
Mechanical Properties and Durability of Plain and Blended Cement Concrete

Alhassan, A. Yunusa¹ & Yunus Ballim²

¹Department of Civil Engineering, Federal Polytechnic Idah, Nigeria

²School of Civil and Environmental Engineering

University of the Witwatersrand, Johannesburg, South Africa

Corresponding Author: Alhassan, A. Yunusa

ABSTRACT

The durability performance of Reinforced Concrete (RC) is influenced by those physical and chemical characteristics of concrete that control the diffusion of gases and liquids through its pores and ions dissolved in the pore water. In the present paper, properties of concrete made with plain and blended cement were characterized in terms of physical and chemical composition at early-age. In addition, the effects of inland exposure condition on the durability performance of the concrete were also investigated. Concrete cubes were made using various concrete mixtures of water-binder ratios (w/b) = 0.40, 0.50, 0.60, 0.75 and binder contents = 300, 350, 400, 450 kg/m³. Concrete cube of 100 mm size were cast and cured in water for 3, 7, or 28 days, then characterized at early-ages in terms of its physical and chemical properties. Companion concrete samples are exposed indoors or outdoors to undergo carbonation under natural environment. At the end of the varying exposure period, the concrete cube samples were characterized at 6, 12, 18 and 24 months in terms of carbonation depths. The results of the concrete early-age properties and medium-term durability characterisation were analyzed. The results show that, increased knowledge of concrete materials and concrete early-age properties is vital in durability considerations for RC structures.

Keywords: Reinforced concrete; Concrete durability; Pore structure; Pozzolans; Portland blended cement.

INTRODUCTION

The use of supplementary cementitious materials (SCMs) is one of the current practices to make the cement and concrete industry more environmentally-friendly. However, Portland cement (PC) is a

hydraulic product while SCMs may be latent-hydraulic e.g. GGBS and pozzolanic e.g. FA byproducts (Mehta and Monteiro, 1993). Partial replacement of PC by SCMs alters thus the reaction kinetics and reaction degrees of such blended

cement. Research already showed that the microstructure of blended cement concrete develops slower because the hydration is slower, initial and final setting times are prolonged, the strength develops slower, the hydration degree of SCMs is low for mixes with high replacement levels, for example (GGBS) and the durability behaviour is different from that of PC concrete (Fulton, 2009; Neville, 1989).

In spite of this time-dependent effect, accelerated degradation tests are mostly executed at an age of 28 days on a lab scale (as is done for PC concrete), in order to evaluate the performance of SCM concrete. This means that the beneficial effect of ongoing hydration of the alternative binders over a longer time period is not taken into account. When these values are used for service life predictions, or mix proportion design the concrete's performance will be underestimated (Bertolini *et al*, 2013, Dhir, *et al*). While accelerated tests at young ages can give unrealistic results, some concrete structures are already exposed to aggressive substances

almost immediately after casting. In those cases, testing at later ages can give too favourable and also unrealistic test results. In this paper, durability performance of plain and blended cement concretes exposed in inland environments in terms of carbonation resistance was experimentally investigated. Moreover, the physical and chemical properties of companion concrete were likewise characterised at early age. This is done with a view of comparing concretes early age properties to its long term durability performance.

MATERIALS AND METHODS

Materials

A single source of Portland cement (CEM I) and blended cement (CEM V) complying with SANS was used throughout this study and its chemical and Bogue compositions are given in Table 1. Granite crusher sand and 19 mm granite coarse aggregate were the fine and coarse aggregate used in the concrete (SANS 1083, 2006; Fulton, 2009). A commercially available plasticizer was used in some of the mixtures.

