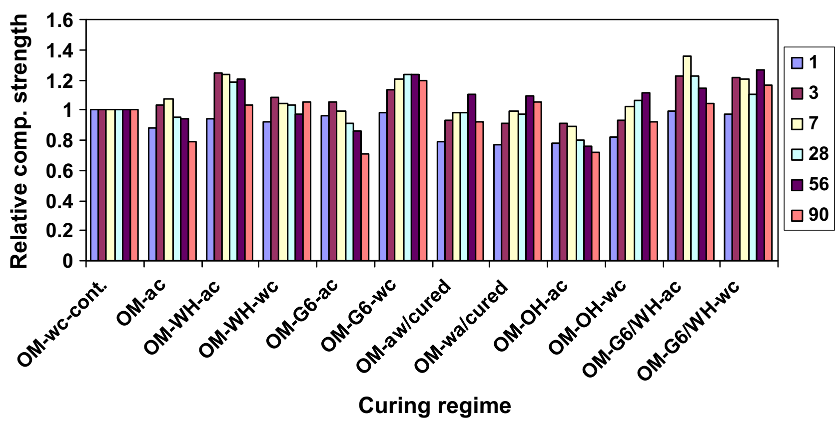

Fig. 11. Relative compressive strength versus curing regime for all the mixes. OM = OPC mortar, ac = curing in air under room temperature, wc = water cured, WH = water bath heated curing, OH = oven heated curing, G6 = ground OPC in duration of 6 h, wa/c = curing in water for first week after casting and after that in air under room temperature up to 90 days, aw/c = curing in air under room temperature for first week after casting and after that in water up to 90 days.

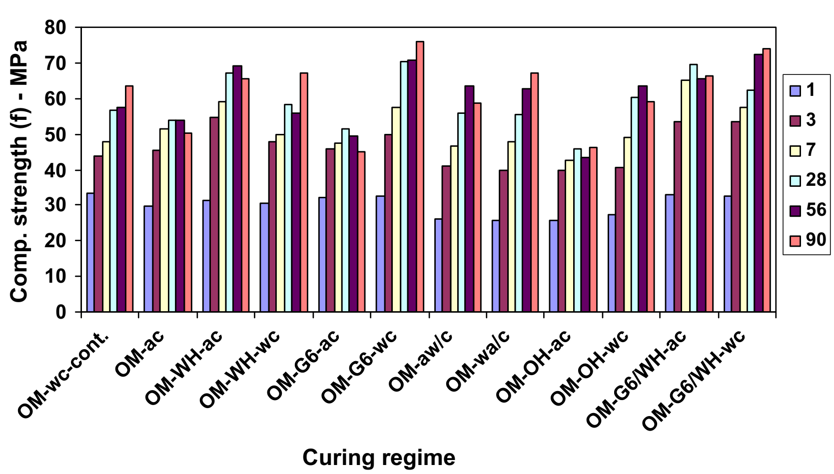

Fig. 12. The variations of compressive strength versus age of specimens for all the mixes. OM = OPC mortar, ac = curing in air under room temperature, wc = water cured, WH = water bath heated curing, OH = oven heated curing, G6 = grounded OPC in duration of 6 h, wa/c = curing in water for first week after casting and after that in air under room temperature up to 90 days, aw/c = curing in air under room temperature for first week after casting and after that in water up to 90 days, f_i = compressive strength of the specimens at i days in MPa.

3.4. Strength loss and strength development

The compressive strength loss of mortars and concretes is a fact. In the process of this research, strength loss has been observed many times for some of the mortars used. This is because of a variety of reasons; some of the observed reasons in the study are as follows:

It seems that the main cause of strength loss of the mortars with the use of ground binders is attributed to phase separation. It is evident that when the phases are separated there is no enough interlocking on the boundary layer (inter-facial zone), thereby permitting two phases to either slide against each other or intrude, which leads to strength loss.

Several researchers reported that a high temperature improves strength at early ages [1–3]. At later ages, the important number of formed hydrates had no time to arrange suitably and this caused a loss of ultimate strength. This behaviour has been called the cross-over effect [4]. For OPC it appears that the ultimate strength decreases nearly linearly, with curing temperature [5]. It seems the main reason for strength loss at later ages is due to the lack of internal water in the specimens to complete the hydration process progression. Usually for the duration 1–28 days, the internal water due to the water–binder ratio is available and adequate for the hydration process; however, beyond 28 days it is reduced and then insufficient for the process of hydration progress; furthermore, strength loss occurs.

The results show that strength loss in ordinary Portland cement mortars depends on the cement fineness and the regime of curing. The reason for the loss of strength can be due to internal or external factors. The internal factors are those linked to the chemical composition of the reacted products. The external factors are due to the variability of specimens, testing procedures, and other factors. One other factor that has an important effect is the temperature. The initial curing temperature has an important effect and can reduce or increase strength at long curing times, i.e. advanced age.

