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Cement and Concrete Research 34 (2004) 283–291

CEMENT AND CONCRETE RESEARCH

Properties of volcanic pumice based cement and lightweight concrete

Khandaker M. Anwar Hossain*

Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3

Received 19 November 2002; accepted 1 August 2003

Abstract

The results of investigations on the suitability of using volcanic pumice (VP) as cement replacement material and as coarse aggregate in lightweight concrete production are reported. Tests were conducted on cement by replacing 0% to 25% of cement by weight and on concrete by replacing 0% to 100% of coarse aggregate by volume. The physical and chemical properties of VP are critically reviewed to evaluate the possible influence on both fresh and hardened state of cement and concrete. The standard tests on different Portland cement–volcanic pumice powder (VPP) mixes provided encouraging results and showed good potential of manufacturing Portland volcanic pumice cement (PVPC) with higher setting time using up to 15% of VPP. The properties of volcanic pumice concrete (VPC) using different percentages of volcanic pumice aggregate (VPA) were evaluated by conducting comprehensive series of tests on workability, strength, drying shrinkage, surface absorption and water permeability. It is concluded that the VPC has sufficient strength and adequate density to be accepted as structural lightweight concrete. However, compared to control concrete, the VPC has lower modulus of elasticity and has more permeability and initial surface absorption.

Keywords: Volcanic pumice; Lightweight structural concrete; Blended cement; Shrinkage-permeability; Strength

1. Introduction

Pumice is a natural material of volcanic origin produced by the release of gases during the solidification of lava. The cellular structure of pumice is created by the formation of bubbles or air voids when gases contained in the molten lava flowing from volcanoes become trapped on cooling. The cells are elongated and parallel to one another and are sometimes interconnected. Volcanic pumice (VP) has been used as aggregate in the production of lightweight concrete in many countries of the world. So far, the use of pumice was dependent on the availability and limited to the countries where it is locally available or easily imported. Satisfactory concrete [1] which is two to three times lighter than normal concrete having good insulating characteristics with high absorption and shrinkage can be manufactured using VP.

VP and volcanic ash (VA) like fly ash (FA) are pozzolanic materials because of their reaction with lime liberated during the hydration of cement [2]. Amorphous silica present in the pozzolanic materials combines with lime (calcium hydroxide) and forms cementitious materials. Jackson [2] stated that pozzolanic cement could be made by replacing up to 40% of cement by pozzolanic 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. Comprehensive research had been carried out in the past on the use of FA, pulverized-fuel ash (PFA), blast furnace slag, rice husk ash, silica fume, etc. as cement replacement material [3–9].

Over recent decades Portland cements containing FA 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 cements containing blast furnace slag vary considerably with contents of well over 50% by weight common in some regions. FA typically replaces 10–30% of the Portland cement although levels of 50–60% have been advocated [8]. While silica fume is added, it commonly comprises 5–10% of the binder. ASTM Standards [10–12] exist for the use of natural pozzolans, FA, and silica fume and blast furnace slag in concrete.

Researches had been conducted worldwide on a large number of natural or artificial lightweight aggregates such

* Tel.: +1-416-979-5000x7867; fax: +1-416-979-5122.
E-mail addresses: dr_k_m_hossain@hotmail.com, ahossain@ryerson.ca (K.M. Anwar Hossain).

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doi:10.1016/j.cemconres.2003.08.004

as Bamboo reinforced, oil palm shells, bottom ash, starch-based aggregate, etc. [13–18]. The mix design of lightweight concrete used for structural purposes is more complicated because it depends on the type of lightweight aggregate. The use of a local product depends on its specific properties and the requirements for a particular job.

Volcanic activities are common phenomena in various parts of the world especially for a country like Papua New Guinea [19]. 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 devastated the province and created an environmental disaster. This research is an attempt to explore the possible utilization of volcanic debris in construction, which cannot only provide low cost cement and concrete but also, can help to decrease environmental hazard.

This paper is focused on the development of VP-based blended cement and lightweight concrete. It also evaluates and presents the properties of such cement and concrete with recommendation for construction and manufacturing industries.

