Computers and Concrete, Vol. 6, No. 6 (2009) 437-450
DOI: http://dx.doi.org/10.12989/cac.2009.6.6.437

Influence of extreme curing conditions on compressive strength and pulse velocity of lightweight pumice concrete

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(Received January 22, 2009, Accepted September 8, 2009)

Abstract The effect of six different curing conditions on compressive strength and ultrasonic pulse velocity (UPV) of volcanic pumice concrete (VPC) and normal concrete (NC) has been studied. The curing conditions include water, air, low temperature (4°C) and different elevated temperatures of up to 110°C. The curing age varies from 3 days to 91 days. The development in the pulse velocity and the compressive strength is found to be higher in full water curing than the other curing conditions. The reduction of pulse velocity and compressive strength is more in high temperature curing conditions and also more in VPC compared to NC. Curing conditions affect the relationship between pulse velocity and compressive strength of both VPC and NC.

Keywords: volcanic pumice; curing; lightweight concrete; pulse velocity; compressive strength.

1. Introduction

Researches had been conducted worldwide on a large number of natural or artificial lightweight aggregates such as: bamboo reinforced, oil palm shells, bottom ash, starch based aggregate etc (Jamal *et al.* 1999, Nisnevich 1997, Glenn *et al.* 1999, Kohono *et al.* 1999, Basri *et al.* 1999, Ghavami 1995, Hossain 2004a,b, Turkmen *et al.* 2006). Pumice is a natural material of volcanic origin produced by the release of gases during the solidification of lava (Nevile 1995). Due to frequent volcanic activities, volcanic pumice (VP) is found abundantly in many parts of the world and the utilization of such natural resource in concrete production can provide low cost sustainable construction (Hossain 2004a,b, Hossain and Lachemi 2007, Hossain 2008a,b).

World pumice (and related materials) production was 16.9 million metric tone (Mt) in 2006 (DiFrancesco *et al.* 2008). Globally, Italy remains the dominant producer of pumice, with production estimated to be 4.0 Mt per year. Other leading countries are Chile, Ecuador, Ethiopia, France, Germany, Greece, Spain, Turkey, and the United States. The main use for pumice is as an aggregate in lightweight building blocks and assorted building products (DiFrancesco *et al.* 2008). Volcanic pumice has also been used as aggregate in the production of lightweight concrete. Pumice was used in ancient Rome over 2,000 years ago and many notable pumice structures are still standing today (Grasser and Minke 1990). In Europe, pumice concrete constitutes about 3% of the total lightweight concrete consumption with 70% of the total consumption in Germany. Lightweight

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concrete made with pumice and pozzolanic cement with volcanic ash/lime (developed in Mexico by the builders of an ancient culture, the Totonacas) has survived more than 2000 years that provides an example of a low strength concrete and very long-term performance (Cabrera *et al.* 1997, Rivera-Villarreal and Cabrera 1999). The use of pumice and perlite as additives was found to provide excellent resistance to freezing and thawing of cement pastes, mortar and concrete (Litvan 1985).

Lightweight concrete with a 28-day compressive strength of 55 MPa and a dry unit weight in the range of 1700-2100 kg/m^3 was produced by incorporating Turkish pumice aggregate (Yeginobali *et al.* 1998). Prefabricated lightweight pumice concrete infill panels were investigated as a retrofit alternative of building frames subjected to quasi-static loading (Humay and Durrani 2001). Investigation on reinforced concretes made with lightweight aggregates (such as pumice and slag) revealed their satisfactory resistance against salt attack/steel corrosion and their suitability of using in load-bearing and enclosure structures (Stepanova 1991). Precast panels made with lightweight pumice concrete (35% and 25% lighter than normal weight and lightweight expanded shale concrete, respectively) having a 28-day compressive strength of 24 MPa were used satisfactorily used in the Rockwood residence in the Hayden island, Oregon, USA (Carmichael 1986). The 73-story World Trade Tower in downtown Los Angeles is the tallest building west of the Mississippi River, and was built using "Vac-Lite" structural lightweight pumice concrete (Hossain and Lachemi 2007).

Recent research suggests the production of lightweight volcanic pumice concrete (VPC) for structural applications having satisfactory strength and durability characteristics (Hossain 2003, Hossain 2004a,b, Hossain and Lachemi 2007, Hossain 2008a,b). VPC also shows better residual strength and strength retaining capacity compared with normal weight concrete (NC) after exposure to elevated temperatures of up to 800^{o}C for different durations (Hossain and Lachemi 2007).

