

Full Length Research Paper

Effects of limited initial curing durations on mechanical properties of concrete

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Mechanical properties (compressive and split tensile strength, sorptivity and coefficient of water absorption) of concrete cube specimens cured in water and ambient air (uncured) for 3, 7, 14, 28 and 90 days were determined. Compressive and split tensile strength properties of concrete specimens that were initially water cured for limited durations of 1, 2, 3, 4, 5, 6, 7, 14, 28 days and subsequently air cured were also determined at 28 and 90 days. The results show that water cured specimens had better mechanical properties than uncured specimens; however maximum compressive strength was recorded for specimens that were initially water cured for only 4 days and then tested at the age of 28 and 90 days.

Key words: Curing, compressive strength, hydration, concrete.

INTRODUCTION

Complete hydration of cement in concrete is very important in ensuring the development of maximum compressive strength, longevity and service performance of concrete structures, but it is rarely ever attained for practical reasons. Curing of concrete is the process used for promoting the hydration of cement and consists of a control of temperature and of the moisture movement from and into the concrete. When hydration of cement ceases before hydration is complete, strength reductions and reduction of durability indexes results. Aitcin et al. (1994) reported compressive strength difference of 17% to 22% between air and moist-cured concrete specimens. In another study by Shafiq and Cabrera (2004), ordinary Portland cement (OPC) concrete dry-cured had total porosity, 5% to 10% higher than wet-cured samples at 28 days. The proper curing of concrete aids the hydration of cement, resulting in improved mechanical properties of concrete; increases in wet curing days have resulted in reduced carbonation depth in concrete (Balayssac et al., 1995). Moist curing significantly promotes self healing of

tensile micro cracks in concrete (Özbay et al., 2013). Curing should start as soon as the concrete sets and should ideally continue till the water filled pores of the concrete are filled with hydration products or hydration reaches its maximum. Compressive strength of moist-cured concrete specimens has been reported to have increased continuously over a 20 year period (Wood, 1991). The early works of Powers (1947) on cement hydration established that cement hydration ceases below 80% relative humidity. Moisture loss to the environment in concrete also plays an important role in cement hydration. The degree of moisture loss is also related to the thickness of the concrete member and the relative humidity of the environment. Thin concrete members tend to lose moisture faster than thick members and a surface of concrete that is not properly cured suffers from inadequate hydration (Carrier, 1983). In earlier study by Carrier and Cady (1970), on moisture loss from concrete in a moderately severe field exposure condition, drying in concrete at a depth of 25 mm was not sufficient to stop hydration of cement at 28 days. This indicates that surface or near surface concrete layer that is not properly cured could deteriorate faster than inner layers.

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Table 1. Composition of OPC by XRF.

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Mn ₂ O ₃	P ₂ O ₅	TiO ₂	Cl-	SR	AR
24.79%	6.35%	0.92%	58.50%	2.87%	4.91%	0.80%	0.65%	0.0%	0.15%	0.06%	0%	3.41	6.88

SR: silica ratio= $\text{SiO}_2 / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$, AR=alumina ratio= $\text{Al}_2\text{O}_3 / \text{Fe}_2\text{O}_3$

Table 2. Particle size distribution of aggregates as percentage by weight passing sieve sizes.

Aggregate	Sieve size (mm)							
	20	10	5	2.36	1.18	0.60	0.30	0.15
Fine aggregates	-	-	92.4	81.6	61	38.3	14.5	5.3
Coarse aggregates	95.00	40.62	0.80	-	-	-	-	-

Table 3. Concrete mix proportions.