Table 1
Comparative study of chemical and physical properties

Chemical compound	Chemical composition		
	Volcanic pumice	ASTM C618 requirement for fly ash (Class F)	Paradise cement: ASTM Type I
	%	%	%
Calcium oxide (CaO)	4.44	–	60–67
Silica (SiO_2)	60.82	–	17–25
Alumina (Al_2O_3)	16.71	–	3–8
Iron oxide (Fe_2O_3)	7.04	–	0.5–6.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	84.5	minimum = 70	
Sulphur trioxide (SO_3)	0.14	maximum = 5.0	1–3
Magnesia (MgO)	1.94	maximum = 5.0	0.1–4.0
Sodium oxide (Na_2O)	5.42	–	0.5–1.3
Potassium oxide (K_2O)	2.25	–	0.5–1.3
Loss on ignition	1.52	maximum = 6.0	1.22
	Physical	Properties	
Fineness, m^2/kg	295	–	320
Residue on 75 μm sieve	2.5%	–	0.1–1.5%
Sp. gravity	–	–	3.5
Unit mass, kg/m^3	–	–	3150
Bulk density, kg/m^3	870 **	–	–

** Oven dry basis.

2. Experimental details

Experimental program was classified into three groups consisting of investigations on materials used, cement and concrete.

2.1. Material investigation

VP used in this investigation was collected from Mount Tavurvur and Vulcan craters located in the Rabaul area of the East New Britain province of Papua New Guinea. The Rabaul area is situated in the worldwide earthquake and volcanic zone known as the 'Belt of fire'.

The cement used was locally manufactured ASTM Type I Portland cement called 'Paradise'. The aggregates used were 20 mm maximum size crushed gravel, 20 mm maximum size volcanic pumice and local river sand. Clean drinking water was for the mixes.

Chemical and physical properties of VP are compared with those of Paradise cement in Table 1. Chemical analysis indicates that the VP is principally composed of silica (about 61%) while the main components of cement is calcium oxide (maximum 70%). VP has cementitious compounds like calcium oxide, alumina and iron oxide (total about 30%). The amount of oxides of sodium and potassium known as 'alkalis' is found to be higher in VP (7.67%) than that in cement (2.6% maximum). Higher alkali presence in the 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.

VP was grinded to fine powder comparable to cement and Table 1 compares the fineness of VP powder (VPP) with those of cement. VPP is found to be coarser than cement, which may lead to the increase of setting time.

The properties of normal crushed gravel aggregates are compared with those of VP aggregate (VPA) and summarized in Table 2. The bulk density results suggest that the VPA is much lighter than normal aggregate. The oven dry density of around 760 kg/m^3 of VPA is very much similar [1] to lightweight sintered expanded shale and clay aggregates having a density of 650 to 900 kg/m^3. As per ASTM C 330 [20], VPA satisfies the requirement of lightweight coarse aggregate for structural concrete as the oven dry density falls within the range of 560 to 1120 kg/m^3. However, the water absorption in VPA is higher (37%) than the range of 5% to 20% as normally occurred in other lightweight aggregates [21]. High water absorption also indicates high degree of porosity in VPA.

The high abrasion value indicates the low strength of VPA. The particle size distributions were performed according to Australian Standard [22] and ASTM C 136-01 [23] and presented in Table 3. Grading of VPA, meet the requirement of lightweight aggregate for structural concrete as per ASTM C 330-00 [20].

2.2. Investigation on blended cement incorporating VPP

A series of tests had been carried out on ASTM Type I Portland cement to study the effect of VPP on the setting times. Total eight mixes having different percentage of VPP ranging from 0% to 25% by weight were used. Three tests for each item in each mix were carried out. Tests were performed according to the Australian standard [24]. The mix designations (numeric before C represents percentage

Table 2
Properties of aggregates

Materials	Bulk density (kg/m^3)		Loss angles abrasion %	Absorption 24 h (%)
	SSD	Oven dry		
20 mm aggregate	2540	2470	–	2.86
River sand	2660	2610	–	2.04
VP aggregate	1183	763	61.2	37

of cement and numeric before VPP represents percentage of VPP), proportions and test results are presented in Table 4. The setting time values in Table 3 are the mean values of three test results.

The compressive strength of blended cement mixes was determined by testing standard 70-mm mortar (Cement + VPP: sand = 1:3 by weight) cubes strictly following Australian Standard [25], using Leighton Buzzard sand. 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 the mixes are presented in Table 4.