The method of curing is one of the main factors affecting the development of concrete. The objective of curing is to keep concrete saturated or as nearly saturated to get the products of hydration of cement in water-filled space. The temperature and the duration of moist curing are the key factors for proper curing (CSA 23.3-94 1994, Tan and Gjorv 1996). High temperature has significant effect on ultimate strength of concrete and temperatures lower than 5^{o}C retard the early hydration of cement paste (Nontananandh 1990). Researchers concluded that curing at moderately high temperature increases early strength (Nevile 1995, Zain 1995).

The strength development of VPC (especially at early age) under hot, cold and tropical environments is important due to porous nature and high water absorption capacity of lightweight pumice aggregate. This paper focuses on the effect of different curing conditions on the compressive strength and pulse velocity of VPC specimens compared to normal concrete specimens up to a curing age of 91 day. The finding of this research will be beneficial for engineers and contractors who are interested in using VPC in construction.

2. Experimental investigations

2.1. Materials

The investigation was based on the VP obtained from Tavurvur and Vulcan craters located in the Rabaul area of the East New Britain province of Papua New Guinea (PNG). Table 1 presents the

Table 1 Chemical and other properties of volcanic pumice and cement

	Volcanic pumice	Portland cement ASTM Type I
Chemical analysis, %		
Calcium oxide (CaO)	4.4	64.1
Silica (SiO_2)	60.8	21.4
Alumina (Al_2O_3)	16.7	5.7
Iron oxide (Fe_2O_3)	7.0	3.5
Sulphur trioxide (SO_3)	0.1	2.1
Magnesia (MgO)	1.9	2.1
Sodium oxide (Na_2O)	5.4	0.5
Potassium oxide (K_2O)	2.3	0.6
Loss on ignition	1.5	1.2
Other properties of cement		

Bogue potential compounds: Tricalcium silicate (C_3S) = 53.4%; Dicalcium silicate (C_2S) = 19.2%, Tricalcium aluminate (C_3A) = 9.5%; and Tetracalcium aluminoferrite (C_4AF) = 10.5%
Compressive strength, MPa: 7- day = 30 MPa; 28-day = 40 MPa
Initial setting time = 120 minutes; Blaine fineness = 320 m^2/kg; Specific gravity = 3.15

Table 2 Grading of aggregates

Sieve size (mm)	20 mm maximum size coarse aggregate %finer			Fine aggregate % finer
	Lightweight		Normal weight	River sand
	VPA	ASTM C-330	GA	
25	100	95-100	100	
19	90	25-60	94	
12.5	40	-	50	
9.5	20	-	28	100
4.75	5	0-10	10	93
2.36				70
1.18				51
300 μm				20
150 μm				15

chemical properties of VP. Locally manufactured ASTM Type I Portland cement (C) whose chemical and physical properties are shown in Table 1 was used.

The coarse aggregates used were 20-mm maximum size crushed gravel aggregate (GA) and volcanic pumice aggregate (VPA). Local river sand was used as fine aggregate. Clean drinking water was used for the concrete mixtures. The particle size distributions of VPA and sand were determined according to ASTM C 136. Grading of VPA and sand (used in this study) meet the requirement of lightweight aggregate for structural concrete as per ASTM C 330 (Table 2). The properties of GA and VPA are compared in Table 3. The bulk density (both dry rodded and loose - determined as per ASTM C 29) and specific gravity (determined as per ASTM C 127) suggest that

Table 3 Properties of aggregates

Aggregates	Specific gravity	Bulk density, kg/m^3 ASTM C 29		Water absorption 24 hour (%)
	Oven dry	Loose Oven dry	Rodded Oven dry	
20 mm coarse aggregate				
	ASTM C 127			ASTM C 127
GA	2.57	1610	1805	1.6
VPA	0.76	565	600	32.1
Fine aggregate				
	ASTM C 128			ASTM C 128
River sand	2.61	-	-	2.0

coarse volcanic pumice aggregate is much lighter than gravel aggregate. Coarse pumice aggregate also has high water absorption (determined as per ASTM C 127), which indicates its high degree of porosity compared with gravel aggregate. As per ASTM C 330, VPA satisfies the requirement of the lightweight coarse aggregate for structural concrete as the oven dry density falls within the range of 560 kg/m^3 to 1120 kg/m^3. The specific gravity and water absorption of river sand (determined as per ASTM C 128) are also presented in Table 3.