Usually, whenever it is desired to understand the behaviour of a phenomenon, it is usual to model its behaviour by a diagram or mathematical equation. Using the relationships can approximately forecast the behaviour of the phenomenon at the later ages. Based on the results obtained from this research, for all OPC mortars the mathematical equation has been determined to forecast the variations of compressive strengths vs. age of curing. Study of the variations of compressive strength vs. age of specimens shows that the best curve fitting for all the mixes is a logarithmic equation as $f = a * \text{Ln}\ (t) + b$; where a and b are constants for each specific mix. It is observed that strength development curve fitting relationships for the best and worst mixes in the investigation are as follows:

For the best mix: $f = 9.0904 * \text{Ln}\ (t) + 36.893$ with $R^2 = 0.9591$; for the worst mix: $f = 3.6209 * \text{Ln}\ (t) + 31.620$ with $R^2 = 0.7157$; where f is compressive strength in MPa, t is age of specimen in days, and R^2 is the coefficient of correlation. Strength development curve fitting for all the mixes are shown in Fig. 13.

4. Conclusions

From the data developed in this study, the following conclusions could be drawn:

1. The results obtained show that effect of the first week water curing of OPC mortars after casting is equal or even more than

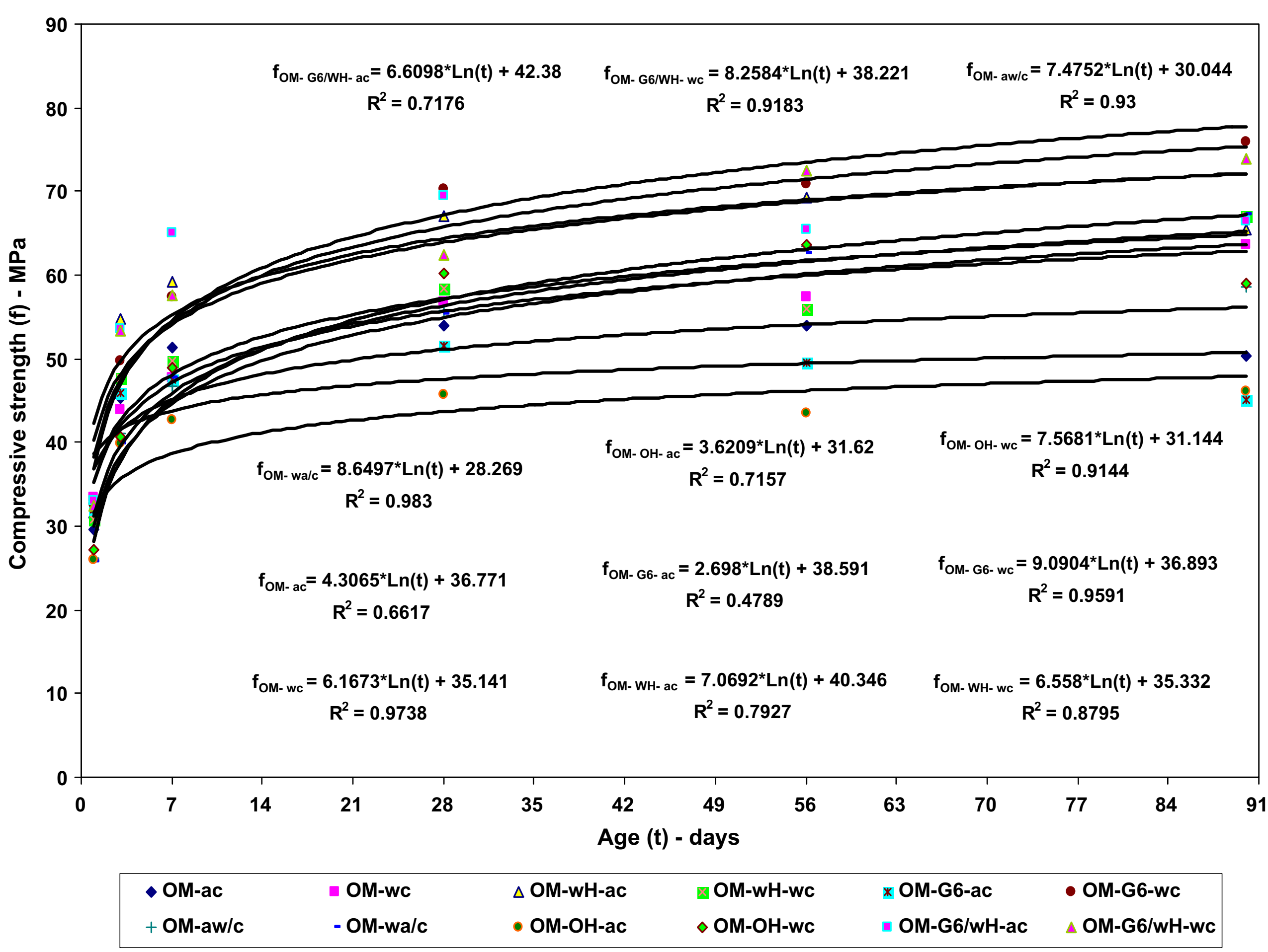

Fig. 13. Strength development curve fitting of OPC mortars. OM = OPC mortar, ac = curing in air under room temperature, wc = water cured, WH = water bath heated curing, OH = oven heated curing, G6 = ground OPC in duration of 6 h, wa/c = curing in water for first week after casting and after that in air under room temperature up to 90 days, aw/c = curing in air under room temperature for first week after casting and after that in water up to 90 days, f_i = compressive strength of the specimens at i days in MPa.

that of 12 weeks water curing after the first week of casting. This is a major advantage which has also confirmed by ACI 308 Committee for structural concrete [3].

2. Study of curing regimes and cement fineness effects on different OPC mortars, shows that the best and worst mixes are as OM–G6–wc and OM–OH–ac mixes, respectively from viewpoint of strength gain.
3. Among 12 mixes of OPC mortars studied, it was found that the mixes OM, OM–G6, OM–wa/c, and OM–G6/WH cured in the water have not shown any strength loss; moreover, strength growth is continued with the age of specimens. The other mixes have strength loss at 56 or 90 days. The maximum observed content of strength loss is equal to 8.7% and is attributed to OM–G6–ac mix at 90 days.