2.3. Investigation on volcanic pumice concrete (VPC) using VPA

This series of tests were performed to investigate the effect of different percentages of VPA on the strength, modulus of elasticity, shrinkage, permeability and other properties of VPC. The concrete mixes had the over all ratio of 1:2:3 and 1:2:4 (cement–fine aggregate–coarse aggregate) on the volume basis. Each of the two mixes is classified into five submixes according to the percentage of VPA as a replacement of normal coarse aggregate (by volume). The coarse aggregate consisted of 20-mm maximum crushed gravel and VPA with river sand as fine aggregate. The coarse aggregates were made saturated surface dry before casting of concrete. This is very important for VPA as it had higher absorption rate. The mix parameters and some characteristics of the fresh concrete are presented in Table 5. The first letter in the mix designation represents submix ID, first numeric represents percentage of VPA of total coarse aggregate by volume, second numeric represents percentage of VPA of total aggregate by weight and the third numeric represents total aggregate cement ratio by weight. The water to cement ratio (w/c) of all the mixes was kept constant at 0.45 by weight.

Table 3
Grading of aggregates

Sieve opening (mm)	Coarse aggregate (% finer)			Fine aggregate (% finer)
	Lightweight		Normal weight	Sand
	VPA	ASTM C-330 [20]	Crushed gravel	
25	100	95–100	100	
19	90	–	94	
12.5	58	25–60	50	
9.5	30	–	28	100
4.75	12	0–10	10	93
2.36				70
1.18				51
300				20
150				15

Table 4
Effect of VPP on the properties of blended cement

Mix designation	% VPP	Blended cement properties					
		Setting initial hours	Time final hours	Compressive strength			
				Age in days			
				1	3	7	28
0C0VPP	0	3.15	5.15	10.6	21.6	28.6	37.5
98C2VPP	2	3.16	5.15	9.9	18.6	26.4	34.5
96C4VPP	4	3.18	5.15	9.7	18.4	26.7	34.9
94C6VPP	6	3.20	5.15	9.5	18.6	26.6	34.8
90C10VPP	10	3.20	5.20	9.3	18.3	26.1	34.2
85C15VPP	15	3.30	5.20	8.9	17.2	25.6	33.2
80C20VPP	20	3.40	5.40	8.4	16.3	22.9	30.0
75C25VPP	25	3.60	5.80	8.0	15.9	22.1	28.4

2.3.1. Investigation on fresh VPC

The effect of VPA on the workability of different fresh VPC mixes was studied by conducting slump tests as per ASTM C 143 [26]. The slump values are tabulated in Table 5 for different submixes. The air content of the mixes was determined by pressure meter as per ASTM C 231 [27] and presented in Table 5. The air content ranges between 2.8% and 4.5%.

2.3.2. Investigation on hardened VPC

The test specimens were 100 mm cubes as per BS1881-part 116 [28] and 150 × 300 mm cylinders as per ASTM C-39 [29] for compressive strength while 150 × 300 mm cylinders were used for indirect tensile strengths as per ASTM C-496 [30]. Total four cubes and six cylinders were

Table 5
VPC mix details

Mix designation	VPA kg/m^3	20 mm aggregate kg/m^3	Slump mm	Air content %
VPC mix 1 = 1:2:3 by volume; cement (C) = 490 kg/m^3; w/c = 0.45; sand = 810 kg/m^3				
A: 100–36.9–2.38	360	0	60	4.2
B: 90–25.6–2.55	320	120	64	3.7
C: 75–19.4–2.80	270	300	70	3.6
D: 50–11.3–3.22	180	590	76	3.2
E: 0–0–4.07	0	1190	84	2.8
VPC mix 2 = 1:2:4 by volume; cement = 430 kg/m^3; w/c = 0.45; sand = 700 kg/m^3				
P: 100–36.9–2.62	410	0	52	4.5
Q: 90–30.6–2.85	370	140	58	3.9
R: 75–22.8–3.18	310	345	64	3.7
S: 50–12.9–3.75	205	690	72	3.5
T: 0–0–4.87	0	1370	80	3.0