2.2. Mix design and properties of volcanic pumice concrete (VPC) and normal concrete (NC)

Extensive series of tests were conducted to develop suitable VPC mixtures (Hossain 2004a,b, Hossain and Lachemi 2007, Hossain 2008a,b). For this study, a structural lightweight VPC mix (incorporating 20-mm maximum size coarse VPA and river sand) and a NC mix (20-mm maximum size GA and river sand) with a target 28-day compressive strength of 20 MPa under normal water curing condition were selected for comparative performance evaluation under different curing conditions. Mix designs of both NC and VPC mixtures are presented in Table 4.

A series of tests on fresh, mechanical and durability properties of selected NC and VPC mixtures were conducted. The slump of fresh concrete mixtures was determined as per ASTM C 143. Air contents for NC and VPC mixtures were determined by pressure meter as per ASTM C 231 and air meter as per ASTM C173/173M, respectively. 28-day compressive and indirect tensile strengths (normal water curing) were determined from 100-mm cubes as per BS 1881: Part 120:1983 and by splitting 100×200-mm cylinders as per ASTM C 496. Modulus of elasticity of concretes was also determined from 100×200 mm cylinders. 100×200-mm cylinders were air dried in the laboratory to determine the 28-day air dry density. Three 75×75×285-mm drying shrinkage specimens were cast for each concrete mix. The shrinkage specimens were cured under water for 7 days and then

Table 4 Concrete mix design and fresh properties

Concrete type	Cement and aggregates (kg/m^3)				Fresh properties	
	w/c	Cement	Fine	Coarse	Slump (mm)	Air content (%)
NC	0.50	270	800	1250	80	1.6
VPC	0.45	400	600	355	70	3.4

Table 5 Mechanical and durability properties

Concrete type	Mechanical properties				Durability properties	
	Density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	12-week drying shrinkage (Micro-strain)	12-week permeability ($\times 10^{-10}$ cm/s)
NC	2360	22	1.9	18.0	430	3.7
VPC	1845	22	2.0	9.6	550	3.2

transferred to a 23±2°C, 50±5 percent relative humidity room where the shrinkage was monitored using a vertical length comparator according to ASTM C-157 every week for a total of 12 weeks. Two 100×200 mm cylinder specimens were cast for each concrete mix for permeability test. The 12-week water permeability was determined after 1 day of moist and remaining days of air curing by applying 1.4 MPa of water pressure in a hydraulic permeability test apparatus. Selected fresh, mechanical and durability properties of NC and VPC mixtures are presented in Tables 4 and 5.

Lightweight aggregates with high absorption properties are associated with high shrinkage in concrete and it is reported that the shrinkage of lightweight concrete can be 50% greater than NC (FIP 1983). This is confirmed from the higher drying shrinkage of VPC compared to NC. The lightweight VPC exhibited lower water permeability compared to NC. Previous investigations also showed that lightweight concrete had equal or lower permeability than its NC counterpart despite wide variations in concrete strengths, testing media and testing techniques (Bremner *et al.* 1993, ACI 213R 2003). The lower permeability is attributed to the development of high quality paste-aggregate transition zone at the interface and the progressive internal curing (due to the presence of absorbed pore water in porous lightweight aggregate) (Bremner *et al.* 1993).

2.3. Investigations on the influence of extreme curing conditions

2.3.1. Test specimens and curing conditions

The test specimens were 100 mm cubes and a total of 6 cubes were cast for each age and for a particular curing condition. All concrete mixtures were prepared in a laboratory counter-current mixer and the cube specimens were demoulded after 24 hours before subjected to different curing conditions. Six types of curing conditions were adopted to study the effect of curing environment on the performance of VPC and NC. The test specimens were cured in water (mean temperature of 22°C), air (mean temperature of 30°C), and at different temperatures of 4°C, 60°C, 80°C and 110°C. The curing at low temperature (approximately 4°C) was done in an incubator by fully wrapping the specimens with plastic. The air and high temperature (60°C, 80°C and 110°C) curing specimens were not wrapped with plastic and the high temperature curing was conducted in an oven. The exposure of specimens in different curing conditions was carried out for 7, 14, 28, and 91 days. The specimens were tested immediately after removing from the respective curing environment and under similar loading conditions. For all tests, each result was the average of best three samples.

2.3.2. Test methods

Pulse velocity of VPC and NC specimens cured under different curing conditions for different ages was determined by using a computer aided PUNDIT according to British Standard (BS 1881, Part 203) incorporating direct transmission. The actual length of the cubical specimens was measured. The apparatus was calibrated and the specimen was placed between the transducers, which were kept face to face in an especially designed bench. The couplant was used for adequate acoustical coupling between the specimen end and the face of each transducer. The time taken by the pulse to traverse the specimen length (the path length) displayed in the digital display of PUNDIT was noted. The pulse velocity was determined using Eq. 1:

$$V=(S/T)\times 10^6 \tag{1}$$

where V is the velocity (km/s), S is the length of specimen or path length (km) and T is ultrasonic transit time (μs).

