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Strength, durability and micro-structural aspects of high performance volcanic ash concrete

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Abstract

This paper presents the results of investigations to assess the suitability of using volcanic ash (VA) as a cement replacement material to produce high performance concrete. Tests were conducted on concrete mixtures replacing 0 to 20% by mass of ordinary Portland cement (OPC) by VA. The performance of high performance volcanic ash concrete (HPVAC) mixtures was evaluated by conducting comprehensive series of tests on fresh and hardened properties as well as durability. The mechanical properties were assessed by compressive strength, while durability characteristics were investigated by rapid chloride permeability (RCP), drying shrinkage (DS), mercury intrusion porosimetry (MIP), differential scanning calorimetry (DSC) and microhardness tests. HPVACs showed better durability properties compared to control concrete with 0% VA. The improved performance of HPVACs was attributed to the refinement of pore structure, and pozzolanic action of VA. HPVAC having a minimum 28-day compressive strength of 60 MPa can be obtained by replacing up to 20% (by mass) of cement by VA. Development of non-expensive and environmentally friendly HPVAC with acceptable strength and durability characteristics (as illustrated in this study) is extremely helpful for the sustainable development and rehabilitation of volcanic disaster areas around the world.

Keywords: High performance volcanic ash concrete; Compressive strength; Drying shrinkage; Rapid chloride permeability; Porosity and pore structure; Calorimetry

1. Introduction

The search for alternative binders or cement replacement materials had been continued for the last decades. Research had been carried out on the use of volcanic ash (VA), fly ash (FA), blast furnace slag (BFS), silica fume (SF), etc. as cement replacement material [1–7]. The VA, pumice, and FA are pozzolanic materials, because of their reaction with lime (calcium hydroxide) liberated during the hydration of cement. Amorphous silica present in the pozzolanic materials combines with lime and forms cementitious materials. These materials can also improve the durability of concrete and the rate of gain in strength and can also reduce the rate of liberation of heat, which is beneficial for mass concrete.

Over recent years Portland cements containing fly ash and silica fume have gained increasing acceptance while Portland cements containing natural pozzolans like rice husk ash and burnt oil shale are common in regions where these materials are available. Replacement levels of Portland cement in blended cement containing blast furnace slag vary considerably, and contents of well over 50% by mass are common in some regions. Fly ash typically replaces 10–30% of the Portland cement although levels of 50–60% have been advocated [6]. When silica fume is added, it commonly comprises 5–10% of the binder. ASTM Standards exist for the use of natural pozzolans, fly ash, and silica fume and blast furnace slag in concrete [8–10].

Volcanic materials such as VA are found abundantly in volcanic areas around the world and finding new and improved ways to build with such materials is becoming widespread. New sources of volcanic materials are being produced steadily. Recently the eruption of volcanoes in Caribbean Island of Monseratt emitted large quantities of such materials. Of course these volcanic eruptions are very dangerous catastrophes but they leave very useful materials after the disaster. The eruption of Mount Pinatubo in Philippines in the early 1990s devastated a fertile beautiful valley into a source of volcanic materials

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which was used as useful building materials for constructing affordable housing. The 1994 volcanic eruption that occurred in the East New Britain province of Papua New Guinea (PNG) completely devastated the province and created an environmental disaster. The meaningful use of volcanic materials can, not only transform them into natural resources to produce low cost construction materials but also lead to sustainable development [1,2,11]. Development of non-expensive and environmentally friendly VA based concrete with acceptable strength and durability characteristics can be extremely helpful in the development and rehabilitation of volcanic disaster areas around.

Comprehensive research had been conducted over the last few years on the use of VA and pumice in cement and concrete production [1,2,11–13]. Research suggested the manufacture of blended PVAC (Portland volcanic ash cement) and PVPC (Portland volcanic pumice cement) with maximum replacement of up to 20% [1].