Table 6
Strength, modulus of elasticity and density of VPC

Mix designation	28 day strength, MPa			Modulus of elasticity (kN/mm^2)	Dry density (kg/m^3)
	Compressive		Tensile		
	Cylinder	Cube	Split cylinder		
VPC Mix 1 = 1:2:3					
A: 100–36.9–2.38	22	28	2.6	10.5	1852
B: 90–25.6–2.55	25	30	2.9	11.0	1940
C: 75–19.4–2.80	27	32	3.0	12.0	1990
D: 50–11.3–3.22	29	36	3.5	14.5	2158
E: 0–0–4.07	35	40	3.7	21.2	2515
VPC Mix 2 = 1:2:4					
P: 100–36.9–2.62	18	24	2.2	10.0	1831
Q: 90–30.6–2.85	23	25	2.0	11.9	1908
R: 75–22.8–3.18	25	28	2.6	12.2	1970
S: 50–12.9–3.75	28	36	3.2	14.5	2145
T: 0–0–4.87	34	40	3.4	20.7	2475

cast from each submix. Three shrinkage specimens 75 × 75 × 285 mm and two cylinders (100 × 200 mm) for permeability tests were also cast for each sub mix. In addition, 100 mm cubes and 100 × 200 mm cylinders were also cast for initial surface absorption and modulus of elasticity tests, respectively. All the specimens were compacted by external vibration using a table vibrator.

The specimens were demoulded 24 h after casting and cured under water at a temperature of 23 ± 2 °C until testing at 28 days. The shrinkage specimens were cured 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 Australian Standard [31] similar to ASTM C-157 [32] at 7,14, 28, 56 and 91 days.

The 91-day water permeability of the 100 × 200 mm cylinder specimens was determined after 1 day of moist and 90 days of air curing by applying 20 MPa of water pressure in a hydraulic permeability test apparatus [21].

Four cubes and three cylinders for compressive strength and three cylinders for tensile strength were tested at an age of 28 day. All strength results (mean values) are included in Table 6.

Initial surface absorption test was conducted by using 150-mm cubes as per BS 1881, Part 5, Clause 6.3.2.1 as non-oven dried [33]. The modulus of elasticity was determined as per ASTM C 469-87a [34].

3. Results and discussion

3.1. Properties of blended cement incorporating VPP

3.1.1. Setting times

The initial and final setting times of blended cement mixes are presented in Table 4. The trend of variation of setting times shows an increase of both setting times with the increase of VPP content. Initial setting time is increased by 14.2% and final setting time is increased by 12.6% while the VPP content is increased from 0% to 25%. Initial setting time is increased from 3.15 to 3.60 h while final setting time is increased from 5.15 to 5.80 h. This is reasonable as the increase of VPP content reduces the cement content in the mix and also decreases the surface area of the cement. As a result hydration process slows down causing setting time to increase. The slow hydration means low rate of heat development [35]. This is of great importance in mass concrete construction and it is there that Portland volcanic pumice cement (PVPC) or a partial replacement of Portland cement by VPP can be mostly used.

3.1.2. Compressive strength

The compressive strength is found to decrease (Table 4) with the increase of VPP content and more than 25% reduction in strength is observed at 25% replacement compared to 0% VPP. This is reasonable due to the reduction of cement content in the mix with the increase of VPP content. The finely divided silica (61%) in VPP can combine with calcium hydroxide (liberated by the hydrating Portland cement) in the presence of water [36] to form stable compounds like calcium silicates, which have cementitious properties. Such pozzolanic action of VPP contributes to the enhancement of strength and long-term durability [36] although the reduction of strength in blended cement due to cement replacement by VPP is not compensated in the current study.

The strength is reduced by 26% (1-day strength), 26.4% (3-day), 22.7% (7-day) and 24.2% (28-day) when VPP content is varied from 0% to 25%. The strength reduction is decreased with the increase of age.

3.2. Fresh properties of VPC

The variation of slump for mixes having different percentages of VPA is presented in Table 5. The high absorption of water by VPA in the initial stages of mixing, can cause balling-up of cement and a loss of slump [35]. To avoid this, the aggregate was made saturated surface dry before casting of concrete.