Table 1: Oxide analysis of binders (%) used

Oxides	LOI	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	TiO ₂	Mn ₂ O ₃	Na ₂ O	K ₂ O	P ₂ O
CEM I	3.04	21.85	5.10	62.84	3.41	2.28	0.43	0.45	0.07	0.32	0.09
CEM V	4.02	30.02	11.59	43.77	2.41	2.34	0.65	0.17	0.13	0.68	0.14

The concrete were made from two binders, 100% CEM I and 100% CEM V consisting GGBS/FA blend. The concrete mixtures consisted of w/b= 0.40, 0.50, 0.60, 0.75 and binder

Contents = 300, 350, 400, 450 kg/m³. Slumps in the range of 25 to 160 mm were achieved. Table 2 gives the concrete mixtures proportion and their respective slumps.

Table 2: Concrete mixtures used in the investigation

Binder combination	Mixture ID	CEM I (kg/m ³)	CEM V (kg/m ³)	Coarse aggregate (kg/m ³)	Fine aggregate (kg/m ³)	Water content (kg/m ³)	Water/binder ratio	Admixture (l)	Slump (mm)
100% CEM I	PC-40	450	-	990	800	180	0.4	4.00	30
	PC-50	400	-	990	877	200	0.5	3.25	60
	PC-60	350	-	1015	869	210	0.6	-	100
	PC-75	300	-	1050	810	225	0.75	-	140
100% CEM V	CC-40	-	450	990	800	180	0.4	1.90	25
	CC-50	-	400	990	877	200	0.5	1.75	65
	CC-60	-	350	1015	869	210	0.6	-	120
	CC-75	-	300	1050	810	225	0.75	-	160

Concrete was produced in 50 litres batch mixes using a horizontal forced action pan mixer of 0.05 m³ capacity. The mixer was charged with coarse aggregate, fine aggregate and binder respectively and the constituents dry mixed for approximately 30s. Water mixed with plasticiser was slowly added for some mix until the mixture was visually consistent. Admixture was added in concrete mixes of 0.40 and 0.50 w/b, achieving slumps of 30 and 60 mm for CEM I and 25 and 65 mm for CEM V respectively. The

dosage of the admixture as shown in Table 2 is given as a percentage of total binder content by mass. The total mixing time was about 3 min. After testing for slump, 100 mm cube moulds were filled, compacted on a vibrating table, and covered with polythene sheets for 24 hours at room temperature before demoulding.

The concrete cubes were thereafter placed in a water bath maintained at 23 ± 2 °C for continuous water curing until their respective test

ages of 3,7 or 28 days. For durability characterisation of the concrete mixture in terms of carbonation, a set of four concrete cubes, each set having been cured for 3, 7, or 28 days and exposed to the natural environment. Prior to exposure of cubes to designated sites, all four sides running from the finishing surface through to its opposite end surface, were coated with two layers of epoxy coating, leaving the two adjacent opposite sides uncoated. A water-based epoxy was used. After sufficient drying of surface coatings over a 24 hour period, cubes were taken to their respective exposure sites and placed at a spacing of at least 50 mm from each other such that the two non-coated surfaces were exposed to air. The natural exposure conditions were chosen based on the EN Classification XC3 and XC4 (EN206, 1997) as indoor, outdoor sheltered, outdoor exposed. These exposure conditions are the highest aggressiveness classification for carbonation-induced corrosion of reinforced concrete in the inland environment. In order to replicate these conditions, concrete cubes were stored in a basement parking garage (indoor exposure), under a bridge alongside a busy highway (outdoor sheltered) and on the roof top of a building in an urban setting

(outdoor exposed). For early age characterisation and for each mixture, 54 concrete cubes were cast, with a set of three and or two cubes, each set having been cured for 3, 7 or 28 days were tested for compressive strength and permeability via the oxygen permeability and water sorptivity tests. While, one cube, each having been cured for 3, 7 or 28 days were tested for chemical composition of the concrete mixtures in terms of Ca(OH)_2 content.

Methods

At the end of the various curing periods and air storage, the concrete cubes were characterized as follows:

For the durability performance of the concrete mixture, the set of four cubes, exposed to each of the three natural sites after 14 days of preconditioning were taken to the laboratory after varying ages for carbonation testing. Carbonation measurements were done at ages of 6, 12, 18, and 24 months after exposure. A solution of 1 % phenolphthalein in ethanol was sprayed onto the freshly broken surface of the concrete and average of the depth of the colourless section was taken as the carbonation depth.

