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Blended cement using volcanic ash and pumice

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Abstract

This paper reports the results of investigation to assess the suitability of volcanic ash (VA) and pumice powder (VPP) for blended cement production. Tests were conducted on cement where Portland cement (PC) was replaced by VA and VPP within the range of 0 to 50%. The physical and chemical properties of VA and VPP were critically reviewed to evaluate the possible influences on cement properties. The investigation included testing on both fresh and hardened states of cement paste. The standard tests conducted on different PC–VA and –VPP mixtures provided encouraging results, comparable to those for fly ash (FA) cement, and showed good potential of manufacturing blended Portland volcanic ash cement (PVAC) and Portland volcanic pumice cement (PVPC) with higher setting time and low heat of hydration using up to 20% replacement.

Keywords: Volcanic ash; Volcanic pumice; Blended cement; Strength; Setting time

1. Introduction

The search for alternative binders or cement replacement materials has continued in the last three decades and from the economical, technological and ecological points of view, cement replacement materials play an undisputed role in the construction industry. Comprehensive research has been carried out in the past by Al-Ani and Hughes [1], Mehta [2], Swamy [3,4], Berry and Malhotra [5] and Bilodeau and Malhotra [6] on the use of fly ash (FA), pulverized-fuel ash (PFA), blast furnace slag, rice husk ash, silica fume, etc., as cement replacement materials. Small amounts of inert fillers have always been acceptable as cement replacement. If the fillers have pozzolanic properties, they impart not only technical advantages to the resulting concrete but also enable larger quantities of cement replacement to be achieved. Volcanic ash (VA), volcanic pumice (VP), PFA and FA are pozzolanic materials because of their reaction with lime (calcium hydroxide) that is 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 that is beneficial for mass concrete.

Over recent decades, Portland cements (PCs) containing FA and silica fume have gained increasing acceptance while PC containing natural pozzolans like rice husk ash and burnt oil shale are common in regions where these materials are available. Replacement levels of PC in blended cement containing blast furnace slag vary considerably, and contents of well over 50% by mass are common in some regions. FA typically replaces 10–30% of the PC although levels of 50–60% have been advocated [6]. When silica fume is added, it commonly comprises 5–10% of the binder. ASTM Standards [7–9] exist for the use of natural pozzolans, FA, and silica fume and blast furnace slag in concrete.

Volcanic activities are common in Papua New Guinea and due to frequent volcanic eruption, volcanic debris such as VA and VP are found abundantly. The 1994 volcanic eruption that occurred in the East New Britain province was the second most destructive one in history, which completely devastated the province and created an environmental disaster.

A comprehensive research program was carried out by the PNG University of Technology, with motivation from local cement and construction industries, in an attempt to explore the possible utilization of volcanic debris in cement and concrete production. This could not only provide low-

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Table 1
Comparative study of chemical and physical properties of materials

Chemical compounds	VA	VPP	Paradise cement
Chemical composition (%)			
Calcium oxide (CaO)	6.10	4.44	60–67
Silica (SiO_2)	59.32	60.82	17–25
Alumina (Al_2O_3)	17.54	16.71	3–8
Iron oxide (Fe_2O_3)	7.06	7.04	0.5–6.0
Sulphur trioxide (SO_3)	0.71	0.14	1–3
Magnesia (MgO)	2.55	1.94	0.1–4.0
Sodium oxide (Na_2O)	3.80	5.42	0.5–1.3
Potassium oxide (K_2O)	2.03	2.25	0.5–1.3
Loss on ignition	1.03	1.52	1.22
Chloride	< 0.01	< 0.012	–
Sulphate	0.08–0.68	0.07–0.78	–
Physical properties			
Fineness (m^2/kg)	242	285	320
Residue on 75 μm sieve (%)	42	2.5	0.1–1.5
Specific gravity	–	–	3.5
Unit mass (kg/m^3)	–	–	3150
Bulk density (kg/m^3)	2450[a]	1870[a]	–

[a] Oven dry basis.

cost concrete but could also help to decrease environmental hazards. The research provided useful information on the properties of VA- and VP-based cement, mortar and concrete [10,11]. This paper concentrates on the possible use of VA and volcanic pumice powder (VPP) in blended cement production.