Determination of compressive strength of cubical concrete specimens after exposure to different curing conditions for various ages was conducted according to BS 1881: Part 120.

3. Results and discussion

3.1. Summary of fresh, mechanical and durability properties of selected NC and VPC

The dry density (Table 4) reveals that the VPC was about 25% lighter than NC. VPC satisfies the criteria of lightweight structural concrete by achieving a strength in excess of 15 MPa and an air dry density of less than 1850 kg/m^3 (Nevile 1995, CSA 23.3-94 1994). The air content of VPC is also higher than NC which can be attributed to the presence of porous VPA. Lower slump value of VPC (compared to NC) confirms the fact that the structural lightweight concrete does not slump as much as normal density concrete (NC) of the same workability due to lower aggregate density (Kostmatka *et al.* 2002, Hossain 2004a,b, Hossain and Lachemi 2007). The 12-week drying shrinkage of VPC was about 550 microstrain compared to about 430 microstrain of NC. This is expected as the aggregates with high absorption properties (like VPA) are associated with high shrinkage in concrete and the shrinkage of lightweight concrete can be 50% greater than NC (FIP 1983). However, the danger of shrinkage cracking can be compensated by the lower modulus of elasticity of VPC.

3.2. Influence of curing conditions on pulse velocity

Fig. 1 presents the variation of ultrasonic pulse velocity with curing age of VPC under six types of curing conditions. The samples under normal water curing produced the highest pulse velocities for all ages of tests. Low temperature (4^{o}C) with full plastic wrapping shows lower pulse velocities than air and water curing. Pulse velocity is increased up to an age of about 14 days in the high temperature curing (60^{o}C, 80^{o}C and 110^{o}C) and afterward a significant reduction is observed. However, three types of curing (except high temperature ones) maintained the VPC in the conditions of fair and good quality.

Fig. 2 shows the variation of ultrasonic pulse velocity with curing age of NC under six types of curing conditions. The full water curing showed highest pulse velocity followed by air, 4^{o}C, 60^{o}C, 80^{o}C and 110^{o}C curing. The pattern of variation is similar to that of VPC and the lowest pulse velocity is obtained in the 110^{o}C curing concrete. Only water, 4^{o}C and air curing maintained the NC in good quality. The developed pulse velocities in VPC were lower than NC.

A general classification of concrete quality in terms of longitudinal pulse velocity is presented in

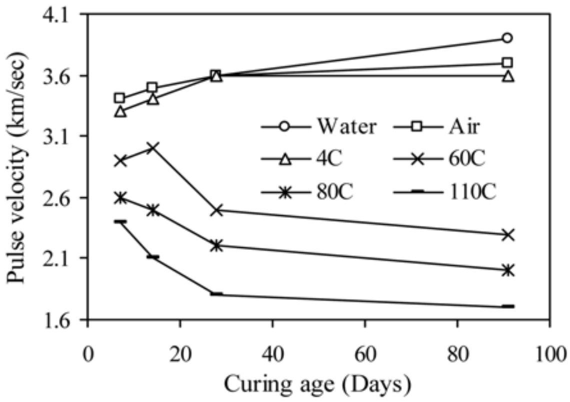


Fig. 1 Variation of ultrasonic pulse velocity of VPC under different curing conditions

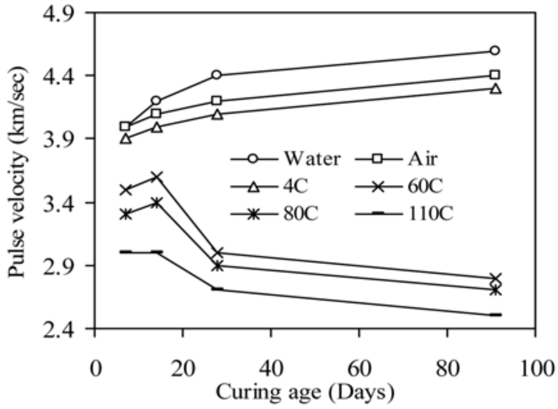


Fig. 2 Variation of ultrasonic pulse velocity of NC under different curing conditions

Table 6 Classification of concrete based on pulse velocity

Quality of concrete	Longitudinal pulse velocity (km/sec)
Excellent	4.5
Good	3.5-4.5
Fair	3.0-3.5
Poor	2.0-3.0
Very poor	2.0

Table 6 (Orchard 1979). The pulse velocity indicates the changes in the structure of concrete due to aging and curing, and it also indicates the soundness of concrete. The ultrasonic pulse velocity increases continuously since cement paste changes from plastic to solid state. Due to increment of water to the cement, the pulse velocity gets unstable since the sample is in a solid/liquid phase and the ultrasonic pulse travels the shortest path. The ultrasonic pulse velocity becomes stable in the final setting of cement and the increment of moisture content enhances the pulse velocity (Nevile 1995). The pulse velocity is increased at the early ages of drying since the rate of gain of strength is higher than the rate of loss of moisture content. It will decrease when the rate of loss of moisture exceeds the gain of strength (Al-Sugair 1995).

