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Carbonation of Concrete Cured Under Different Conditions

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Abstract. *Concrete is cured under different conditions to preserve the moist state of the concrete matrix for continuous hydration as it is done on most construction sites. In this study, the effect of different curing techniques on the carbonation depth of concrete mix is presented. Concrete matrix of mix ratio 1 :2 :4 with a water-cement ratio of 0.5 was prepared and cast into cubes of sizes 150 mm. After 24 hours, the concrete cubes were removed from moulds and cured using different techniques for 3, 7, 28, 56, and 91 days. Thereafter, the compressive strength of the concrete cubes and carbonation depths were determined for each curing day. The curing techniques investigated were immersion in water (IM), sprinkling (SP), polyethylene membrane (PM), damp sand (DS), indoor (OI), outdoor (OT), and saturated wet covering (SWC). The results indicated that carbonation depth differed with each of the concrete cured in different techniques. It was observed that concrete exposed outside was worst affected by carbonation followed by those cured indoor, while those cured with polythene showed the least carbonation depth. It was concluded that the polythene membrane curing technique was the best curing technique to limit the effect of carbonation of concrete.*

Keywords: *Carbonation Depth; Curing Technique; Permeability; Compressive Strength; Construction Site.*

1 Introduction

To obtain good concrete, placing an appropriate mix must be followed by curing in a suitable environment, especially during the early stages of hardening. All concrete requires curing so that cement hydration can proceed to allow for the development of strength, durability, and other mechanical characteristics. (Jackson & Akomah, 2018) opine that curing is one of the critical steps in concrete production, but it is one of the most neglected and misunderstood procedures. According to (Ding et al. 2013) curing is the treatment of newly placed concrete during the period in which it is hardening so that it retains enough moisture to limit shrinkage and resist cracking.

Curing is designed primarily to keep the concrete moist by preventing loss of moisture from it during the period in which it is gaining strength. Curing can be achieved by keeping the concrete element completely saturated or as much saturated as possible until the water-filled spaces are substantially reduced by hydration products (Gowripalan et al. 1990). This implies that if the humidity of the ambient air is at least that high, then there will be no need for active curing to ensure continuing hydration because there will be little movement of water between the concrete and ambient air. If the concrete is not cured and is allowed to dry in the air, it will gain only 50% of the strength of continuously cured concrete (Mamlouk & Zaniewski, 2006).

The duration of curing of the concrete element has a great effect on improving its strength. According to (Mamlouk & Zaniewski, 2006) concrete cured for about three days will reach about 60% of its strength, but when cured for up to seven days its strength would have reached 80%. (Aluko, 2005) reported that several curing techniques can be applied depending on various factors considered on-site or due to the construction method. They range from the most popular water-submerged curing to moist sand, water-spray curing, polythene membrane sealing, and steam curing (autoclaving). Also, there has been the introduction of membrane-forming curing agents/compounds, which are widely accepted in developed nations because they can be applied quicker than sheets and require the least amount of curing protection. They work by sealing the surface of the concrete but do not prevent the complete evaporation of mixed water. (Ding et al., 2013) reported that the carbonation of concrete is closely associated with the moisture level of the concrete. Thus, there seems to be a relationship between carbonation and curing methods.

Carbonation poses durability challenges to concrete that permits the transfer of moisture through it. It occurs due to the ingress of atmospheric CO_2 into the concrete. Studies conducted by (Sagüés et al. 1997) established a mechanism of carbonation, which results when CO_2 diffuses into concrete, lowering the pH of concrete to about 9 to 10. At such a low pH value, the existing passive protection layer at the steel surface breaks down, and corrosion ensues. Both the calcium hydroxide $Ca(OH)_2$ and calcium silicate hydrate CaH_2O_4Si react with CO_2 forming calcite, which due to its low solubility, precipitates within the pores, altering the concrete properties (Peter et al., 2008). Consequently, carbonation leads to reduced porosity and pore size distribution (Bier et al. 1987) as well as lower permeability, and diffusion.