2. Experimental investigation

2.1. Material investigation

The VA and VP used in this investigation were collected from the Rabaul area in the East New Britain province of Papua New Guinea and the source is a volcano called Mount Tavurvur. The Rabaul area is situated in the world-wide earthquake and volcanic zone known as the 'Belt of fire'. The VA was damp when collected and was dried in

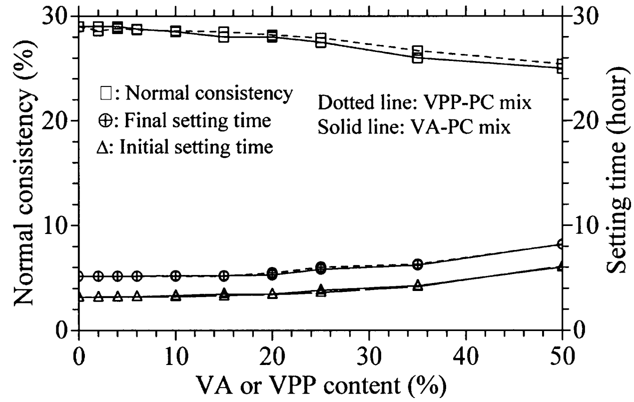

Fig. 1. Effect of VA and VPP on setting time and normal consistency.

open air for about 4 weeks before it was used. The cement used was a locally manufactured ASTM Type I PC called 'Paradise'.

Chemical and physical properties of VA and VP ground to fine powder form (VPP) are compared with those of the Paradise cement in Table 1. Chemical analysis indicated that the VA and VPP have very similar compositions and are principally composed of silica (about 60%) while the main component of cement is calcium oxide (maximum 65%). Both VA and VPP have compounds such as calcium oxide, alumina and iron oxide (total about 31%). The amount of oxides of sodium and potassium known as 'alkalis' is found to be higher in VA (5.83%) and VPP (7.69%) than that in cement (2.6% maximum). Higher alkali presence in the VA and VPP, if present in soluble forms, may have deleterious effects leading to disintegration of concrete due to reaction with some aggregate and may affect the rate of gain in strength of cement.

Dry sieve analysis for VA was carried out according to Australian Standard (AS) 1141.11:1996 [12] and results show that the VA is composed of a sandy fraction of about 42% and the remaining 58% is made up of silty fraction. VA (fineness of 242 m^2/kg) is found to be much coarser than cement (fineness of 320 m^2/kg), which may lead to an

Table 2
Effect of VA and VPP on the properties of cement and mortar

Mix details	Normal consistency (%)		Setting time (h)				Compressive strength of mortar (MPa)							
			Initial		Final		Age (days)				Age (days)			
	VA	VPP	VA	VPP	VA	VPP	VA				VPP			
							1	3	7	28	1	3	7	28
100–0	29.0	29.0	3.15	3.15	5.15	5.15	10.6	21.6	28.6	37.5	10.6	21.6	28.6	37.5
98–2	29.0	28.6	3.15	3.16	5.15	5.15	10.0	19.9	27.1	36.0	9.9	18.6	26.4	34.5
96–4	29.0	28.8	3.15	3.18	5.15	5.15	9.4	19.3	27.2	35.6	9.7	18.4	26.7	34.9
94–6	28.8	28.7	3.20	3.20	5.15	5.15	9.0	18.9	26.5	34.7	9.5	18.6	26.6	34.8
90–10	28.5	28.6	3.30	3.20	5.15	5.20	9.1	18.4	26.6	35.1	9.3	18.3	26.1	34.2
85–15	28.0	28.5	3.45	3.30	5.15	5.20	8.7	18.1	24.2	29.6	8.9	18.0	25.6	33.2
80–20	28.0	28.2	3.45	3.40	5.45	5.25	8.3	17.8	25.9	33.9	8.4	16.7	22.9	30.0
75–25	27.5	27.9	3.80	3.60	6.00	5.80	7.9	17.0	22.4	26.7	8.0	15.9	22.1	28.4
65–35	26.0	26.7	4.25	4.15	6.30	6.20	7.1	15.5	21.3	23.9	7.5	15.1	21.1	24.3
50–50	25.0	25.4	6.00	6.10	8.15	8.20	4.2	6.4	8.1	16.5	5.1	7.4	9.2	16.4