Durability of concrete is one of its most important desirable properties and it is essential that the concrete made with VA and pumice based blended cements should be capable of preserving its durability throughout the life of structures like other blended cement concretes made with SF, FA, and BFS [12,13]. This paper presents the results of a comprehensive experimental investigation studying the strength and durability characteristics of high performance volcanic ash concrete (HPVAC) having a 28-day compressive strength in excess of 60 MPa.

2. Experimental program

2.1. Materials

The VA used in this investigation was collected from the Rabaul area of the East New Britain province of PNG and the source was a volcano called Mount Tavurvur. The Rabaul area is situated in the worldwide earthquake and volcanic zone known as the ‘Belt of fire’. Raw VA, collected from the source was dried and sieved to remove larger particles and other debris. The cement used was locally manufactured ordinary Portland cement (OPC) conforming to ASTM Type I.

Chemical and physical properties of Papua New Guinea VA are compared with those of OPC and Class N fly ash in Table 1. The Portland cement has a specific gravity of 3.15 and Blaine fineness of 320 m^2/g. Chemical analysis as per ASTM C 114-00 [14] indicated that the main oxide component of VA is silica (about 59%) and the main oxide component of OPC is calcium oxide (about 64%). The oxide contents provided in the chemical analyses (Table 1) are not indicative of the chemical components present, but are purely analytical summations. Thus the 64% CaO in OPC does not mean that there is 69% of CaO present. Actually there is almost zero (less than 1% as shown in Table 1) CaO (free lime); the compounds actually present are C_3S, C_2S, C_3A, etc. Quantitative X-ray diffraction (XRD) analysis of OPC and blended OPC with 20% VA as cement replacement, provided valuable information on this aspect. The phase composition of these materials is presented in Table 2.

The Blaine fineness and oven dry bulk density of VA are 285 m^2/kg and 2450 kg/m^3, respectively (Table 1). VA seems to satisfy most of the criteria of Class N fly ash as per ASTM C 618-00 [8]. Analysis of multiple samples from the single PNG deposit does not show any significant changes in the chemical composition of VA. Table 1 also presents the chemical composition of a Mexican volcanic ash. Comparative study shows that the oxide components of VA can vary from source to source.

Volcanic eruptions inject water vapour (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrochloric acid (HCl),

Table 1
Chemical and physical properties of cementing materials

Oxide compounds	VA Papua New Guinea	VA Mexico	ASTM C 618 requirement for fly ash (Class N)	Portland cement (PC) ASTM Type I
	Mass %	Mass %	Mass %	Mass %
Chemical composition				
Calcium oxide (CaO)	6.10	1.00	–	64.1
Silica (SiO_2)	59.32	68.20	–	21.4
Alumina (Al_2O_3)	17.54	11.20	–	5.7
Iron oxide (Fe_2O_3)	7.06	1.8	–	3.5
$SiO_2+Al_2O_3+Fe_2O_3$	83.9	81.2	Minimum = 70	30.6
Sulphur trioxide (SO_3)	0.71	0.01	Maximum = 4	2.1
Magnesia (MgO)	2.55	0.20	–	2.1
Sodium oxide (Na_2O)	3.80	0.20	–	0.5
Potassium oxide (K_2O)	2.03	3.40	–	0.6
Equivalent alkali (Na_2O)	5.14	2.44	–	0.89
Free lime (CaO)	–	–	–	0.6
Loss on ignition	1.03	–	Maximum = 10	1.1
Physical properties				
Fineness, m^2/kg	285	–	–	320
Retained on 45 μm sieve, %	12	–	Maximum = 34	–
Density, kg/m^3	–	–	–	3150

Table 2
Potential phase composition of the cementing materials from X-ray diffraction