Cement content (kg/m ³)	Sand (kg/m ³)	Coarse aggregates (kg/m ³)	Free w/c ratio
530	458	1,302	0.30

Study by Sajedi and Razak (2011) show that, the effect of the first week water curing of OPC 50 mm mortar cubes after casting is equal or even more than that of 12 weeks of water curing after the first week of casting. Alizadeh et al. (2008) reported compressive strength increases of concrete cubes cured in water compared to air cured cubes at 7 and 28 days using Portland cement at cement content of 400 kg/m³. Importantly, compressive strength increases were reported to be more significant after 1, 3 and 6 days of moisture curing than 27 days, though strength increase was recorded at 27 days. At specimen ages of 7 and 28 days, Alizadeh et al. (2008) study showed that there were no significant compressive strength difference between 6 and 27 days of wet curing; this appears to suggest that the first 6 days of wet curing is more important in compressive strength development. The study of Ozer and Ozkul (2004) shows that initial limited water curing does not only improve compressive strength of concrete compared to air curing, but that as initial limited period gets longer the compressive strength gets higher.

The challenges inherent in site concrete production usually limit the application of water curing method. Moreover, since curing of concrete is a long term process it is virtually impossible to cure site concrete indefinitely. However the use of internal curing, burlap and foam barriers for the first few days after casting has been used to improve hydration of cement in site concrete. With the practical limitations of the application of wet curing to site concrete, the issue of how long concrete could be wet cured to achieve optimum performance becomes relevant. The ACI Committee 305 (1991). For example recommends continuous water curing for at least the first

few days when concreting in hot weather when moisture loss could be high.

Though continuous water curing for the first few days is recommended, it is important to determine the actual results of limited early water curing on strength and durability properties of concrete. An understanding of the effects of limited water curing on strength and durability properties of concrete specimens will aid curing specifications when concreting, particularly in the tropics. In this work, the effects of limited initial water curing on mechanical properties (compressive and split tensile strength, sorptivity and coefficient of water absorption) of concrete specimens were investigated and a comparison was made between water cured and air cured specimens at ages of 28 and 90 days.

MATERIALS AND METHODS

A commercial brand of OPC available in Nigeria was used for this study. The compositions of the OPC used determined by X-ray fluorescence (XRF) are given in Table 1.

Crushed granite of 20 mm maximum size with specific gravity of 2.63 was used as coarse aggregates; natural river bed quartzite sand with specific gravity of 2.73 was used as fine aggregates. The results of the sieve analysis of the aggregates are given in Table 2. The particle size distribution of the fine aggregates correspond to zone 2 sand by the BS 882: 1983 classification. The concrete mix proportions used are given in Table 3.

The concrete was mixed in a tilting drum mixer for 3 min, and manually compacted in two layers in 100 mm steel moulds. A chloride free lignosulfonate based plasticizer (Fosroc Conplast P505) complying with BS EN 934 (2001) standard was used to increase the slump for the mixes.

The laboratory work of this study was done in two stages:

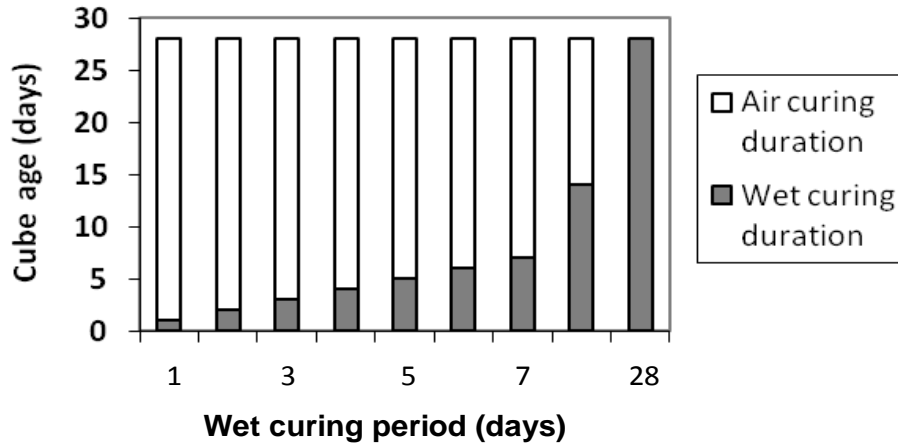


Figure 1. Relative proportions of specimen curing durations at 28 days for stage II study.