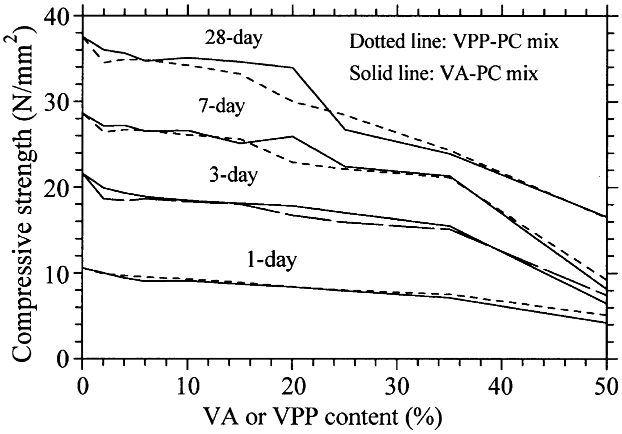

Fig. 2. Effect of VA and VPP on the strength.

increase in setting time. The fineness of VPP (for this study, fineness of 285 m^2/kg is used) can be controlled by the user during the grinding process. The fineness of VA can also be increased or controlled by removing a percentage of the sandy fraction from the original sample before blending with cement or by grinding the material to a finer particle size. The unit mass and bulk density revealed that the VPP is much lighter than VA and cement. The replacement of cement by these materials on a mass basis will increase the volume and decrease the density of blended paste compared to pure cement paste. This can influence the properties of the hardened and fresh pastes.

2.2. Tests on cement–VA and cement–VPP mixtures

A series of tests were carried out on cement paste to study the effects of VA and VPP on the normal consistency and setting times. Ten mixtures having different % of VA and VPP, ranging from 0 to 50% by mass, were used. Three tests were carried out for each item in each mixture. Tests were performed according to AS/NZS 2350.3:1999 [13] and AS/NZS 2350.4:1999 [14]. The mix details and test results are presented in Table 2. The first numeric in the mix designation represents % of cement and the second numeric represents % of VA or VPP. The normal consistency and setting time values in Table 2 are the mean values of three test results.

The same mixtures were used to study the effect of VA and VPP on the compressive strength of mortars. Mortar cubes were manufactured with standard Leighton Buzzard sand. Standard 70-mm cubes (Cement + VA or VPP/sand = 1:3 by mass) were cast strictly following the AS/NZS 2350.11:1977 [15]. The water used in each mortar mix was that derived from normal consistency of that mix as presented in Table 2. The cubes were removed from the mould after 24 h and then cured under water until they were tested immediately after removal from water while still wet. The compressive strengths (average of four tests for a particular age) for each mix are presented in Table 2.

3. Results and discussion

3.1. Effect on normal consistency and setting time of cement

The variation of normal consistency with different percentage of VA and VPP are presented in Fig. 1. The normal consistency is decreased by 13.8% for VA and by 12.4% for VPP when the VA or VPP content varied from 0 to 50%. The normal consistency is decreased by 3.79% when the VPP content is increased from 0 to 25% compared to 5.17% in the case of VA. The decrease in normal consistency is due to the reduction of cementitious binder in the fresh mixture with the increase of VA or VPP content. On the other hand, specific gravity of VA or VPP is less than that of cement, which resulted in the larger volume of VA or VPP compared to the volume of cement replaced as the replacement was made by mass. As a result, the overall volume was increased needing more water to form a paste of same consistency for different % of VA and VPP in the mixture.