1.1 Statement of The Research Problem

Durability is a major concern for concrete structures exposed to aggressive environments. Many environmental phenomena are known to significantly influence the durability of reinforced concrete structures (Šavija & Luković, 2016). Carbonation is one of the major factors to cause structural deterioration. Carbonation is the reaction of the hydration products dissolved in the pore water with the carbon dioxide in the air which reduces the pH of concrete pore solution from 12.6 to less than 9 and steel passive oxide film may be destroyed and accelerate uniform corrosion (Parrott, 1990).

Furthermore, extreme climate change has been occurring globally not only in the simple form of temperature increases but also in a wide range of extreme climatic events, such as abnormal drought conditions and frequent typhoons. Among these various events, the greatest problem is found in global warming. The earth ‘s temperature has risen since the period of rapid industrial growth in the 1970s, and global warming occurs at the local level of regions and cities as well as the national level. The greenhouse gases that influence global warming include various types of chemical components, such as carbon dioxide (CO_2), perfluorocarbons (PFCs), nitrous oxide (N_2O), and methane (CH_4). Atmospheric CO_2 generates calcium carbonate by reacting with concrete hydration products. This result in reinforcing bar corrosion and concrete durability reduction due to lowered alkalinity. Therefore, this study tends to investigate how curing techniques could limit the negative effect of carbonation.

2 Experimental Procedures

2.1 Materials

The materials used for the production of concrete specimens are ordinary Portland cement (type 42.5N) as a binder. Locally crushed granite and sand free from carbon content were used as coarse and fine aggregates, respectively. The coarse aggregate had a maximum aggregate size of 12mm while the fine aggregate has a fineness modulus of 2.42. Portable water free from impurity and organic matter of any kind was also used. All aggregates were ensured to be free from deleterious substances such as organic impurities, clay and other unsound particles.
A naphthalene-based superplasticizer was used (CONPLAST SP 561) as an admixture.

Mould size of 150 x 150 x 150 mm metal were used to cast the samples. A phenolphthalein indicator solution comprising 1g of phenolphthalein indicator in a solution of 70 ml ethanol and 30 ml demineralized water was used for carbonation testing.

2.2 Preliminary Tests

The properties of the aggregate used were determined. Sieve analysis, Specific gravity, total moisture content, bulk density, dry density, aggregate impact value, and aggregate crushing value were some of the properties determined. The characterization of the aggregate was conducted following the standard procedure of EN 12350-2, EN 12350-6, and EN 12350-7. The properties of the aggregates used are shown in Table 1.

Table 1. Physical Properties of Aggregates

Physical Property	Sand	Granite
Specify Gravity	2.63	2.66
Uniformity Coefficient (Cu)	2.17	1.70
Coefficient of Curvature (Cc)	0.84	0.71
Moisture Content (%)	5.4	1.05
Bulk Density (Kg/m^3)	1357.98	1663.52
Dry Density (Kg/m^3)	212.18	811.47
Aggregate Crushing Value (%)	-	36.47
Aggregate Impact Value (%)	-	21

2.3 Preparation of Concrete and Test Samples

Concrete samples were prepared following the concrete mix design of wet-mix concretes for general use. The mix proportions used are as presented in Table 2.

Table 2. Mix Design (kg/m^3)

Constituents	Theoretical Mixture	Actual-Water Content (%)	Quantity
CEM 1 42.5N	340		340
Total water (effective water + water absorption)	197		
River Sand 0/4	944	0.31	944
Gravel 4/12	878	0.22	878
Admixture	1	1	1

Concrete constituents (granite, sand, cement, and water) and the COMPLAST SP 561 superplasticizer were weighed appropriately. The mix ratio was 1:2:4 by weight of cement, sand, and granite while the water-to-cement ratio was 0.5. It was then mixed in an electric mixer for a total period of 5 minutes, when a uniform and consistent concrete was formed, it was poured into a mould of size 150 x 150 x 150 mm and compacted on a vibrating table. The tops of all specimens were levelled and finished with a steel trowel. Afterward, the specimens were covered with polythene to avoid any loss of water. After 24 hours, the specimens were demoulded and then placed in their respective curing media; ponding (PD), polythene membrane (PM), damp sand (DS), saturated wet covering (SWC), indoor (IND), outdoor (OUT), and sprinkling (SP) for 3,7, 14, 28, 56 and 90 days. On respective days of curing, the samples were retrieved and tested for compressive strength according to EN 12390-1 and carbonation depth. Excess moisture from the surface of the specimen was wiped before placing it in the testing machine. The specimen was tested within 1 hour after removal from the curing environment. A total of 126 concrete samples were cast.