Phase	OPC	Blended cement (OPC+20% VA)	Leachable constituents in Papua New Guinea ash fall (mg/kg)
C_3S	68.1	56.3	Aluminium (Al) = 4.2, Boron (B) = 0.078, Barium(Ba) = 0.301, Cadmium (Cd) = 0.007, Chlorine (Cl) = 118, Cobalt (Co) = 0.0032, Copper (Cu) = 0.284, Fluorine (F) = 19.2, Iron (Fe) = 2.12, Lithium (Li) = 0.034, Magnesium (Mg) = 18.1, Manganese (Mn) = 1.23, Sodium (Na) = 118, Lead (Pb) = 0.086, Silicon (Si) = 5.2; Strontium (Sr) = 1.56; Zinc (Zn) = 0.45; Mercury (Hg) = 0
C_2S	14.1	9.5	
C_3A	8.1	5.1	
C_4AF	9.2	7.4	
Other	2.4	8.2	
Total	99.7	86.5	
Glassy fraction [a]	0.3	13.5	

[a] Obtained by difference.

hydrofluoric acid (HF) and VA into the atmosphere. HCl and HF dissolve in water and fall as acid rain whereas most SO_2 is slowly converted to sulphuric acid (H_2SO_4) aerosols. VA particles may absorb these aerosol droplets onto their surfaces. When ash falls to the ground, the soluble components (leachates) can by washed away by water, potentially resulting in changes to local water chemistry and hence quality. Chemical changes in the underlying soil can occur as a result of leaching of the aerosols coating individual grains. Table 2 shows concentrations of leachable constituents including heavy metals (Copper, Lead, Zinc, Mercury, etc.) in ash fall from the eruption of Mount Tavurvur volcano in Papua New Guinea.

The fine and coarse aggregates were local natural river sand and 20 mm maximum size crushed limestone, respectively. The particle size distributions as per ASTM C 136-01 [15] for aggregates are presented in Table 3. The bulk density and water absorption of aggregates are also presented in Table 3.

A naphthalene-formaldehyde condensate was used as a superplasticizer (SP) in HPVAC mixtures. This SP was a brown liquid containing 41.2% solids. Ordinary drinking water was used in the concrete mixes.

2.2. Mix proportions and mix details

The mix proportions of HPVAC mixtures derived from extensive preliminary investigation on trial mixes are presented in Table 4. HPVAC mixtures were designed to provide a minimum 28-day compressive strength of 60 MPa. VA was introduced as cement replacement and its proportions were varied from 0 to 20% by mass. Control mixes incorporating OPC were also prepared for comparison purposes. The numeric in mix designations represents the percentage of VA by mass.

2.3. Test specimens, curing conditions and testing details

Comprehensive series of tests on fresh, mechanical, durability and micro-structural properties of HPVACs such as slump, air content, compressive strength, density, drying shrinkage (DS), rapid chloride permeability (RCP), mercury intrusion porosimetry (MIP), differential scanning calorimetry (DSC) and microhardness were carried out.

The slump values of fresh HPVACs were determined as per ASTM C 143-00 [16] while the air contents were determined by pressure meter as per ASTM C 231-97 [17]. Superplasticizer (SP) content was adjusted in order to achieve a slump that ranges between 75 and 80 mm. The water-to-binder ratio (W/B) was kept constant at 0.3 for all the mixtures. No air entraining admixtures was used.

Compressive strength test was performed on 150 × 300-mm cylinders at an age of 28 and 56 days as per ASTM C-39 [18]. Three specimens were tested for each test at each age and mean values were reported. The specimens were removed from the moulds after 24 h of casting and then placed in a water tank at 23 ± 2 °C. After 28 days of water curing, they were transferred to a relative humidity room maintained at 23 ± 2 °C and 50 ± 5 relative humidity until testing.

Three drying shrinkage specimens 75 × 75 × 285 mm were cast for each HPVAC mix. The shrinkage specimens were cured

Table 3
Properties of aggregates and VA

Grain size distribution of aggregates

Sieve size, mm	Fine % passing	Coarse % passing
20	100	100
12.7	100	71
9.5	100	28
4.75	93	0
2.36	70.5	
1.18	51.5	
0.6	35	
0.3	20.5	
0.15	8.5	

Physical properties aggregates and VA

	Bulk density (kg/m^3)		Water absorption (%)
	Oven dry	SSD	
Coarse	2570	2640	2.49
Fine	2610	2660	0.60
VA	2450	2440	0.41