Slow hydration and high evaporation in high temperature curing made the wide variation in pulse velocities in both VPC and NC. This effect is found to be higher in VPC as the absorption capacity of VP aggregate is higher than the crushed gravel by about 35%. The rate of hydration and the rate of gain in strength are faster than the rate of loss of water up to an age of around 91 day in both NC and VPC under water, 4°C and air curing. But VPC specimens showed lower rate of gain in strength than NC specimens due to higher loss of water. In high temperature curing conditions, rate of gain in strength was faster than the rate of loss of water up to an age of around 14 day in NC specimens and may be less than 7 day in VPC specimens.

3.3. Influence of curing conditions on the compressive strength

The variation of compressive strength with age for different curing conditions is shown in Fig. 3. The strength development in NC and VPC expressed as a percentage of respective water curing strength and also expressed as a percentage of 28-day water curing strength is compared in Figs. 4 and 5, respectively. The strengths are expressed as a percentage of water curing strength as this condition is considered to be the benchmark of the two mixes of identical design strength.

The specimens in water, normal air and 4°C curing conditions show increase in strength with age (Fig. 3). The development of strength under 4°C curing is slower than water and air curing conditions. In general, water curing yields higher strength than 4°C and air curing for both NC and VPC (Figs. 3, 4). The probable reason is that full water curing provides the required moisture and sufficient vapour pressure to continue hydration. This also indicates that the compressive strength of

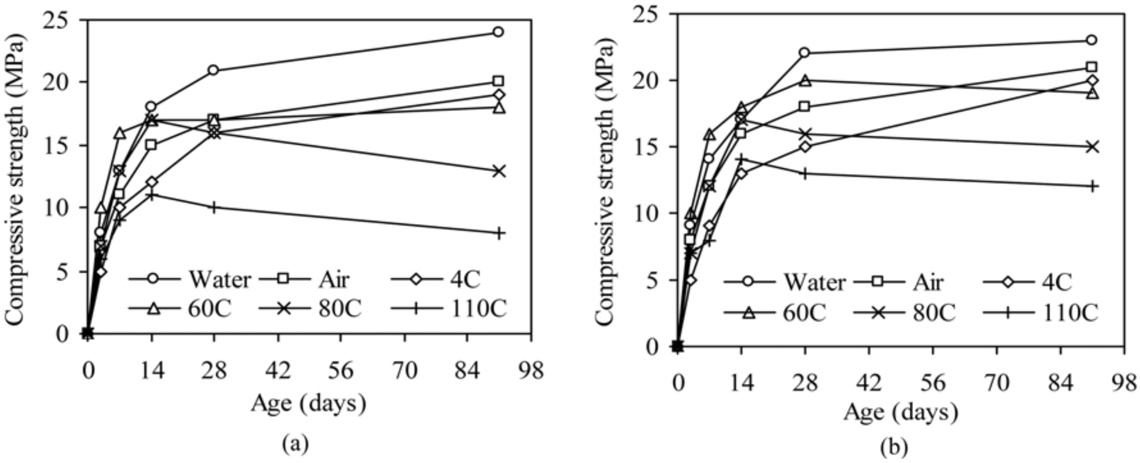


Fig. 3 (a) Effect of curing conditions on the compressive strength of VPC, (b) Effect of curing conditions on the compressive strength of NC