To characterise the concrete mixtures in compressive strength terms, 100 mm concrete cube samples were tested at 3, 7 and 28 days after casting under standard moist curing conditions. The compressive strength test were carried out in accordance with the SANS 5863 (1994) method using an Amsler compression testing machine with a capacity of 2000 kN. All samples were weighed in a saturated, surface dry condition to an accuracy of 5 g before being tested;

The durability index test for pore structure characterisation of the concrete mixtures were carried out on specimen obtained from concrete cube samples at between 28 and 32 days after casting under saturated moist curing conditions. This is in accordance with the durability index tests method. The oxygen permeability and water sorptivity tests were performed in a temperature and humidity controlled room following the procedures outlined in the SANS test specification of 2010, it is a revised version of the Durability Index Testing originally developed by Ballim (Alexander et al., 1999, Ballim, 1994). At the appropriate time after moist curing concrete

cube samples were removed from the laboratory room for the coring operation. The discs obtained from the coring operation (70 ± 2 mm \varnothing and 30 ± 2 mm thick) were then transferred to a 50 ± 2 °C ventilated oven to be dried for a minimum of 7 days \pm 4 hours before being tested for oxygen permeability and water sorptivity.

The portlandite content of the concrete mixtures was determined from specimen obtained from concrete cube samples after 3, 7 and 28 days of standard moist curing periods after casting. Thermogravimetric analysis (TGA) was performed on powdered specimens. The powdered specimens are obtained following the procedure described in Alhassan (2014). The procedure involve drilling to a depth of 20 ± 5 mm with a 7 mm diameter drill bit on the interior surface of a cube after it has been oven dried. The samples obtained is then sieved through a $63\mu\text{m}$ sieve size and preserved under vacuum in airtight bottles until tested. The chemical composition of the specimens were determined in terms of the $\text{Ca}(\text{OH})_2$ content using the TGA test. The thermal decomposition behaviour of the powder specimens were studied

by tracing mass and heat changes using a Perkin Elmer TG400 thermogravimetric analyser coupled to a Setaram differential analyser. The thermal analyser used in this study, enables the thermogravimetric (*TG*) curve and the derivative thermogravimetric (*DTG*) curve to be obtained simultaneously on the specimen. A plot of temperature against mass loss (*TG* curve) and derivative mass loss (*DTG* curve) is obtained automatically. The weight loss obtained from the *TG* and the *DTG* curves were used to estimate the amounts of calcium hydroxide ($\text{Ca}(\text{OH})_2$) and calcium carbonate (CaCO_3) present in the specimen;

EXPERIMENTAL RESULTS AND DISCUSSION

Results for the carbonation depth for the concrete cubes are presented in Figure 1. The results presented are discussed in terms of the concrete physical and chemical properties while the influence of the exposure condition on the depth of carbonation was also examined and discussed. While, results of tests and discussion on early-age characterisation of the concrete are given in this section and in Figures 2 - 5 for the compressive strength, permeability, sorptivity and

chemical composition respectfully. From the presented results, it is evident that these characteristics are influenced by w/b, extent of initial moist curing and the binder type and content.

From the carbonation coefficients results for the different concrete types, it is evident that the carbonation rate of the concretes followed similar pattern for the different w/b investigated. Hence, it is only the 0.5 w/b concretes carbonation rates results that is presented for the different exposure sites. Generally, the trends observed were distinctly influenced by the concrete physical and chemical characteristics as well as the micro climate condition of the exposure sites. Thus, variations of the carbonation rates for the concretes will be explained in relation to each of these influencing factors. The general carbonation behaviour of the mixtures under indoor, sheltered and unsheltered exposure conditions are compared in Figure 1. Clearly, the concretes stored under indoor and sheltered exposure give higher carbonation rates than those kept under the unsheltered exposure conditions. The differences in behavior are related to effect of rain for the exposed