Table 4
Mix proportion of HPVAC mixtures

Mix designation	VA (%)	W/B	Water (W) kg/m^3	Cement (C) kg/m^3	Aggregates kg/m^3 Fine	Aggregates kg/m^3 Coarse	SP[a] (%)	TA/C
VA-0[b]	0	0.30	150	500	760	1016	0.50	3.55
VA-5	5	0.30	150	475	754	1016	0.95	3.73
VA-10	10	0.30	150	450	748	1016	0.95	3.92
VA-15	15	0.30	150	425	742	1016	0.85	4.14
VA-20	20	0.30	150	400	736	1016	0.80	4.38

Numerics in mix designation represent percentage of VA; B: Binder.

[a] SP content (based on solid mass) in percentage by weight of binder.

[b] Control HP OPC concrete.

under water for 7 days and then transferred to a 23±2 °C, 50±5% relative humidity room where the shrinkage was monitored using a vertical length comparator according to ASTM C-157 [19] at 1, 2, 4, 8 and 12 weeks.

For RCP, MIP and DSC, the specimens were removed from the mould after 24 h of casting and placed in a water tank at 25 °C. After 28 days of water curing, they were transferred to an environmental chamber maintained at 23±2 °C, 50±5% relative humidity. The specimens were kept there for 4 weeks until testing at 56 days.

The rapid chloride permeability test (RCPT) was conducted as per ASTM 1202-97 on 100×50-mm concrete slices to determine resistance to chloride ion penetration [20]. The chloride ion resistance of concrete gives an indirect measure of its permeability and internal pore structure, as more current passes through a more permeable concrete.

The porosity and pore size distribution were measured using MIP, which had a measuring pressure ranging from 0.01 to 200 MPa [13]. The contact angle selected was 140° and the measurable pore size ranged from 0.004 to 144 μm. The Washburn equation was used to calculate the pore radii [21]. The samples in the form of pellets of about 5 mm in size, consisted of hardened cement mortar, were collected from the crushed concrete cubes and immediately soaked in acetone to stop the further hydration. The samples were dried in an oven at 60 °C for 48 h before testing.

The DSC test was performed on the hardened mortar samples taken from the crushed concrete cylinders after 56 days of curing to determine the quantity of $Ca(OH)_2$ formed in the mortars. The samples used weighted around 60 mg. The samples were heated at a constant heating rate of 10 °C/min to 1100–1200 °C, in a dynamic helium atmosphere. The DSC data analysis gave graphs of heat flow between the sample and reference crucibles vs. temperature. DSC thermograms showed peaks due to endothermic (heat absorbing) and exothermic (heat releasing) reactions. The $Ca(OH)_2$ content was equivalent to the area (enthalpy) under the respective endothermic peaks. The size of the area under the curve was related to the quantity of the material in the sample.

Based on the ASTM E 384-99 [22] testing method, a Vickers indenter was used to determine the microhardness in bulk pastes and in the transition zone between aggregates and hardened cement paste (hcp). To eliminate the influence of dispersed sands on the transition zone, mixes without fine aggregates were also cast into cylinders. Slices cut from the middle of the cylinders were polished with 600# paper then 1500# paper to obtain an adequate surface with a minimum of damage. Slices were then carefully sealed to avoid carbonation, which might lead to larger measured hardness values because the carbonation product ($CaCO_3$) is much harder than the reactants. As the typical width of the interfacial transition zone (ITZ) is about 50 μm, the applied load in the microhardness test was determined to be 0.05 N so that the spacing between indentation points should be at least two times the diagonal of the indentation while ensuring a sufficient number of points was taken to map the ITZ [23]. The measured range was up to 250 μm away from the surface of aggregates although the actual width of the transition zone can be far smaller than 50 μm. Six determinations were performed on the surface of each sample, and the profiles of microhardness yielded by the average values were derived.

3. Results and discussion

3.1. Fresh properties of HPVAC

The air contents and slump values of non-air entrained HPVACs are presented in Table 5. Air content ranged between 2.6% and 3.2%. Generally air content of the HPVACs increased with the increase of VA content. All the mixtures were produced at a slump that ranged between 76 and 80 mm.