2.4 Curing of Samples

The concrete specimens were cured using six different techniques until when their compressive strengths were determined at ages 3, 7, 14, 28, 56, and 90 days. The curing techniques that were applied are:

1. Ponding (PD): This involved the submersion of the concrete cube specimens in water.
2. Sprinkling (SP): This involved the spraying of water on the concrete cube specimens twice daily.
3. Polythene Membrane (PM): The specimens were covered with at least two layers of polythene membrane to prevent moisture movement from the concrete specimens.
4. Saturated Wet Covering (SWC): This involved covering the concrete cube specimens underneath the burlap which was kept wet periodically.
5. Damp Sand Curing (DS): This involved burying the entire concrete cube specimens in wet sand which was kept moist by wetting them with water daily.
6. Indoor (IND): This served as the control. It involved no form of active curing by just exposing the specimens to ambient air in the Laboratory.
7. Outdoor (OUT): It involved no form of active curing by just exposing the specimens to the environment.

All the curing methods, except that of damp sand and outdoor curing, were carried out in the laboratory under the same environmental conditions of 27°C temperature and 75% relative humidity. Damp sand curing and outdoor curing was done outside the laboratory and exposed to varying environmental condition.

3 Result and Discussion

3.1 Sieve Analysis

The grain size analyses of the fine aggregates used are presented in Figure 1. The fine aggregates have a uniformity coefficient (C_u) of 2.17 and a coefficient of curvature or coefficient of gradation (C_c) of 0.84. As C_u is lesser than 6 and C_c is lesser than 1 (according to

Unified Soil Classification), the fine aggregates are classified as gap-graded medium to coarse sand. From the sieve analysis of the aggregate, D_{10} is 0.39 mm. This implies that the effective particle size of the sand used for the experiment is 0.39 mm i.e. 10% of the particles are finer and 90% of the particles are coarser than 0 .39 mm. 0.4% was retained on a 5mm sieve size, 1.13% was retained on 2.36mm sieve size, 12.41% was retained on 1.18mm sieve size and 0.6mm retained the most percentage of the sand particles with a percentage of 47.53%. The sand is gap-graded so it is supposed to have little pores which might not be good for structures where permeability is of great concern.

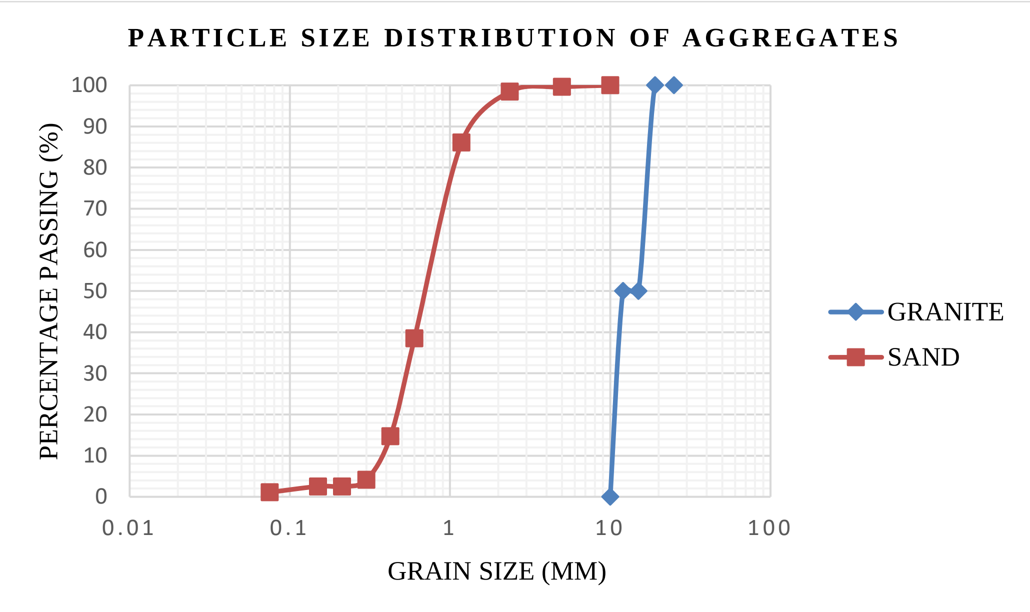

Figure 1. Particle size distribution

3.2 Workability

The workability of the fresh concrete is determined by the slump test following section 7.2 of BS 5328, for all the mix proportions of concrete at water/cement ratios of 0.5.

