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Cement and Concrete Research 35 (2005) 1141–1144

Cement and Concrete Research

Volcanic ash and pumice as cement additives: pozzolanic, alkali-silica reaction and autoclave expansion characteristics

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Received 2 February 2004; accepted 20 September 2004

Abstract

This study reports the results of investigation to assess the suitability of volcanic ash (VA) and pumice (VP) powder to be used as cement additives. Pozzolanic activity of VA and VP was tested according to the Italian standard and found to be acceptable. The strength activity index with Portland cement and the effectiveness of VA and VP admixture in controlling alkali-silica reaction and autoclave expansion were tested according to ASTM standards. Mortar cubes were specially prepared as per ASTM standards for these studies using different mixes with varying percentages of VA and VP (0–40%) as cement replacement. The results are then compared with ASTM requirements to assess the suitability of VA or VP as cement additives.

Keywords: Volcanic ash; Volcanic pumice; Pozzolan; Alkali-silica reaction; Autoclave expansion; Cement additive

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 on the use of fly ash (FA), pulverized-fuel ash (PFA), blast furnace slag (BFS), rice husk ash, silica fume (SF), etc., as cement replacement materials [1–6]. 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. PFA and FA are pozzolanic materials, because of their reaction with lime that is liberated during the hydration of cement. Amorphous silica present in the pozzolanic materials combines with lime (Calcium hydroxide) 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 containing fly ash and silica fume have gained increasing acceptance whilst Portland cement 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 [7,8,9] exist for the use of natural pozzolans, fly ash, and silica fume and blast furnace slag in concrete.

Volcanic activities are common in various parts of the world and due to frequent volcanic eruption, volcanic debris such as: volcanic ash and pumice are found abundantly. The 1994 volcanic eruption that occurred in the East New Britain province of Papua New Guinea was the second most destructive one in history, which completely devastated the

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doi:10.1016/j.cemconres.2004.09.025

province and created an environmental disaster. A comprehensive research program was carried out 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 cost concrete but also help to decrease environmental hazards.

The research provided useful information on the properties of VA and VP based cement, mortar and concrete [10–13]. Research suggested the manufacture of blended PVAC (Portland volcanic ash cement) and PVPC (Portland volcanic pumice cement) similar to PFAC (Portland fly ash cement) with maximum replacement of up to 20% [11]. Durability of concrete is one of its most important desirable properties and it is essential that the concrete made with VA and VP blended cement should be capable of preserving its durability throughout the life of structures like other pozzolanic concretes made with SF, FA, PFA and BFS [13]. Hence it is very important to know the pozzolanic, alkali-silica reaction and autoclave expansion characteristics of volcanic ash (VA) and finely ground volcanic pumice (VP) to evaluate their potential use as cement additives and this paper will concentrate on these issues.

2. Experimental investigation

2.1. Material investigation

Volcanic ash (VA) and volcanic pumice (VP) used in this investigation were collected from the Rabaul area in the East New Britain province of Papua New Guinea 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'. The cement used was a locally manufactured ASTM Type I Portland cement (PC) called 'Paradise'.

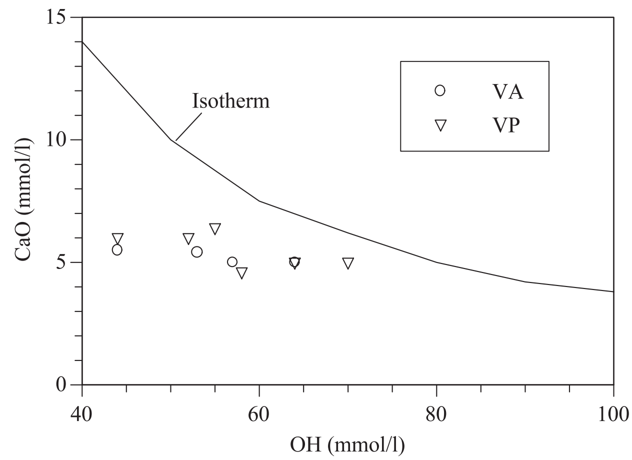

Fig. 1. Pozzolanic activity test of VA and VP.