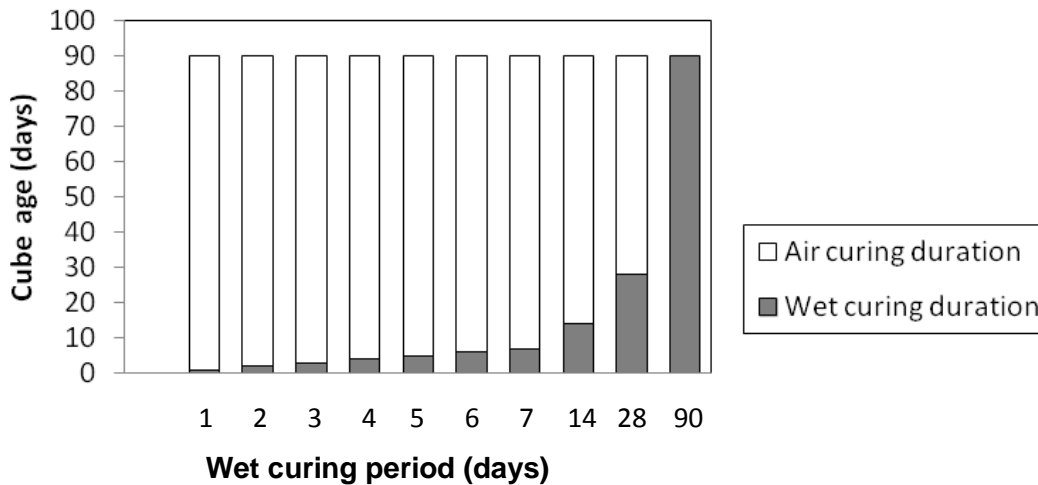


Figure 2. Relative proportions of specimen curing durations at 90 days for stage II study.

Stage I: In stage I, two sets of concrete specimens of the same mix proportions were cast and de-molded after 24 h; one set were continuously cured in water while the second set were stored on the laboratory floor (uncured) and the compressive strength determined at the same age of 3, 7, 14, 28 and 90 days. The sorptivity, coefficient of water absorption of the cubes and the split tensile strength of the cylinders (150 mm x 300 mm) was determined at 90 days. Concrete specimens that were continuously cured in water were used as control.

Stage II: In the stage II study, the cubes and cylinders were de-molded after 24 h and cured in water for limited durations of 1, 2, 3, 4, 5, 6, 7, 14 and 28 days and thereafter removed and stored on the laboratory floor and their strength determined at 28 and 90 days (inclusive of the wet hydration period). Specimens that were continuously cured in water for only 3 days were removed at the end of 3 days and subsequently stored on the laboratory floor and tested after 25 days of air storage. The same specimens were later tested at 90 days. The relative durations of water and air curing periods at test ages of 28 and 90 days are shown in Figures 1 and 2. However, the specimens that were continuously cured in water

for 28 and 90 days were removed from the curing tank and tested at that age. The coefficient of water absorption, sorptivity and split tensile strength of the stage II specimens were determined at 90 days.

The compressive strength of the cubes and split tensile strength of the cylinders was determined using *ELE ADR 3000* digital compression machine. The compressive strength of the concrete cubes were determined at a loading rate of 3.00 kN/s using BS 1881: Part 4 (1970) standard procedures; the split tensile strength of the cylinders were determined at a loading rate 2.10 kN/s in compliance with BS 1881: Part 117(1983) standard procedures. Three samples were tested for each parameter investigated and the results represent the average of three test specimen results.

Coefficient of water absorption

Coefficient of water absorption is a measure of permeability of concrete (Ganesan et al., 2008; Giannotti da Silva et al., 2008). This is determined by measuring water uptake in dry concrete in a

Table 4. Effects of water curing on physical properties of concrete stage I study.

Plasticizer (l/m ³)	Slump (mm)	Water cured compressive strength (N/mm ²)					Sorptivity $s (m \times \sqrt{t})$	Coefficient of water absorption $K_a (m^2/s) \times 10^{-8}$	Tensile strength (N/mm ²)
		3 days	7 days	14 days	28 days	90 days			
4.2	33	50.37	56.25	59.29	63.69	69.68	0.994	4.428	4.708

Table 5. Effects of air curing on physical properties of concrete for stage I study.