3.2. Hardened properties of HPVACs

The compressive strengths of HPVACs are presented in Table 5. Generally compressive strength decreased with the increase of VA content and increased with the increase of age. The decrease in strength with the increase of VA content was due to the increase of total aggregate-to-cement ratio (TA/C) by mass in HPVACs (Table 4). However, the finely divided silica (59%) in VA can combine with calcium hydroxide in the presence of water to form stable compounds like calcium silicates, which have cementitious properties [12]. Such pozzolanic action of VA can contribute to the enhancement of strength and long-term durability of HPVACs. A HPVAC having a 28-day compressive strength of 82 MPa, 75 MPa, 67 MPa and 62 MPa can be developed using 5, 10, 15 and 20% of VA, respectively.

Table 5
Slump, air content, density and compressive strength of HPVACs

Mix ID	Slump (mm)	Air content (%)	28-day density kg/m^3	Compressive strength (MPa) 28-day	Compressive strength (MPa) 56-day
VA-0[a]	78	2.6	2580	80	85
VA-5	76	2.8	2556	82	86
VA-10	78	3.0	2532	75	79
VA-15	80	3.1	2513	67	70
VA-20	78	3.2	2496	62	64

[a] Control HP OPC concrete.

A slight decrease in density with the increase of VA was observed due to the replacement of comparatively heavier cement by lighter VA (Table 5). However, up to 20% VA replacement, the decrease was only 3.25% compared to control concrete (0% VA). The 28-day density of HPVACs ranged between 2496 kg/m^3 and 2556 kg/m^3.

3.3. Durability of HPVACs

3.3.1. Drying shrinkage (DS)

The variation of DS in HPVACs with different percentages of VA is presented in Fig. 1. The DS of HPVACs was slightly higher compared to control concrete (0% VA). The DS also increased with the concrete age. However, the rate of increase was higher within the first 6 weeks. The 12-week DSs in HPVACs with 5%, 10%, 15% and 20% VA were about 516, 508, 502 and 488 microstrain, respectively compared to about 471 microstrain in control concrete. The DSs of 5 and 10% HPVACs were higher than those of 15 and 20% HPVACs although the overall DS in HPVACs was higher than control concrete (0% VA) within the curing age of 12 weeks. The maximum DS did not exceed 600 microstrain for any HPVACs. Similar effects were observed by Gopalan et al. [24] in FA concrete. However, Samarin et al. [25] reported that good quality Australian fly ashes usually result in a reduction of shrinkage compared to control OPC concrete.

The DS is affected by twin influences of TA/B and W/C [26]. DS increases with the increase of W/B and decreases with the increase of TA/B for normal concrete. For the HPVACs with constant W/B of 0.3, the TA/B was decreased from 3.55 to 3.46 while VA content was increased from 0 to 20%. This may be one of the contributing factors for higher DS in HPVACs compared to control concrete.

3.3.2. Resistance of HPVACs against chloride ion penetration

The results of RCP tests are summarized in Table 6. A comparison among different concretes showed better chloride resistance and lower permeability of HPVACs as compared to control OPC concrete. Chloride ion resistance of HPVACs increased with the increase of VA content. The ASTM C 1202-97 [20] specifies the concrete as having very low permeability if the charge that passes through ranges between 100 and 1000 C. All HPVACs showed RCP values lower than 1000 C but higher than 100.

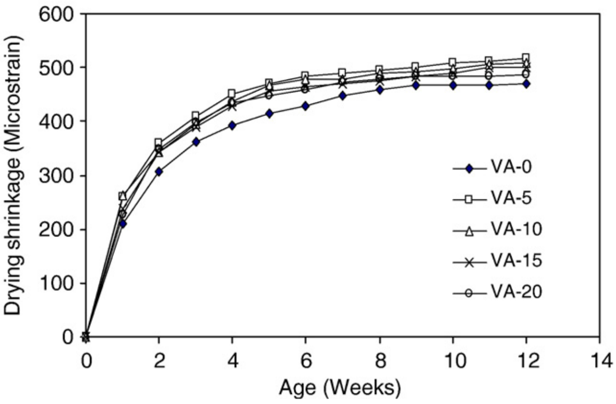

Fig. 1. Variation of drying shrinkage (DS) in HPVACs.