Chemical and physical properties of VA and finely ground VP are compared with those of PC in Table 1. Chemical analysis indicated that VA and VP have very similar compositions and are principally composed of silica (about 60%) while the main components of PC are calcium oxide (maximum 65%). Both VA and VP have compounds like 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 VP (7.69%) than that in cement (2.6% maximum). Higher alkali presence in the VA and VP may have deleterious effects leading to disintegration of concrete due to reaction with some aggregate and affect the rate of gain in strength of cement.

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 increase in setting time. The fineness of VP (for current research, fineness of 285 m^2/kg is used) can be controlled by the user during the grinding process. The unit mass and bulk density revealed that the VP is much lighter than VA and cement.

Table 1
Comparative study of chemical and physical properties

Chemical compounds	VA (%)	VP (%)	PC (%)
Chemical composition			
Calcium oxide (CaO)	6.10	4.44	60–67
Silica (SiO_2)	59.32	60.82	17–25
Alumina (Al2O$_3$)	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
Physical properties			
Fineness, m^2/kg	242	285	320
Compressive strength of 50 mm cubes, MPa			
7-day			26
28-day			32
Specific gravity			3.15
Unit mass, kg/m^3			3150
Bulk density, kg/m^3	2450[a]	1870[a]	–

[a] Oven dry basis.

2.2. Pumice and volcanic ash as pozzolanic materials

VA and VP have the potential to be used as additives to Portland cement for the manufacture of blended cements

Table 2
Effect of VA and VP on the alkali-silica reaction

VA or VP content (%)	VP		VA	
	Length change (mm)	Expansion (%)	Length change (mm)	Expansion (%)
0 (control mix)	0.089		0.089	
10	0.115	129	0.101	113
20	0.095	105	0.088	99
30	0.087	98	0.082	92
40	0.081	91	0.075	84

Table 3
Effect of VA and VP on the autoclave expansion

VA or VP content (%)	VP	VA
	Autoclave expansion (%)	
0 (control mix)	0.40	0.40
10	0.28	0.25
20	0.24	0.21
30	0.19	0.17
40	0.16	0.14

like other pozzolanic materials such as fly ash [11,12]. Several tests were conducted to study the suitability of VP and VA as pozzolanic materials.

The pozzolanic activity of VP and VA was tested according to the Italian Standards [14] where the samples were mixed with cement and water and kept for 1–2 weeks. The total alkalinity (OH^-) and lime concentration (CaO) is then measured. The material is considered pozzolanically active if the level of concentration falls below the lime solubility isotherm (Fig. 1). The results indicate that all VP and VA samples fall below the lime solubility isotherm and are therefore pozzolanically active. Being pozzolanically active, VP and VA have cementitious characteristic and can economically be used as a cement additive to manufacture blended cement.

2.3. Pumice and volcanic ash as cement additives

2.3.1. Alkali-silica reaction

Tests were performed to determine the effect of ground VP and natural VA on the expansion caused by the alkali-silica reactions. The test was performed, with some modification, according to ASTM C 311 [15], which requires a control mixture to be prepared with 400 g of low alkali cement, 900 g of borosilicate glass and water to obtain a flow of 100–115%. The test mixes on the other hand, used Portland cement (ASTM type I), clean silica sand instead of borosilicate glass and finely ground pumice or natural VA passing through 45 μm sieve. The VP and VA replaced the Portland cement by 10%, 20%, 30% and 40% (by mass) in four different mixes. Mortar cubes, 50×50 mm in dimensions, were prepared from these mixes and stored in temperature around 38±2 °C. The cube lengths were measured periodically to the nearest 0.002 mm for 14 days. The average expansion values of the cubes on day 14 as compared to the lengths recorded on day 1 are given in Table 2. The ASTM C 618 [16] requires that, for the effectiveness in the alkali-silica reactions, the expansion (the ratio between the length change of the test mix and that of the control mix) at day 14 should have a maximum value of 100%. Mix 1 with 10% VP or VA content showed the maximum length change and the highest reduction in length value. Mixes with 30 and 40% VP or VA content, on the other hand, satisfy the ASTM C 618 [16] requirement.