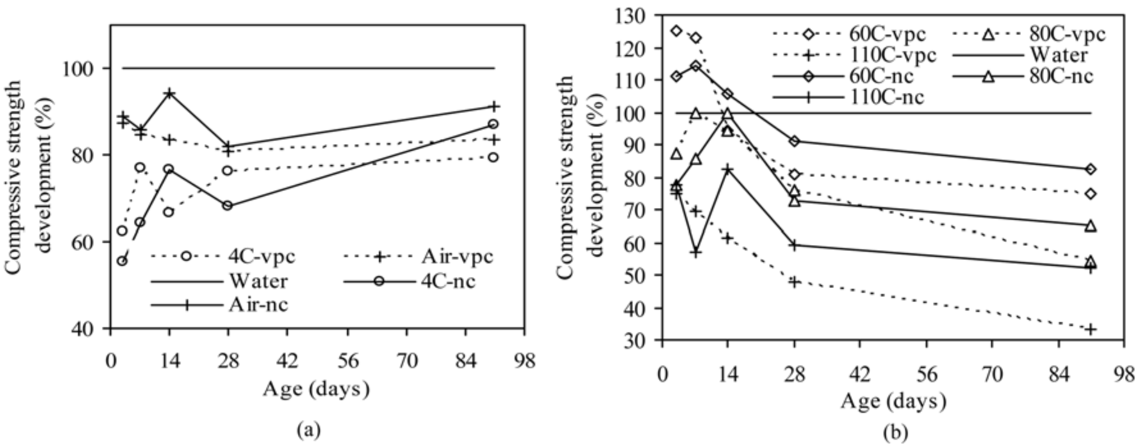


Fig. 4 (a) Comparative strength development as % of respective water curing strength, (b) Comparative strength development as % of respective water curing strength concrete is not significantly influenced by the overall water content rather by moisture movement in concrete specimens (Zain 1995). Another reason is the retardation of early hydration of cement paste while curing at a temperature lower than 5°C as was the case for 4°C curing (Nontananandh 1990). Hydration proceeds at a much slower rate when the concrete temperature is low. Temperature below 10°C is unfavourable for the development of early strength; below 4°C the development of early strength is greatly retarded; and at or below freezing temperatures, down to -10°C, little or no strengths develops (Kostmatka *et al.* 2002).

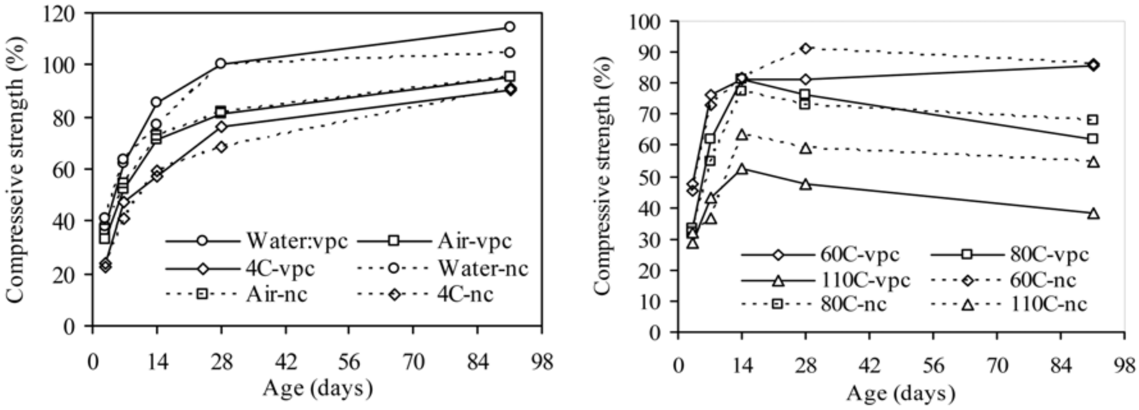
The strength development in VPC and NC under 4°C curing condition (Fig. 4a) varies from 55% to 88% of water curing strength although the early strength development (between 3 and 7 day) is found to be higher in VPC. On the other hand, early strength development in air cured VPC and NC is identical but overall strength development in NC is better during the curing age of 91-day. The strength development of NC and VPC ranges between 80% and 92% of water curing strength. The air cured samples developed better strength in both NC and VPC than the 4°C cured samples due to the reasons described above.

Increase in temperature to a moderate level at early ages (Fig. 3) produces higher strength in both NC and VPC as can be seen from the 60°C curing curves. The early age (3 to 7 day) strength development is about 128% and 115% higher in NC and VPC respectively than water curing strength (Fig. 4b). The higher strength development continues up to an age of around 14 day. From 14-day onward up to a curing age of 91day, the trends in both NC and VPC show a decrease in strength development compared to water curing. The strength development drops to about 83% and 75% in NC and VPC, respectively compared to water curing strength. The overall strength development in NC is better than VPC. This is due to the fact that the curing at moderately high temperature enhances the hydration of cement paste and increases early strength (Nevile 1995, Zain 1995). Besides early strength gain, there are other advantages of curing at temperatures of around 60°C; for example, there is reduced drying shrinkage and creep as compared to concrete cured at 23°C for 28 days (Tepponen and Erikson 1987). It is also recommended to keep the enclosure temperature at 60°C under steam curing until desired concrete strength is reached and strength will not increase significantly if the temperature is raised from 60°C to 70°C (Kostmatka *et al.* 2002). Curing temperature above 70°C may result in damage and should be avoided.