Table 6
RCP, porosity, pore diameter and DSC test results of HPVACs

Mix designation	RCP	Porosity	Avg. pore diameter	Endothermic peak area
	Coulombs	(% v/v)	(µm)	J/g
				Ca(OH)$_2$
VA-0 [a]	1034	10.45	0.0362	105
VA-5	767	9.23	0.0352	83
VA-10	586	8.49	0.0347	72
VA-15	493	7.35	0.0339	54
VA-20	405	6.85	0.0332	39

[a] Control HP OPC concrete.

3.4. Micro-structural properties

3.4.1. Porosity and pore size distribution measurements

The porosity and pore size distribution as measured by MIP are reported in Table 6. A significant decrease in porosity and average pore diameter was observed in HPVACs by the addition of pozzolanic VA as compared to the control OPC concretes. The beneficial effect of the addition of VA can also be identified from the lower volume of pores (larger than 0.01 µm) in HPVCs compared to control OPC concrete (Fig. 2). The increase in impermeability and chloride resistance can be attributed to the refinement of pore structures of HPVACs in presence of VA.

3.4.2. Microhardness

Microhardness testing is a powerful tool for characterizing the micro-structural properties of hcp and ITZ [27]. In this research, this testing method was applied to characterize the influence of VA addition on the properties of bulk paste and the ITZ around aggregates. The reported microhardness values in the ITZ are results of concretes exposed to room temperature (25 °C). Also reported are microhardness test data on bulk pastes in concretes exposed to room temperature.

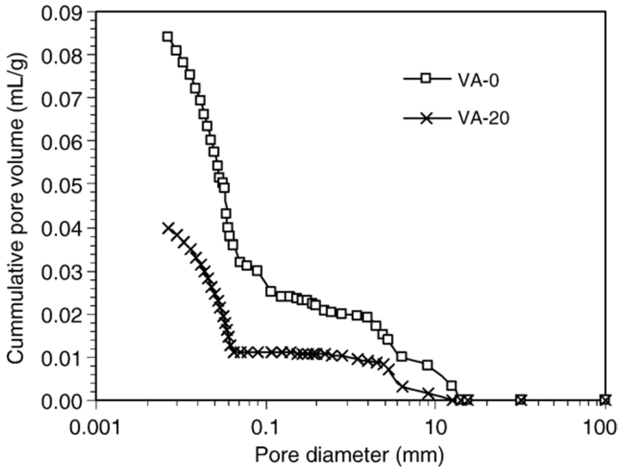

Fig. 2. Pore size distribution in HPVAC and control concrete.

Fig. 3 shows variation of ITZ ranges, i.e., where the microhardness test resulted in lower Vickers Hardness Numbers (Hv) than those in the middle of the hardened bulk cement pastes. The extent of the weak zone (ITZ range) is about 40 μm for OPC concrete (0% VA) compared to about 45 μm of HPVAC with 20% VA. No obvious increase in width of the weak zone (ITZ range) was observed when VA content was increased from 0 to 20%. Increased microhardness values in the vicinity of the aggregate were observed in all specimens, and this may be due to the presence of stiff inclusions in the excited range around the indentation, which restrains the flow of material under the indentation [23].

Microhardness test results on bulk pastes are shown in Fig. 4. The trend shows an increase of microhardness up to 10% of VA and beyond 10%, microhardness decreases. The trend for microhardness variation is quite similar to that of compressive strength versus % of VA as shown in Table 5.