2.3.2. Autoclave expansion

The autoclave expansion test provides an index of potential delayed expansion caused by the hydration of CaO, or MgO, or both, when present in the Portland cement. This test was performed in accordance with ASTM C 151-00 [17]. In this study, in addition to the control mix, four other mixes with 10%, 20%, 30% and 40% of the cement replaced by finely ground VP and natural VA passing through 45 μm sieve were tested. The control mix had 650 g of Portland cement (ASTM type I) and sufficient water to give a paste of normal consistency in accordance with the procedure described in ASTM C 187-98 [18]. Cubes, 25×25 mm in dimensions, were prepared from these paste mixes. The change in length of the test specimens was calculated by subtracting the length comparator reading before autoclaving from that after autoclaving, and reported as percent of effective gage length to the nearest 0.01%. The test results are presented in Table 3. The autoclave expansion of the paste mixes decreased with the increase of VP and VA content. All mixes containing up to 40% VP or VA, satisfy the ASTM C 618 [16] requirement of 0.8% maximum.

2.3.3. Strength activity index

The strength activity index test was performed on VP and VA materials using a slightly modified form of ASTM C 311[15], which calls for the replacement of the cement in the mortar mix, by 20% of VP or VA. In this study, in addition to the control mix, four other mixes with 10%, 20%, 30% and 40% of the cement replaced by finely ground VP and natural VA passing through 45 μm sieve. The control mix had 500 g of Portland cement (ASTM type I), 1375 g of graded standard sand and 242 ml of water. Mortar cubes, 50×50 mm in dimensions, were prepared from these mixes and stored in a saturated limewater solution until

Table 4
Compressive strength and strength activity index (SAI) of the mixes

VP and VA content (%)	VP				VA			
	Avg. strength (MPa)		SAI (%)		Avg. strength (MPa)		SAI (%)	
	7 days	28 days	7d	28 days	7 days	28 days	7 days	28 days
0 (control mix)	27	36	–	–	27	36	–	–
10	26	34	96	94	27	36	100	100
20	23	30	85	83	26	34	96	94
30	22	28	81	78	22	27	81	75
40	21	24	78	67	21	24	78	67

tested for their uniaxial compressive strengths at 7 and 28 days. The results are presented in Table 4. It is found that the compressive strength generally decreases with the increase in the VP or VA content. The strength activity index (SAI), which is the ratio between the strength of the tested samples and the strength of the control samples, is calculated at 7 and 28 days (Table 4). The SAI value ranges between 78% and 100% at 7 days and between 67% and 100% at 28 days. SAI values for mixes with 10%, 20% and 30% VA or VP content are more than 75% as required by ASTM C 618 [16].

3. Conclusions

The effect of volcanic ash (VA) and finely ground volcanic pumice (VP) in controlling the alkali-silica reaction shows that the value for 10% VA or VP mix is much higher than the value of 100% required as per ASTM C618 [16]. Mixes with 30% and 40% VA or VP mix satisfy this requirement. Strength activity index (SAI) values for mixes with 10%, 20% and 30% VA or VP content are more than 75% and satisfy the requirement of ASTM C 618 (16). The SAI value for 40% VA or VP mix, on the other hand, does not satisfy the ASTM C 618 [16] requirement. It is then safe to conclude that the mixes with 10% and 40% VA or VP can not be recommended as additives. The compressive strength values of the mixes with 30% and 40% VA or VP are significantly reduced because of the presence of VA and VP. The mix with a 20% VA or VP content, reasonably compromises all the required criteria. It shows a relatively reasonable expansion value and a reasonable compressive strength value. This study recommends the use of 20% VA or VP as a cement additive.

Acknowledgement

The author is grateful to the Papua New Guinea University of Technology and PNG Ready Mixed Concrete for providing assistance in this project. The author is also grateful to the Technical staffs of the materials laboratory of the Department of Civil Engineering and National Analysis laboratory. Assistance of the PNG Halla Cement Factory and The PNG Department of Works is appreciated.

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