The slump values for mixes with similar w/c of 0.45 are found to decrease (84 to 60 mm for Mix 1 and 80 to 52 mm for Mix 2) with the increase of % of VPA in the submixes from 0% to 100%. The lighter the mix, the less is the slump values. The reason for this is that the work done by gravity is lower in the case of lighter VPA. Due to lower aggregate density, structural low-density concrete does not slump as much as normal density concrete with the same workability. A low-density mixture with a slump of 50 to 75 mm can be placed under condition [21] that would require a slump of 75 to 125 mm for normally density concrete. This is found to be true in the current study. For 100% VPC, a slump of 52 to 60 mm represents satisfactory workability compared to 80–84 mm slump of 0% VPC (control mix). However, to make VPC with 50% to 100% VPA having satisfactory workability, the range of slump values should be 50 to 75 mm. With higher slumps (in excess of 125 mm), the large aggregate particles tend to float to the surface, making finishing difficult.

3.3. Hardened properties of VPC

3.3.1. Strength, density and modulus of elasticity

The compressive strength is decreased with the increase of % VPA as shown in Table 6 due to the replacement of normal strong crushed gravel aggregate by relatively weak pumice aggregate. In Mix 1, the 28-day cylinder strength of VPC decreases from 35 to 22 MPa while the cube strength decreases from 40 to 28 MPa when VPA content varies from 0% to 100% by volume. In Mix 2, the 28-day cylinder strength of VPC decreases from 34 to 18 MPa while the cube strength decreases from 40 to 24 MPa.

The 28-day cylinder strength of Mix 1 is reduced by 39% compared to 45% in Mix 2 when VPA is increased from 0% to 100% by volume. The 28-day cube strength of Mix 1 is reduced by 33% compared to 40% in Mix 2 when VPA is increased from 0% to 100% by volume.

The amounts of cement and fine aggregate (sand) as well as w/c were kept constant in the submixes of a particular mix (Table 5). The major change in the submixes was the amount of VPA and this is the key factor affecting the strength of VPC. As a consequence, Mix 2 shows lower strength than Mix 1 due to high percentage of comparatively weaker VPA.

The variation of tensile strength (Table 6) also shows trend, similar to that of compressive strength. The splitting tensile strength is decreased from 3.7 to 2.6 MPa for Mix 1 and from 3.4 to 2.2 MPa for Mix 2. The strength is decreased from 0% to 29% in Mix 1 compared with 0% to 36% in Mix 2 as the VPA content is increased from 0% to 100% by volume. The tensile strength of Mix 2 is lower compared with Mix 1 as expected.

It is concluded that the concrete strength depends on the strength, stiffness and density of coarse aggregates. The compression failure pattern in VPC indicates that VPA governs the failure as observed from broken cubes and cylinders. Generally, the lower the density, the lower is the strength. VPC is lighter than control concrete (0% VPA). The porosity also affects the compressive strength. VPC has higher porosity than the control concrete as indicated by higher air content of about 4.5% (Table 5) in fresh VPC compared to control concrete (0% VPC).

The relationship between cube strength (f_{cu}) and cylinder strength (f_c) of VPC can be derived as: $f_{cu} = 0.976f_c + 5.07$.

The ratio of compressive (f_c) and tensile (f_t) strength f_c/f_t ($= 11.0$) is found to be similar to that of normal concrete.

The modulus of elasticity, E, (Table 6) is decreased by about 42% for both Mixes 1 and 2 when percentage of VPA is increased from 0% to 100%. The E values of 100% VPC is about 10 kN/mm^2 compared to 21 kN/mm^2 of control concrete (0% VPC). The development of E is influenced by type of coarse aggregate, type of cement, w/c ratio of the mix and curing age. The E of lightweight aggregate concrete is usually between 40% and 80% of ordinary concrete of the same strength [37]. The E values of concrete made with expanded clay aggregate vary from 10 kN/mm^2 to 16 kN/mm^2 when compressive strength varies from 15 to 30 MPa. On the other hand, E of gravel aggregate concrete ranges between 18 to 26 kN/mm^2 within the compressive strength range of 20 to 40 MPa [37]. The E of concrete is a function of compressive strength and normally E increases with the increase of compressive strength. Various building codes have provided empirical equations relating E and compressive strength. The E value of concrete also depends on the stiffness of coarse aggregate, interfacial zone between the aggregates and paste and the elastic properties of constituent materials.