3.4.3. DSC test results

The variation of $Ca(OH)_2$ in concrete mixtures at a curing age of 56 days (obtained from DSC tests) with different percent of VA is shown in Table 6. The quantity of $Ca(OH)_2$ formed in the hydration of the cement decreased with the increased substitution of VA for OPC. The endothermic peak for $Ca(OH)_2$ was observed at around 450 °C. Lowering of $Ca(OH)_2$ also indicated that the pozzolanic reactivity of VA consumes $Ca(OH)_2$ resulting from the hydration of cement. The pozzolanic reaction of VA with $Ca(OH)_2$ should improve the corrosion resistance of HPVACs compared to control OPC concrete [13]. This was justified from the higher chloride resistance of HPVACs compared to control concrete as observed in the current study. VA acted as fine granulates and upon hydration it had the capability of partially obstructing voids and pores. This leads to a decrease of pore size with refinement of pore structure and to a smaller effective diffusivity for chloride or other species as confirmed from the experimental results (Table 5 and Fig. 2). This can improve the long-term corrosion resistance of VA concrete based structures.

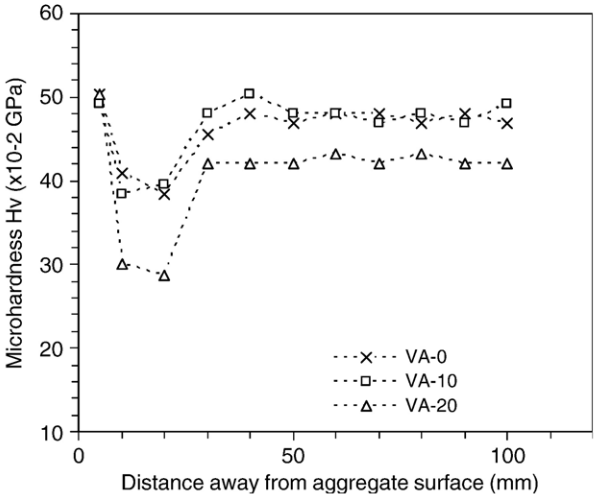

Fig. 3. Influence of VA on microhardness profiles in the ITZ.

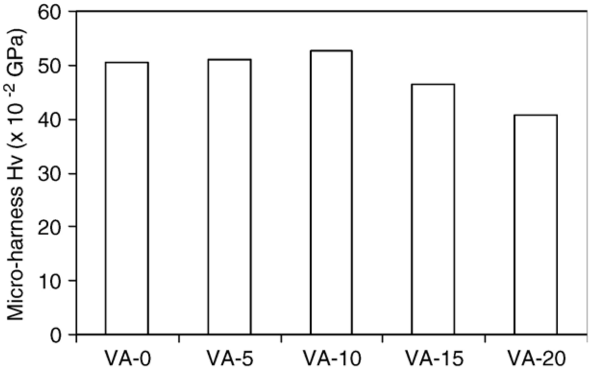

Fig. 4. Influence of VA content on the microhardness of hardened cement paste.

3.4.4. Discussion

Previous investigation showed that VA addition to concrete improves long-term corrosion resistance, lower corrosion rate and lower weight loss of embedded steel bars [28]. The role of VA is related with both the initiation and the progression of corrosion. The pozzolanic reaction of VA with calcium hydroxide, also produces a denser concrete and thus inhibits the ingress of chloride ions. This takes place at a slower rate. The XRD curves of specimens taken around the steel bars revealed that the calcium hydroxide content of the VA concrete specimens is lower than that of the plain concrete specimens (Fig. 5) [28]. This indicates that the pozzolanic reactivity of VA consumes calcium hydroxide resulting from hydration of the cement. This improves the corrosion resistance of VA concrete mixes compared to plain concrete mixes. Comparatively higher Friedel's salt formation in VA concrete (with 20% VA) compared to plain concrete is confirmed from the XRD spectra in Fig. 5. The VA certainly does not have C_3A which can adsorb more chloride ions to form Friedel's salts. The presence of lower C_3A content in VA blended cement compared to OPC confirms the fact (Table 3). It is more likely that VA has aluminium in the glass that is available for the chemical reaction resulting in Friedel's salt production. Friedel's salt formation consequently lowers the levels of free chloride and hence reduces the chloride ion diffusivity of concrete. This process reduces the localized corrosion of steel. Similar phenomena were also observed in FA concrete [29–31].