Plasticizer (l/m ³)	Slump (mm)	Air cured Compressive strength (N/mm ²)					Sorptivity $s (m \times \sqrt{t})$	Coefficient of water absorption $K_a (m^2/s) \times 10^{-8}$	Tensile strength (N/mm ²)
		3 days	7 days	14 days	28 days	90 days			
4.2	33	50.53	51.33	58.71	59.35	62.29	1.406	6.700	3.775

time of 1 h. The concrete specimens were heated in an oven at 98°C until a constant weight was attained at ten days and the cubes were allowed to cool gradually to room temperature for 24 h. Four sides of 100 mm cube samples were sealed with 1 mm thick silicone sealant to a height of 30 mm to allow water absorption on only one surface of the cube. The samples were immersed to a depth of 10 mm in water. After immersion in water for one hour, the cubes were taken out and the wet surface was wiped of excess water and weighed. The coefficient of water absorption of the specimens at 90 days was calculated from the formula,

$$K_a = \left[\frac{Q}{A} \right]^2 \times \frac{1}{t}$$

where K_a is the coefficient of water absorption (m²/s), Q is the quantity of water absorbed (m³) by the oven dry specimen in the time (t), $t=3600$ s and A is the surface area (m²) through which water was absorbed (Ganesan et al., 2008).

Sorptivity

Sorptivity is a measure of the capillary forces exerted by the pore structure causing fluids to be drawn into the body of the material (Ganesan et al., 2008; Hall, 1989). The concrete specimens were heated in an oven at 98°C until a constant weight was attained at ten days and then allowed to cool to room temperature for 24 h. The four sides of the cubes were coated with silicone sealant to allow the flow of water on only one surface of the cube specimen. The cube specimens were immersed to a depth of 10 mm in water on only one surface. The initial mass of the cube was taken at time 0 and at time intervals of 1, 2, 4, 8, 10, 20, 30, 60 and 90 min, the samples were removed from water and excess water blotted off and the sample weighed. It was then placed back in water and the process repeated at the same selected time intervals. The sorptivity value of the specimens at 90 days were calculated using the formula,

$$i = S/\sqrt{t}$$

where i is the cumulative water absorption per unit area of the

surface (m³/m²); S is the sorptivity (m/\sqrt{t}) and t is the elapsed time (s) (Stanish et al., 1997).

RESULTS

The results of stage I tests on cube and cylinder specimens are given in Tables 4 and 5. Table 6 shows the results of the stage II study.

DISCUSSION

Compressive strength

The stage I study results in Tables 4 and 5 shows that water cured specimens, as expected had higher compressive strength at 90 days compared to air cured specimens. The compressive strength of air cured cubes were 9.53% less than that of water cured at 90 days. The growth of CSH gels promoted by continuous cement hydration in the water cured specimens resulted in the strength increases recorded.

The results of stage II study in Table 6 shows that at 28 days, cubes exposed to longer initial curing duration tend to have higher compressive strength compared to cubes that were cured for only one day. At the age of 28 days, the maximum compressive strength of 75.83 N/mm² was however recorded for specimens cured in water for only 4 days. At the age of 90 days, cubes that were only cured for 4 days recorded the maximum compressive strength of 76.93 N/mm². Though the maximum compressive strength of cube specimens was recorded after only 4 days of initial water curing and test ages of 28 and 90 days, more solid hydration products were formed at longer initial wet curing durations as seen from the results of durability properties measured. When concrete is fully saturated at the early days by curing, subsequent

Table 6. Effects of water curing duration on compressive strength for stage II study.