The density of VPC is decreased with the increase of % VPA (Table 6). This is due to the replacement of comparatively heavier normal 20 mm gravel aggregate by lighter VPA. Compared to normal concrete (0% VPA), the density of VPC is less. The Mix 1 is 24% and Mix 2 is 25% lighter than normal concrete. In this study, only the coarse fraction of total aggregate was replaced by VPA and river sand was used as fine aggregate.

According to CSA Standard [38], all VPCs using a VPA replacement within the range of 50% and 100% of coarse aggregate by volume developed strength in excess of 15 MPa and an air dry density of between 1850 and 2150 kg/m^3 satisfying the criteria for semi-lightweight structural concrete. However, the density of 100% VPC (100% VPA aggregate) mixes satisfies the criteria for structural low-density (lightweight) concrete having a density of less than 1850 kg/m^3. They also satisfy the criteria of structural lightweight concrete as per ASTM C 330 [20], which requires minimum 28 day cylinder compressive strength of 17 MPa and maximum dry density of 1850 kg/m^3. Much lighter VPC can be obtained by partial or total replacement of fine aggregate as well as full replacement of coarse aggregate by using combined fine and coarse VPA following the grading requirement suggested by ASTM C 330 [20].

3.3.2. Drying shrinkage

Drying shrinkage for the submixes of VPC Mix 1 with different percentages of VPA is presented in Fig. 1. The shrinkage of the VPC is found to be higher than that of normal representative concrete (0% VPA). Aggregates with high absorption properties are associated with high shrinkage in concrete [39] as confirmed from the increase in shrinkage with increase of the amount VPA in concrete.

The cement and fine aggregate (sandy fraction) content in all the VPC submixes were constant for a particular mix. But the percentage of VPA is increased from 0% to 100% by volume or 0% to 36.9% by weight. Consequently, the

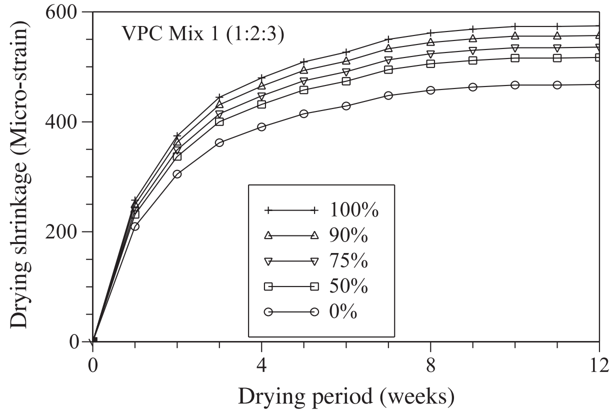

Fig. 1. Effect of % of VPA and age on the drying shrinkage of VPC.

shrinkage is higher in the concrete specimens having higher VPA content as can be seen from Fig. 1.

The shrinkage in 100% VPC over the age of 12 weeks is found to be approximately 22% (mean value) higher than those in the representative normal concrete (0% VPA). The 12-week drying shrinkage in 100% VPC was about 610 microstrain compared to about 460 microstrain in normal weight concrete (0% VPC). It is suggested that the drying shrinkage of structural low density concrete ranges from slightly less than to 30% more than that of normal density concrete [21]. It is also reported that the shrinkage of lightweight concrete can be 50% greater than normal weight concrete [40]. Concrete made with lightweight aggregates having open textured and irregular surface can produce a shrinkage of 1000 microstrain.

Like hydration of cement, drying shrinkage is the long lasting process that depends on w/c, degree of hydration, curing temperature, relative humidity, duration of drying, aggregate properties, admixture and cement composition [41,42]. The drying shrinkage [1] is affected by twin influences of aggregate-to-cement and water-to-cement ratios. Shrinkage increases with the increase of water cement ratio and decreases with the increase of aggregate cement ratio of concrete. Previous study [43] showed that for each 1% increase in mixing water, concrete shrinkage increased by about 2%. For the current series of tests on VPC (w/c is kept constant at 0.45), as the percentage of VPA is increased from 0% to 100% by volume, the aggregate–cement ratio is decreased from 4.07 to 2.38 by weight. As a consequence, the decrease in shrinkage with the increase of VPA is justified. High initial drying shrinkage and comparatively low tensile strength may lead to the danger of shrinkage cracking. However, the danger of shrinkage cracking can be compensated by the lower modulus of elasticity of VPC (Table 5).