The variation of setting times with the percentage of VA and VPP is also presented in Fig. 1. The trend shows an increase in both setting times with the increase of VA or VPP content. Initial setting time is increased by 90% (compared to 93.7% in VPP) and final setting time is increased by 58% (compared to 59.2% in VPP) while the VA content is increased from 0 to 50%. For the case of VPP, initial setting time is increased by 14.28% (compared to 20.6% in VA) and final setting time is increased by 12.62% (compared to 16.5% in VA) when VPP content is increased from 0 to 25%. This is reasonable as the increase of VA or VPP content reduces the cement content in the mixture and also decreases the surface area of the cement. As a result, the hydration process slows down causing setting time to increase. The slow hydration means low rate of heat development. This is of great importance in mass concrete construction, for which Portland volcanic ash cement (PVAC) or Portland volcanic pumice cement (PVPC) can be mostly used, besides other general use.

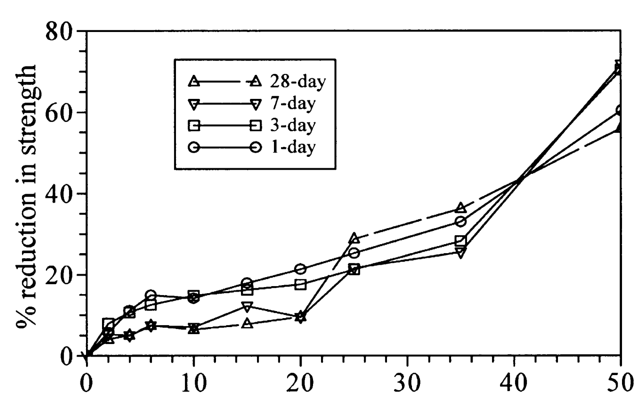

Fig. 3. Effect of VA on the compressive strength.

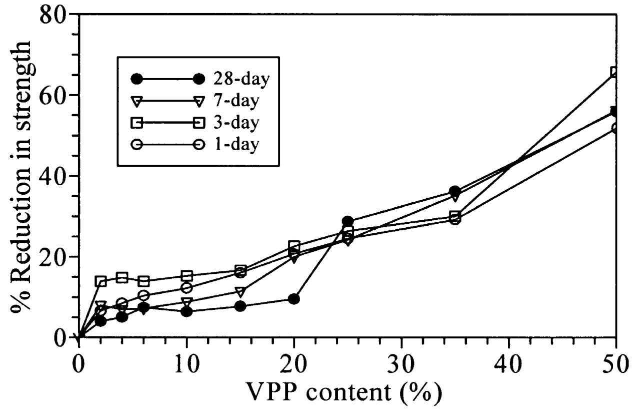

Fig. 4. Effect of VPP on the compressive strength.

3.2. Effect on strength

The variation in the compressive strength is shown in Fig. 2. The compressive strength is found to decrease with an increase of VA or VP content. This is reasonable due to the reduction of cement content in the mix with the increase of VA or VPP content. The finely divided silica (61%) in VA or VPP can combine with calcium hydroxide (liberated by the hydrating PC) in the presence of water [16] to form stable compounds such as calcium silicates, which have cementitious properties. Such pozzolanic action of VA or VPP contributes to the enhancement of strength and long-term durability [16] although the reduction of strength in blended cement due to cement replacement by VA or VPP is not compensated in the current study.

The reduction in strength with the increase of VA content is presented in Fig. 3. It can be seen that the strength is reduced by 21% (1 day), 18% (3 days) and 9.5% (7 and 28 days) when VA content varies from 0 to 20%. Strength reductions at 35% VA are 19% (7 days) and 31% (28 days) while at 50% VA, the reductions are 70% (7 days) and 52% (28 days).