3.2 Compressive Strength Test

Compressive strength test results are presented in Figure 2. It was observed that the concrete compressive strength values increased as the curing ages increased progressively. Both the Outdoor and Indoor curing techniques gave the lowest compressive strength of 32.81 N/mm^2 and 32.57 N/mm^2 at 90 days respectively. Damp Sand Curing was consistently high ranking in terms of its compressive strength compared to others at almost all curing ages. The ponding curing method was also closely ranked with the damp sand method of curing. At 56 days of curing, it was found that the strength of concrete cured using the sprinkling method (SP) was 36.62 N/mm^2 representing about 110% of the strength obtained from concrete cured with saturated wet covering (SWC), while the strength of concrete left outside door was about 97% of SWC with compressive strength value of 31.27 N/mm^2

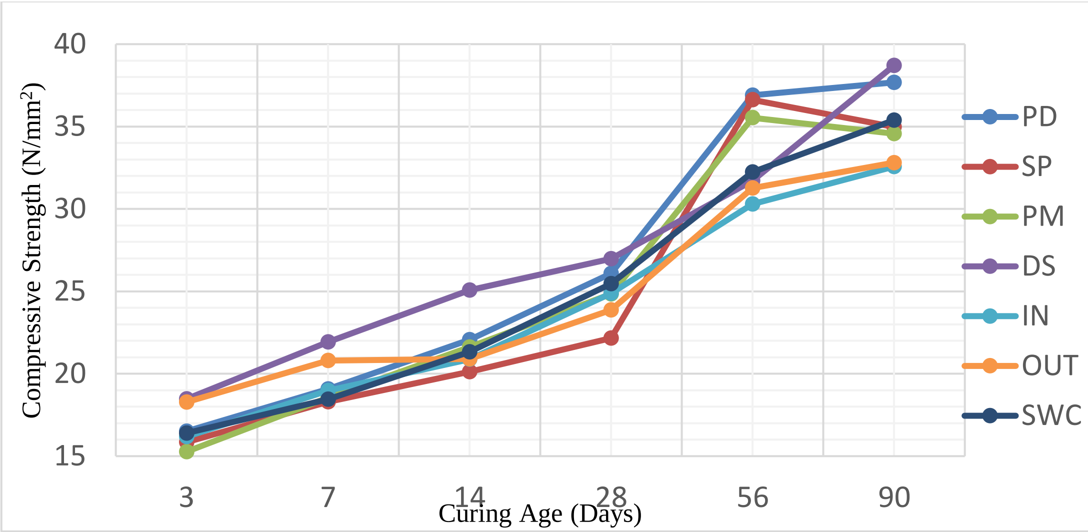

Figure 2. Concrete Compressive Strength (N/mm2) at all Curing Ages (Days) for various Curing Technique

3.3 Carbonation Depth of Concrete.

In this experiment, 7 different curing techniques were tested and carbonation depth was determined for each concrete cured using the techniques.