3.3.3. Permeability

The 100×200 mm cylinder specimens were cured under water until the date of testing. The permeability values obtained were mainly comparative under similar condition of tests for different VPC mixes.

The effect of percentage of VPA on the permeability of VPC at the age of 28 days is shown in Fig. 2. The permeability is increased from approximately 3.6×10^{-10} cm/s to around 13×10^{-10} cm/s when VPA content is increased from 0% to 100% by volume. Compared to normal (0% VPA) concrete, the permeability of VPC with 100% VPA is about 3.5 times greater.

The increase in permeability with the increase of VPA is due to the replacement of normal coarse aggregate by comparatively porous VPA. As expected, Mix 2 shows higher permeability than Mix 1 due to higher VPA content and comparatively lower density.

Permeability refers to the amount of water migration through concrete when the water is under pressure or the ability of concrete to resist water penetration. Permeability of concrete is a function of permeability of paste, permeability and gradation of aggregate, paste–aggregate transition zone and paste to aggregate proportion. Permeability also depends on w/c (increase with the increase of w/c) and initial curing conditions [44]. To be watertight, structural concrete should have a w/c of not more than 0.48 for exposure to fresh water and not more than 0.44 for exposure to seawater [45]. A typical value of permeability of concrete used in the offshore structures in the North Sea is 10×10^{-10} cm/s [46]. The permeability of rock used as aggregate in concrete varies from 1.7×10^{-9} to 3.5×10^{-13}, mature continuously moist hardened cement paste from 0.1×10^{-12} to 120×10^{-12} cm/s and mature good-quality concrete has permeability of 1×10^{-10} cm/s [21].

The higher permeability of VPC will allow higher moisture movement and have the harmful effect of corrosion needing special care for protection of reinforcement.

3.3.4. Initial surface absorption (ISA)

Table 7 shows the variation of ISA at the age of 28 day for all the submixes. The significant difference in absorp-

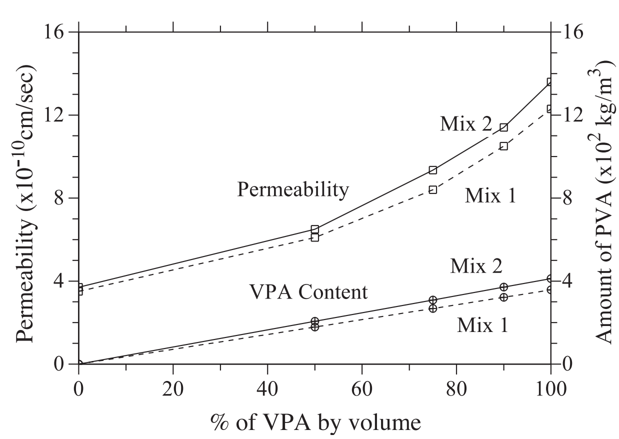

Fig. 2. Effect of various parameters on the permeability of VPC.

Table 7
ISA of concrete mixes

Mix designation	28-day ISA ($\times 10^{-2}$ ml/m^2/s) (min)			
	10	30	60	120
Mix 1				
A: 100–36.9–2.38	3.584	2.372	1.442	1.386
B: 90–25.6–2.55	3.215	2.128	1.293	1.243
C: 75–19.4–2.80	3.031	2.006	1.219	1.172
D: 50–11.3–3.22	2.899	1.919	1.166	1.121
E: 0–0–4.07	2.635	1.744	1.060	1.019
Mix 2				
P: 100–36.9–2.62	3.799	2.515	1.528	1.469
Q: 90–30.6–2.85	3.376	2.235	1.358	1.306
R: 75–22.8–3.18	3.213	2.127	1.292	1.242
S: 50–12.9–3.75	3.073	2.034	1.236	1.188
T: 0–0–4.87	2.741	1.814	1.103	1.060

tion capacity is observed from the 10th to the 120th min test. The high porosity and high absorption capacity of VPA have made VPC to show the higher value of absorption than control concrete (0% VPA). Mix 2 VPC mixes absorbed more water than Mix 1 VPC mixes due to the presence of higher quantity of VPA. The absorption of 100% VPC is approximately 35% higher than that of control concrete (0% VPA).