Parameter	Test age (days)	Water curing duration									
		1 day	2 days	3 days	4 days	5 days	6 days	7 days	14 days	28 days	90 days
Compressive strength (N/mm ²)	28	64.90	66.07	68.25	75.83	65.49	73.19	68.41	71.03	65.24	-
	90	71.83	72.12	71.79	76.93	74.10	76.22	71.31	72.27	73.60	69.68
Tensile strength (N/mm ²)	90	4.383	4.887	4.107	4.751	4.331	4.072	5.185	4.725	4.751	4.708
Sorptivity $s (m \times \sqrt{t})$	90	1.252	1.250	1.250	1.200	1.185	1.185	1.180	1.180	1.097	0.994
Coefficient of water absorption $K_a (m^2/s) \times 10^{-8}$	90	3.625	3.620	3.620	3.618	3.600	3.569	3.466	3.428	3.158	3.128

exposure and moisture loss to the atmosphere affects only the surface, water vapour pressure in the inner depth of the concrete is usually adequate to promote hydration (Carrier and Cady, 1970). The difference in degrees of hydration between the concrete surface that lost moisture and inner layers where hydration continues would not be reflected in compressive strength, since compressive strength measurement is not a surface layer phenomenon, but that of the whole specimen. The saturated state of the stage II test specimens could be attributed to the relatively low compressive strength value of 65.24 N/mm² recorded at 28 days and 69.68 N/mm² recorded at 90 days, since these specimens were tested after removing them from the curing tank. The higher compressive strength recorded for the relatively dry specimens compared to water saturated specimens in the stage II study results shown in Table 6 is attributable to increase in secondary forces of cement gels and subsequent reduction in the disjoining pressure due to drying (Popovics, 1986; Tan and Gjør, 1996). The stage II test results generally indicate that appreciable hydration took place after the cubes were removed from water. Water that saturated the concrete pores due to water curing was still available for hydration after the specimens were removed from water, this agrees with the results of the study of Carrier and Cady (1970).

In addition, a comparison can be made between the stage I and stage II test results, since the concrete mix proportion is the same. The stage II results show that the compressive strength of the cubes that were water cured for only 1 day and tested at 28 days was 9.35% higher than the Stage I cubes that were air cured and tested at 28 days. Similarly, stage II specimens that were water cured for only 3 days and tested at the age of 28 days had compressive strength 15% higher than stage I air cured specimens tested at 28 days. These results show significant beneficial effects of early initial water curing for a few days over air curing.

Tensile strength

From the results of stage I study in Tables 4 and 5, split tensile strength of the cylinders that were water cured

was higher than that of air cured cylinders at 90 days. The split tensile strength of the water cured cylinders were 24.72% higher than that of air cured cylinders.

Similarly, the tensile strength of stage II study specimens shown in Table 6 tends to increase with increase in curing duration, with the exception of a few anomalous results after 3, 5 and 6 days of limited curing that can be attributed to inadequate compaction.

Sorptivity and coefficient of water absorption

From the results of stage I study shown in Tables 4 and 5, the sorptivity and coefficient of water absorption of the water cured specimens were lower than that of air cured specimens as expected. However comparing the results of stage I and II results in Tables 5 and 6, the sorptivity of cubes cured for only 1 day was 10.95% lower than air cured cubes at the age of 28 days. Similarly, the coefficient of water absorption of stage II specimens that were cured for only 1 day was 45.90% lower than that of stage I air cured specimens tested at the age of 28 days. The water curing of concrete results in the development of other solid hydration products in addition to CSH gels. The presence of these solid hydration products contributed to the development of a more compact concrete microstructure, resulting in lower values of sorptivity and coefficient of water absorption of water cured specimens; as initial water curing duration increased, more solid hydration products were formed.

Conclusions

The results presented in this study have shown that limited initial water curing is very important in improving mechanical properties of concrete. It also shows that the initial 4 days of curing was sufficient to develop compressive strength higher than the compressive strengths at 28 and 90 days of continuous water curing. From the sorptivity and coefficient of water absorption values of specimens that were continuous water cured, continuous water curing resulted in an improved microstructure of the concrete specimens. The results

also shows that hydration continued in concrete specimens that were initially water cured for limited days long after the specimens were removed from water. Concrete specimens that were water saturated had been shown to record lower compressive strength than dry concrete at both 28 and 90 days.

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