samples, which tends to temporarily block the pores at surface concrete, thereby inhibiting CO₂ ingress during periods of precipitation. The wetting and drying period experienced by samples on the exposed site also contributed to the reduced carbonation rate, since both the outdoor sheltered and unsheltered exposure conditions have similar micro-climates in terms of CO₂ content, RH and temperature (Alhassan, 2014). In addition,

concrete cube samples exposed outdoor to rain and sun have higher internal humidity during the summer months from precipitation effects, thus reducing CO₂ ingress during this period. Furthermore, these concretes had improved pore structures from rapid hydration effects as a result of its high internal moisture content during the summer months.

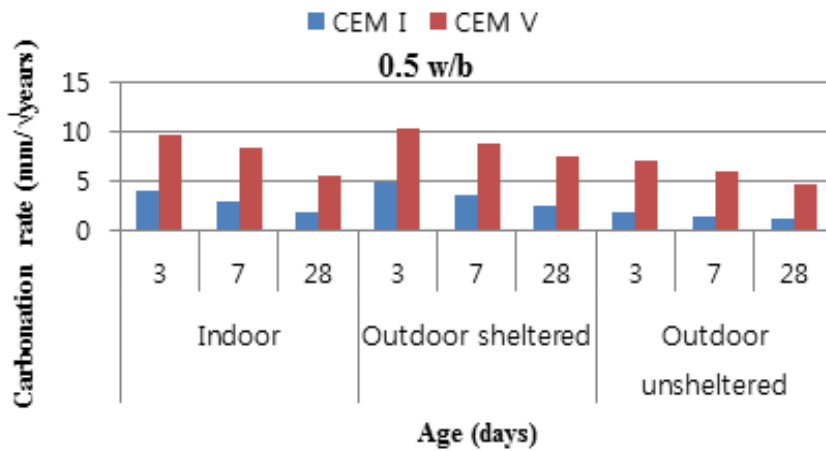


Fig. 1: Carbonation rate results for the various concrete mixtures

The influence of SCMs is clearly evident in the concrete, generally showing increase in carbonation regardless of the exposure site's microclimate. Under sheltered exposure, CEM V behaved similarly as CEM I, with both mixtures giving relatively high carbonation progressions. However, the same

CEM V mixtures behaved differently under unsheltered exposure conditions, exhibiting lower carbonation. The different behavior of CEM V mixes under unsheltered exposure may be related to availability of precipitation which in turn promotes pozzolanic activity in a

manner not attainable under the partial saturation conditions of sheltered exposures. From Figure 1, It can be seen that CEM V addition led to a greater carbonation rate, which is consistent with the trend observed by Osborne, (1999), and Papadaki, (2000). The changes in pore structure were not adequate in CEM V concrete to counteract the reduction in CH content, and hence the carbonation rate increased. The reason for this is that CEM V had a low free lime content and the greater amount of hydrated products formed after the pozzolanic reaction were noncrystalline low alkaline C-S-H with a large specific surface area; hence, these samples were easily carbonated (Lin and Fu, 1987). In addition, in the presence of CEM V, the amount of CH available to react with CO₂ is lower, for two reasons; first, less CaO is added to the concrete. Second, some of the CH reacts with the added SCM. Thus, if the concrete pore structure modification does not govern over the reduction in CH, the carbonation may proceed faster due to the fewer amounts of carbonatable materials available per unit area of CO₂ to react with. This explains why carbonation tends to proceed faster in concrete

containing mineral admixture. However, due to the slower pozzolanic reaction, porosity can be expected to be higher during the initial stage, thus allowing more rapid diffusion of CO₂ (Mehta, 19991, Manmohan and Mehta, 1981)