The VPP mixtures also show a similar pattern of strength variation. It can be seen from Fig. 4 that the strength is reduced by 26% (1-day strength), 26.4% (3 days), 22.7% (7 days) and 24.2% (28 days) when VPP content varies from 0 to 25%. The strength is reduced to a large extent when VA content exceeds 35%.

Tests were also carried out considering the practical circumstances to guess how much mortar strength is possible to obtain when locally available sand is used. Results confirmed that it is possible to obtain a mortar having a strength of 21 MPa (7 days) and 24 MPa (28 days) using locally available sand and replacing 35% of cement by VA or VPP.

4. Recommendation for blended cement production

The properties of PC–VA mixtures and PC–VPP mixtures are compared to the requirements of PC and blended Portland fly ash cement (PFAC) according to AS 3972:1997 [17] in Table 3. The setting time satisfies the requirements of both PC and PFAC. The compressive strength of the 20% VA mixture satisfies the requirements of both Type C PC and Type FC of PFAC. Fineness index of the mixture does not satisfy the requirements of PC but certainly satisfies the requirement of PFAC. On the other

Table 3
Assessment of feasibility of VA and VPP based blended cement manufacture

Items	Requirement for PVFAC [17]		Requirement for PC [17]				Test data for PVAC		Test data for PVPC	
Setting time	Both Types FA and FC		Types A, B, C and D				20%VA	50%VA	15%VPP	20%VPP
	Initial set: $\geq$1 h		Initial set: $\geq$1 h				3.45 h	6.00 h	3.30 h	6.10 h
	Final set: $\leq$12 h		Final set: $\leq$12 h				5.45 h	8.15 h	5.20 h	8.20 h
Test method	[13,14]		[13,14]				[13,14]		[13,14]	
Compressive strength (MPa)	Minimum strength		Minimum strength				VA content		VPP content	
	Type FA	Type FC	Type A	Type B	Type C	Type D	20%	>20%	15%	>15%
3 days	20	18	20	28	18	20	18	<18	18	<17
7 days	32	25	32	38	25	28	26	<26	25.6	<25
28 days	45	32	45	52	32	38	34	<34	33.2	<33
Test method	[15]		[15]				[15]		[15]	
Fineness index	Types FA and FC		For all types				For VA		For VPP	
	Amount retained on 45 μm sieve maximum 25%		Not less than 280 m^2/kg and not more than 420 m^2/kg				Fineness of 242 m^2/kg		Fineness of 285 m^2/kg	
Test method	[18]		[19]				[19]		[19]	

hand, the compressive strength of 15% VPP mixture satisfies the requirements of both Type C PC and Type FC of PFAC. Fineness index of the mixture also satisfies the requirements.

It is possible to manufacture blended PVAC and PVPC equivalent to Type FC PFAC using up to 20% VA and 15% VPP, respectively. However, due to an increase of setting time, the heat of hydration in both PVAC and PVPC should be less than normal PC.

5. Conclusions

The results suggest that the normal consistency and setting time of PC are affected by the replacement of cement by VA and VPP. Manufacture of PVAC and PVPC similar to PFAC of type FC [17] is possible with maximum replacement of up to 20%. A possible use of this PVAC and PVPC will be in mass concrete construction due to lower heat of hydration and higher setting time compared to PC. The PNG Halla cement factory has implemented the recommendation of the research and started the production of PVAC and PVPC. PVPAC or PVPC can only be used if they meet the requirement of the specific job, including strength and durability. The latter has not been discussed in this paper. However, the beneficial effects of VA and VPP on the long-term durability of concrete are reported [16,20,21]. A campaign in the form of poster, pamphlet and advertisements is conducted to market the blended cements and to build consumer confidence. Cheaper and environmentally friendly PVPC and PVAC are now in use in the rehabilitation projects of volcanic areas of Papua New Guinea.

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