The development of higher early strength in both NC and VPC is absent for temperatures above 60°C (Fig. 3). The strength at 110°C is found to be the minimum over the whole curing period compared to other curing conditions. The compressive strength development (Fig. 4b) in NC under 80°C drops from 78% to 65% compared to a drop from 88% to 54% in VPC between the curing age of 3 and 91 days. On the other hand, a drop of 78% to 52% in NC and 75% to 33% in VPC is observed in 110°C curing. In both NC and VPC, high temperature curing slows down the rate of strength development and also shows a gradual deterioration of strength with curing age. The reduction of strength development and deterioration of strength at high temperature curing especially above 60°C are higher in VPC compared to NC.

A rise in temperature speeds up the chemical reaction of hydration and thus affects beneficially by increasing the early strength of concrete. The high initial rate of hydration at higher temperatures retards the subsequent hydration and produces a non-uniform distribution of the products of hydration within the paste resulting a higher concentration of the products in the vicinity of the hydrating grains. This can adversely affects the long term strength as observed in specimens curing at 60°C.

Both NC (22 MPa) and VPC (22 MPa) have developed (Fig. 3) the targeted 28-day water curing



(a) (b)

Fig. 5 (a) Compressive strength development as % of 28-day water curing strength, (b) Compressive strength development as % of 28-day water curing strength

strength of 20 MPa. The 28-day strengths (Fig. 5) under different curing conditions expressed as percentage of 28-day targeted strength are as follows:

• 4°C curing - 68% in NC compared to 76% in VPC; air curing - 82% in NC compared to 81% in VPC, 60°C curing - 91% in NC compared to 81% in VPC, 80°C curing - 73% in NC compared to 76% VPC and 110°C curing- 59% in NC compared to 48% in VPC.

The 91-day strengths (Fig. 5) under different curing conditions expressed as percentage of 28 day targeted strength are as follows:

• 4°C curing - 86% in NC compared to 90% in VPC; air curing - 91% in NC compared to 95% in VPC, 60°C curing - 83% in NC compared to 85% in VPC, 80°C curing - 65% in NC compared to 62% VPC and 110°C curing - 52% in NC compared to 38% in VPC.

Both VPC and NC fail to attain the targeted strength under 4°C, air and elevated temperature curing conditions within the curing age of 91 days. Extension of curing period from 28 day to 91 day in 4°C, air and 60°C curing conditions leads to the development of higher percentage of 28-day targeted strength in VPC compared to NC. The 4°C curing seems to be more beneficial for VPC compared to NC. The reduction of strength in VPC is higher than NC when the curing age is extended to 91 day.

Comparatively higher loss of water in VPC due to high temperature curing is the main cause of lower strength development. This is also related to the higher degree of porosity of VPC as indicated by higher air content of about 3.4% in fresh VPC and also to higher degree of porosity in VPA. The rate of hydration also slows down due to loss of water as time progresses. The excessive loss of water in the early ages significantly hampers the strength development process. If this continues throughout the curing period, as was the case in high temperature curing in this study, the strength development will be significantly affected.

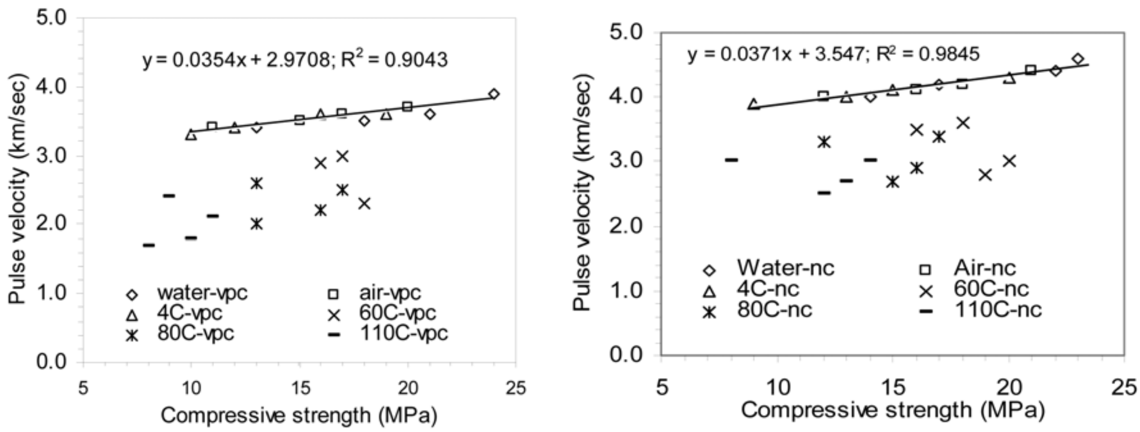
Loss of water also causes the concrete to shrink, thus creating tensile stresses within the concrete. If these stresses develop before the concrete has attained adequate tensile strength, surface cracking can results (FIP 1983). The surface cracking was observed in both NC and VPC specimens at the age of 91-day under 110°C curing. This was also another cause of reduction of strength at high temperature curing with the increase of curing age.