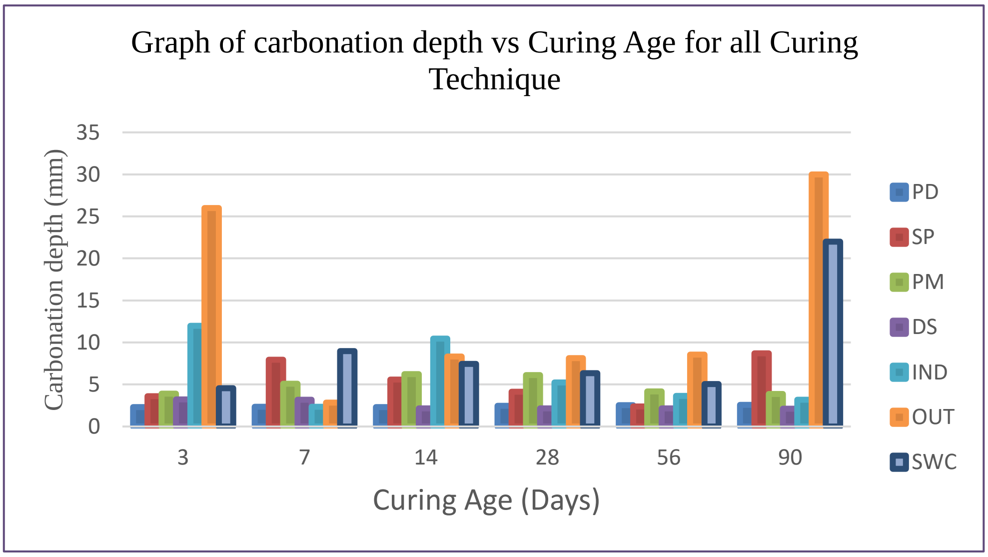

Figure 3. Carbonation depth against curing ages for all the curing techniques applied

From Figure 3, it was observed that the carbonation depth values increased as the curing ages increased for only the ponding (PD) curing technique. For Sprinkling (SP), Polythene membrane (PM), and Saturated Wet Covering (SWC) curing types, the carbonation depth peaks at 7- day (7.95 mm), 14 – day (6.22 mm), and 7 – day (8.96 mm) respectively, and thereafter rapidly drops. Also, all three (3) curing techniques increased disparagingly in 90 days. The damp sand (DS) curing method and ponding (PD) curing method closely set off the same type of trends while the indoor (IND) and outdoor (OUT) curing methods do not have an identified pattern. However, we could observe that the Outdoor (OT) curing technique had the highest carbonation depth at 90 days of curing at 30mm while the Saturated wet covering (SWC) curing technique followed with 22mm. Also, we could deduce that ponding (PD) and damp sand (DS) techniques had the lowest carbonation depth. This could be a result of the constant moisture and shelter that prevents excessive ingress of natural CO_2 into the pores of the concrete matrix. However, both the Indoor (IND) and Outdoor (OUT) curing methods had huge carbonation depths from the start at day 3 of curing. This could be due to the effect of immediate exposure to natural CO_2 immediately after casting concrete specimens.

On the contrary, it is observed that damp sand (DS), ponding (PD), and polythene membrane (PM) methods of curing gave the least carbonation depth in this same order. Although, polythene membrane (PM), curing has a great value on day 14 and day 28 of curing.

3.4 Relationship Between Compressive Strength, Carbonation Depth and Curing Techniques.

Table 3 seeks to establish the relationships between carbonation depth of concrete cured via different curing methods and their respective compressive strength. This was done through the determination of Pearson's Correlation Coefficient.

Table 3. Relationships between Compressive Strength, Carbonation Depth, and Curing Techniques

Curing Methods	*Curing Days*	*Compressive strength (N/mm2)*	*Carbonation depth (mm)*	*x=X-**X***	*y=Y-**Y***	*x^2*	*y^2*	*(X-**X**)*(Y-**Y**)*
Ponding	3	16.81	2.31	-8.46	-4.03	71.56	16.28	34.13
	7	19.07	2.35	-6.20	-3.99	38.43	15.95	24.76
	14	22.07	2.3	-3.20	-4.04	10.24	16.36	12.94
	28	26.08	2.48	0.81	-3.86	0.66	14.93	-3.13
	56	36.89	2.55	11.62	-3.79	135.04	14.40	-44.09
	90	37.68	2.58	12.41	-3.76	154.03	14.17	-46.72
Sprinkling	3	15.85	3.6	-9.42	-2.74	88.72	7.53	25.85
	7	18.3	7.95	-6.97	1.61	48.57	2.58	-11.19
	14	20.12	5.6	-5.15	-0.74	26.52	0.55	3.83
	28	22.16	4.15	-3.11	-2.19	9.67	4.81	6.82
	56	36.62	2.4	11.35	-3.94	128.84	15.56	-44.77
	90	34.97	8.72	9.70	2.38	94.10	5.64	23.05
Polythene Membrane	3	15.27	3.9	-10.00	-2.44	99.99	5.97	24.44
	7	18.55	5.1	-6.72	-1.24	45.15	1.55	8.36
	14	21.61	6.22	-3.66	-0.12	13.39	0.02	0.45