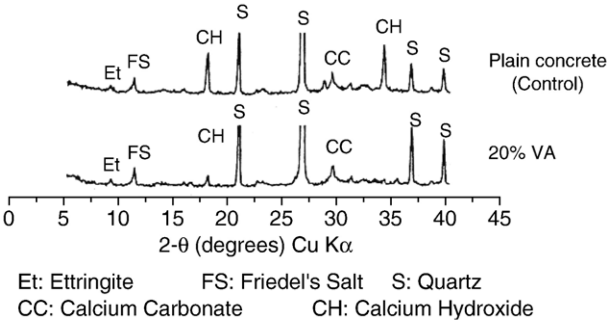

Fig. 5. XRD spectra of specimens.

Previous study reported that the addition of fly ash leads to a decrease in concrete porosity, which is directly related to its chloride resistivity [30,31]. A reduction of chloride diffusivity in concrete to half its value was observed as a consequence of a 50% replacement of cement by fly ash. The VA used in this study closely conforms to the ASTM Specification for Class N fly ash which does not necessarily mean that these materials behave like fly ash. However, it is reported that the incorporation of VA as cement replacement in mortar leads to the refinement of pore structure and to the decrease of total pore volume with the increase of curing age [13]. A lower porosity corresponds to a lower free cross-section and to an increase in path tortuosity, affecting the diffusion of solvated species. The beneficial effects of VA concerning corrosion initiation and corrosion rate similar to fly ash appear to be justified.

4. Conclusions

Development of high performance volcanic ash concrete (HPVAC) with different percentages (0 to 20% by mass) of volcanic ash (VA) as cement replacement having a constant water-to-binder ratio (W/B) of 0.3 is reported. The fresh and hardened properties of HPVACs were assessed along with durability and micro-structural properties. This paper demonstrates that VA can be used as a cement replacement material to manufacture HPVACs having satisfactory strength and durability characteristics. The following conclusions were drawn from the study:

1. Non-air entrained HPVACs with different dosages of superplasticizer having a slump value that ranged between 75 mm and 80 mm showed satisfactory workability with no segregation or excessive bleeding.
2. Generally strength decreased with the increase of VA content and increased with the concrete age. HPVACs having a 28-day compressive strength in excess of 60 MPa can be achieved by using up to 20% VA.
3. The drying shrinkage (DS) of HPVACs was slightly higher compared to control concrete (0% VA). The increase in VA content beyond 10% reduced the DS and the DSs of 5% and 10% HPVACs were higher than those of 15% and 20% HPVACs. The maximum DS did not exceed 600 microstrain for any HPVACs.
4. Chloride ion resistance of HPVACs increased with the increase of VA content. All HPVACs showed rapid chloride permeability (RCP) values within the range of 100–1000 C, which suggested that they have very low permeability as per ASTM C 1202-97 [20].
5. DSC tests confirmed the presence of lower quantity of $Ca(OH)_2$ in HPVACs compared to control concrete (0% VA). The presence of lower $Ca(OH)_2$ was an indication of the pozzolanic reaction of VA to produce a denser concrete and hence, lead to improved chloride ion resistance of HPVACs compared to control concrete. Refinement of pore structure of HPVACs was also confirmed from the Mercury Intrusion Porosimetry (MIP) test results.
6. Microhardness test results revealed no obvious increase in the width of the ITZ in HPVACs compared to control concrete.

This study also warrants investigations (which are now in progress) on alkali–silica reactivity and sulfate resistance characteristics of HPVACs due to the presence of high alkali and aluminium oxide content, respectively in VA. Although the chemical composition of VA can vary from source to source, general behaviour of HPVAC mixes should follow similar trend as observed in this study. Hence proposed mixes can be used as guidelines for the development of HPVACs incorporating VAs from different sources.

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