Since all desirable properties of concrete are improved by curing, the curing environment should be adequate and curing period should be long enough so that concrete can achieve at least 70% of the targeted compressive strength (Kostmatka *et al.* 2002). If high performance is desired both NC and VPC should be moist cured.

3.4. Correlation between pulse velocity and compressive strength

Various attempts have been made to correlate UPV measurements and compressive strength (Demirboga *et al.* 2004, Gul *et al.* 2006). In this study, development of pulse velocity and compressive strength in NC and VPC with age and different curing conditions shows some similarity (Figs. 1-3). Both pulse velocity and compressive strength increases with the increase of curing age for water, air and 4°C curing conditions. On the other hand, both pulse velocity and compressive strength increase with the increase of curing age of up to 14 and 28-days for high temperature curing (60°C, 80°C and 110°C). Beyond this age, both pulse velocity and compressive strength decrease and the rate of decrease is higher with the increase of curing temperature.

Figs. 6(a,b) show the relationship between pulse velocity and compressive strength at different curing conditions for VPC and NC. In general, pulse velocity increases with the increase of compressive strength. Excellent correlation between pulse velocity and compressive strength under water, air and 4°C curing conditions is observed for both NC and VPC. However, due to scatter in the data, good correlation does not exist (for both NC and VPC) for high temperature curing (60°C, 80°C and 110°C). The form of statistical correlation is normally influenced by many factors such as concrete mix, age of concrete, degree of hydration, temperature and moisture content (Sturrup *et al.* 1984). In this study, all these factors are incorporated and the sensitivity of UPV to detect the effect of these factors definitely affected its correlation with the compressive strength. Therefore, care should be taken when UPV is used as an alternative tool for non-destructive evaluation of compressive strength of concrete exposed to different temperatures and moisture conditions (curing effect).



(a) (b)

Fig. 6 (a) Correlation between pulse velocity and compressive strength of VPC, (b) Correlation between pulse velocity and compressive strength of NC

4. Conclusions

The performance of normal weight concrete (NC) and lightweight volcanic pumice concrete (VPC) under different curing conditions is studied based on compressive strength and ultrasonic pulse velocity (UPV) measurements for a duration of 91 days. The study leads to the following conclusions:

(1) In both NC and VPC, the pulse velocity generally increases with the increase of age under water, air (30^{o}C) and 4^{o}C curing conditions while the trend shows a decrease under higher temperature (60^{o}C, 80^{o}C and 110^{o}C) curing.

(2) The variation in pulse velocities in VPC is much wider compared to that observed in NC due to comparatively slower hydration and higher evaporation in high temperature curing. This is attributed to the higher absorption capacity and porosity of VP aggregate. The pulse velocities of VPC are lower than those of NC.

(3) The method and duration of curing have significant influence on the engineering properties for both types of concrete. Both NC and VPC under 4^{o}C, air and elevated temperature curing conditions fail to develop the targeted 28-day water curing strength.

(4) Curing at moderately high temperature enhances the development of early age strength compared to water curing strength in both VPC and NC. Curing at 4^{o}C in both NC and VPC slows down the rate of development of early age strength.

(5) In both NC and VPC, high temperature curing slows the rate of strength development and also shows a gradual deterioration of strength with curing age. The reduction of strength development at high temperature curing especially above 60^{o}C is higher in VPC compared to NC.

(6) Although VPC seems to be more vulnerable to high temperature curing, its performance is found satisfactory compared to representative NC of similar strength. Water or moist curing is found to be the most satisfactory method of curing for better performance of both NC and VPC.

(7) Correlation between pulse velocity and compressive strength of both NC and VPC is affected by curing conditions. Care should be taken when UPV is used as an alternative tool for evaluation of compressive strength specially at elevated temperature curing.

Acknowledgements

The author is grateful to the Papua New Guinea Department of Works and the PNG Ready Mixed Concrete Co. Ltd. for assistance.

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