The development in strength for the different mixtures as influenced by w/b, and curing time is presented in Figure 2. As expected, compressive strengths increase steadily with decrease in w/b for any given mixture. Similarly, strengths increase progressively with age, as is typical of concrete mixtures under moist curing condition. Note that as the moist curing age of the concrete increases, hence the hydration of its binder components, the gain in compressive strength with CEM V blended concretes becomes more apparent especially at low w/b ratio. It may be recalled that while 28-day strength is a standard value, it is the 3 or 7 day strengths that are realistically representative of site curing practice. Analyzing the ratios of the 28 days and 7 days compressive strengths for all the concrete mixtures tested, the CEM V concretes presented higher values compared to the CEM I concretes. Increased compressive strength gain at later ages for this CEM V

concretes can be attributed to its slower hydration rate and chemical pozzolanic effect, as well as to the physical effect of the generally tiny SCM particles. Detwiler and Mehta (1989) and Goldman and Bentur

(1993) stated in their work that the improvement in compressive strength in blended cement concrete is primarily dependent on the micro filler effect of the SCMs.

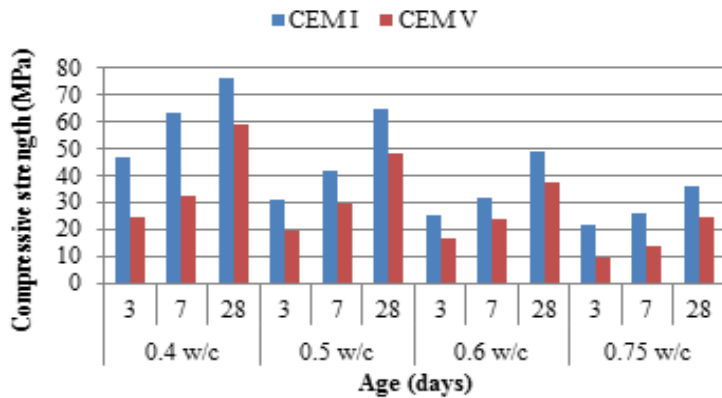


Fig. 2: Compressive strength results for the concrete mixtures

The permeability results for the concrete mixtures are presented in Figure 3. This result shows that, increasing w/b and decrease extent of initial moist curing of concrete resulted in decreased oxygen permeability index (OPI) values with the CEM V blended concretes presenting higher OPI values. Although the influence of moist curing on the permeation properties of the concrete can be seen clearly in some of the mixtures, it is clustered for the others. However, there are distinct trends of improvement in concrete permeation as the w/b decreases. This is due to the

increasing volume and degree of interconnection of capillary pores within the cement paste. In addition, as w/b decreases or as curing time increases (therefore the degree of hydration increases), the reduction of concrete paste porosity is mainly due to the reduction in pores of larger dimensions that have been filled or are connected by C-S-H gel pores. Graf and Grube (1986) state that as hydration proceeds, the initially water filled and fully interconnected pores within the cement paste are filled with hydration products and become discontinuous. The increased gain

in impermeability at later ages for the *CEM V* blended concretes can be attributed to a combination of the pozzolanic and micro filler effects of *GGBS/FA*. The *CEM V* blended concretes however performed better

than the *CEM I* concretes at all w/b ratios under continuous initial moist curing.