4. Comparison of OPC mortars heated in bath water or oven shows that water heated has the higher results than those of oven heated and it also is more practical and feasible. It was also observed that the specimens have higher strengths in air under room temperature compared to water cured after heating in water at 60 °C for duration of 20 h. This is a new finding which has a significant effect on constructional activities and is also more economic; while oven heated results in higher strengths when the specimens are cured in the water after heating.
5. Strength development curve fitting of OPC mortars is a logarithmic equation as $f = a * \text{Ln}(t) + b$. The results obtained show that the values of correlation coefficient, i.e. R^2, for the best and worst mixes are as 0.9591 and 0.7157, respectively.
6. Based on the results of the study it is evident that the usual produced OPC in factories does not have the optimum fineness. The results show that the higher strength can be gained for OPC mortars; i.e. about 20%, when the cement particles are more ground. This investigation work shows that the best specific surface area of OPC is 1.64 times of the SSA of OPC produced in the factories.

References

[1] Shariq Mohd, Prasad Jagdish, Masood Amjad. Effect of GGBFS on time dependent compressive strength of concrete. Constr Build Mater 2010;24(8):1469–78.
[2] Al-Gahtani AS. Effect of curing methods on the properties of plain and blended cement concretes. Constr Build Mater 2010;24(3):308–14.
[3] ACI Committee 308, recommended practice for curing concrete, MCP, American Concrete Institute, Farmington Hills, USA; 1998.
[4] Powers TC. A discussion of cement hydration in relation to the curing of concrete. Proc Highway Res Board 1947;27:178–88.
[5] Ramezanianpour AA, Malhotra VM. Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporated slag, fly ash or silica fume. Cem Concr Compos 1995;17(2):125–33.
[6] Cakir O, Akoz F. Effect of curing conditions on the mortars with and without GGBFS. Constr Build Mater 2008;22(3):308–14.
[7] Neville AM. Properties of concrete. 3rd ed. USA: Longman Scientific and Technical; 1992.
[8] Sharon Huo X, Wong Ling Ung. Experimental study of early-age behavior of high performance concrete deck slabs under different curing methods. Constr Build Mater 2006;20(10):1049–56.
[9] Nawy EG. Concrete construction engineering handbook. Boca Raton (NY): CRS Press; 1997. p. 20–55.
[10] Oner M, Erdogdu K, Gunlu A. Effect of components fineness on strength of blast furnace slag cement. Cem Concr Res 2003;33(4):463–9.
[11] Zhang YM, Napier-Munn TJ. Effects of particle size distribution, surface area and chemical composition on Portland cement strength. Powder Technol 1995;83(3):245–52.
[12] Bonaveti V, Donaz H, Rahhal V, Irassar E. Influence of initial curing on the properties of concrete containing limestone blended cement. Cem Concr Res 2000;30(5):703–8.
[13] Neville AM, Brooks JJ. Concrete technology. Malaysia: Prentice Hall; 2008.
[14] ASTM C230/C230M-08 Standard specifications for flow table for use in tests of hydraulic cement.
[15] Higginson, EC. The effect of cement fineness on concrete, fineness of cement, ASTM STP 473; 1970.