	28	24.84	6.13	-0.43	-0.21	0.18	0.05	0.09
	56	35.53	4.17	10.26	-2.17	105.28	4.73	-22.31
	90	34.56	3.86	9.29	-2.48	86.32	6.17	-23.08
Damp Sand	3	18.47	3.22	-6.80	-3.12	46.23	9.76	21.24
	7	21.93	3.18	-3.34	-3.16	11.15	10.01	10.57
	14	25.08	2.16	-0.19	-4.18	0.04	17.51	0.79
	28	26.97	2.15	1.70	-4.19	2.89	17.59	-7.13
	56	31.72	2.14	6.45	-4.20	41.61	17.68	-27.12
	90	38.7	2.12	13.43	-4.22	180.38	17.84	-56.74
Indoor Curing	3	16.18	12	-9.09	5.66	82.62	31.99	-51.41
	7	18.97	2.35	-6.30	-3.99	39.68	15.95	25.16
	14	20.87	10.45	-4.40	4.11	19.35	16.86	-18.06
	28	24.87	5.25	-0.40	-1.09	0.16	1.20	0.44
	56	30.8	3.66	5.53	-2.68	30.59	7.21	-14.85
	90	32.57	3.19	7.30	-3.15	53.30	9.95	-23.03
Outdoor Curing	3	18.28	26	-6.99	19.66	48.85	386.35	-137.38
	7	20.81	2.83	-4.46	-3.51	19.89	12.35	15.67
	14	20.9	8.33	-4.37	1.99	19.09	3.94	-8.68
	28	23.87	8.15	-1.40	1.81	1.96	3.26	-2.53
	56	31.27	8.57	6.00	2.23	36.01	4.95	13.36
	90	32.81	30	7.54	23.66	56.86	559.59	178.38
Saturated Wet Covering	3	16.4	4.55	-8.87	-1.79	78.66	3.22	15.91
	7	18.46	8.96	-6.81	2.62	46.37	6.84	-17.81
	14	21.32	7.45	-3.95	1.11	15.60	1.22	-4.37
	28	25.46	6.33	0.19	-0.01	0.04	0.00	0.00
	56	32.23	5.05	6.96	-1.29	48.45	1.68	-9.01
	90	35.39	22	10.12	15.66	102.43	245.10	158.45
	AVERAGE	25.27	6.34		TOTAL	2138.88	1549.30	31.30
							CORRELATION	0.02
							CORREL	0.02

The Pearson's correlation method was used to determine the relationship between compressive strength and carbonation depth with respect to their curing methods. The correlation value **ρ = 0.02,** since the value of **ρ** falls between 0 and +0.5, it implies that there exists a weak positive correlation between carbonation depth and compressive strengths of the concrete specimens. This means that as the compressive strength of the concrete specimen increases, there is a tendency for the carbonation depth to also increase.

4 Conclusions

The following conclusions are drawn based on the results obtained from the various tests and discussion of findings:

- The compressive strength of concrete of the damp sand curing method produced specimens with the highest compressive strength while Air curing (Indoor and Outdoor) produced the lowest. This suggests that the effect of moisture cannot be overemphasized during curing. The effect of moisture and higher relative humidity could be seen in the different types of curing.
- The Concrete specimens of all methods of curing considered, produced concrete that had compressive strengths that met the minimum required by standards.
- The compressive strength of 38.7 N/mm^2 for DS at 90 days was found to be the highest while 15.27 N/mm^2 for PM at 3 days was found to be the lowest.
- The compressive strength of air curing (IND and OUT) were relatively higher during the initial curing phase than in the later phase.
- The resultant of increased carbonation depth is usually concrete cancer and increased spalling of concrete which eventually becomes detrimental to the structural integrity of the structural element and the Structure as a whole.
- It is also to be noted that the influence of CO_2 can be strength-dependent. When concrete produces very high strength, the influence of the CO_2 concentration can be reduced, unlike normal-grade concrete like that used in this study. Hence, absolute care and concern should be raised when curing concrete elements, especially low-grade concrete as they are more prone to the damaging effects of carbonation.
- The porosity and the exposure time are very important parameters to carbonation, as they affect the result of carbonation depth.

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