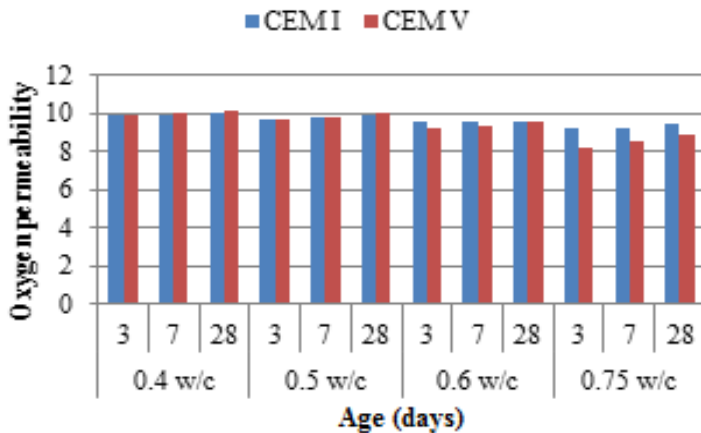


Fig. 3: Oxygen permeability results for the concrete mixture

The portlandite contents for the concrete mixtures are given in Figure 4. The use of different binder type and content influenced the $Ca(OH)_2$ content of the concretes, with increasing w/b and decreasing binder contents resulting in decreased $Ca(OH)_2$ content for all the concrete mixtures investigated. From the $Ca(OH)_2$ plots presented, it can be noted that the $Ca(OH)_2$ content increases as the concrete moist curing ages increases for the plain concretes while a decrease in $Ca(OH)_2$ content were noted for the blended concretes. The reason for

the increase in portlandite for the plain concretes is that, *CEM I* concrete produces $Ca(OH)_2$ during hydration and its content increases with hydration time. While, the decrease in $Ca(OH)_2$ content for the blended cement concrete can be attributed to both the high dilution effect related to the fact that $Ca(OH)_2$ results from cement hydration which in turn is directly related to the cement proportion in the mixture, as well as the pozzolanic reaction between $Ca(OH)_2$ and *GGBS/FA* which consumes some $Ca(OH)_2$, and may extend over a

long time period (Mehta and Monterio, 1993).

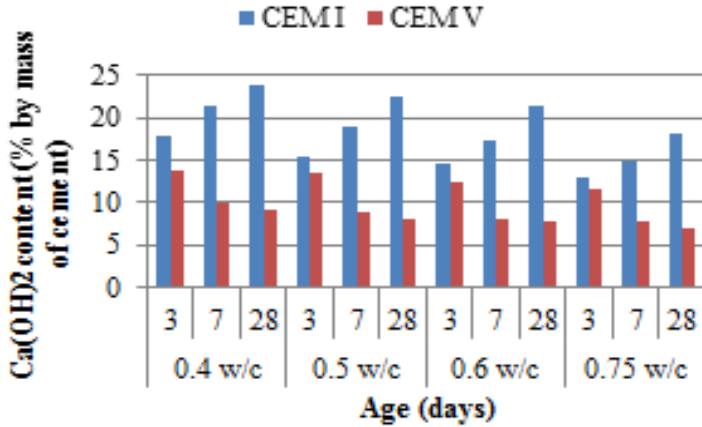


Fig. 4: Ca(OH)₂ content results for the concrete mixture

It can also be noted from the figure that the $Ca(OH)_2$ content for both the blended and unblended concretes are not significantly different at 3 and 7 days. This shows that GGBS/FA have little effects on the normal hydration process of CEM I concretes at early ages. This

behaviour is in agreement with earlier works by Marsh and Bonnery (1986) and Marsh and Day (1988), using CEM I and FA blended concretes, but it is however in conflict with the work of Dalziel (1986) reported in March and day (1988).

CONCLUSIONS

From this investigation, the effect of long term exposure condition on the rate of carbonation of concrete thus microclimate and concrete properties, the following conclusion can be drawn:

A lower w/b ratio and prolonged curing age of concrete in water generally led to a slower rate of carbonation, mainly due to pore structure densification, as indicated

its durability performance and service life were examined. Based on the

by a decrease in cumulative and differential pore volume. Structural elements exposed outdoor but sheltered will present the highest carbonation rate. Thus, such elements should be more carefully designed and constructed if its design service life in terms of the

initiation limit state is to be achieved;

It is evident that concrete elements exposed outdoor to rain and sun are at risk of corrosion due to the high *RH* as a result of the occasional

The cumulative pore volume for blended cement concrete was smaller than plain cement concrete. The pore size modification due to pozzolanic reaction had better pore volume and hence the densest pore structure. Although the pore structure of blended concrete was denser than that of plain concrete, the carbonation coefficients of these blended mixtures were higher than that of the plain concrete.

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precipitation during summer months. However, the risk of carbonation may be very low for such concrete elements because of the low or high saturated pore structure, depending on the period of the year;

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