Most artificial lightweight concrete exhibits significantly higher water absorption than normal weight concrete. In lightweight concrete, the moisture movement is governed [47] by the fineness of cement, the richness of the mix, the w/c and the curing environment at early ages.

3.3.5. Recommendation for PVPC

Test results from Portland cement–volcanic pumice powder mixes are compared to the requirements of Portland cement and Portland fly ash cement according to Australian Standards [24,25,48–51] in Table 8. The setting times satisfy the requirements of both Portland and Portland fly ash cement. The compressive strength of 15% VPP mix satisfies the requirements of both Type C Portland cement and Type FC of Portland–fly ash cement. Fineness index of the mix also satisfies the requirements. Due to increase of setting time, the heat of hydration should be less than normal Portland cement. It is possible to manufacture blended PVPC equivalent to Type C of Portland cement and Type FC of Portland fly ash cement using up to 15% VPP. Chemical compositions of VPP satisfy the requirements of Class F fly ash as per ASTM C618 [52] (Table 1). Setting time and compressive strength of 15% blended cement also satisfy the criteria of Type IS: Portland blast furnace slag cement as well as Type IP–Portland–pozzolan cement as per ASTM C-595 [53].

3.3.6. Mix design recommendation for VPC

Design mixes with various percentage of VPA as replacement of normal coarse aggregate in this study have provided wide range of options for the ready mix companies and private users. They can choose their mix based on strength and lightweight requirement. The Gazella Restoration Authority (GRA) in-charge of the rehabilitation of volcanic disaster areas of Papua New Guinea has used VPC in their projects. Local people in volcanic areas are now using low cost VPC in various constructions. The performance of the proposed design mixes is validated in the field and the strength of the field concrete is found to be within 5% of that found in the study. Proposed design mixes can be used as guidelines for mix design of VPC for similar condition and type of mix.

4. Conclusion

This paper demonstrates how the use technology can transform the cause of social and environmental disaster into a natural resource and, hence, can be used in the postdisaster rehabilitation construction projects. It is confirmed that the volcanic pumice can be used as a resource in cement and

Table 8
Assessment of feasibility of Portland VP cement manufacture

	Requirement for Portland fly ash cement [48]		Requirement for Portland cement [49]				Test data for Portland volcanic pumice cement	
Setting time	Both Types FA and FC		Types A, B, C and D				15% VPP	
	Initial set: 1 h		Initial set: 1 h				3.30 h	
	Final set: 12 h		Final set: 12 h				5.20 h	
Test method	[24]		[24]				[24]	
Compressive strength, MPa	Minimum strength		Minimum strength				VA content	
	Type FA	Type FC	Type A	B	C	D	15%	>15%
3 day	20	18	20	28	18	20	18	< 17
7 day	32	25	32	38	25	28	25.6	< 25
28 day	45	32	45	52	32	38	33.2	< 33
Test method	[25]		[25]				[25]	
Fineness index	Types FA and FC		For all types				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 295 m^2/kg	
Test method	[51]		[50]				[50]	

concrete production and can be used in low cost construction especially in volcanic areas. The following conclusions are drawn:

1. Blending ASTM type I Portland cement with 0% to 25% VPP increases the initial setting time from 3.15 to 3.60 h and increases the final setting time from 5.15 to 5.80 h.
2. It is feasible to manufacture blended PVPC using up to 15% VPC. Fifteen percent PVPC satisfies the requirement of both Portland fly ash cement of Type FC and Portland cement Type C as per Australian Standards [48,49] and Type IS: Portland blast-furnace slag cement as well as Type IP–Portland–pozzolan cement as per ASTM [53].
3. To make VPC with 50% to 100% VPA as replacement of coarse aggregate by volume, a range of slump between 50 and 75 mm will provide satisfactory workability.
4. The modulus of elasticity, E, of VPC with 100% VPA is approximately 10 kN/mm^2 compared to 21 kN/mm^2 of control concrete (0% VPA) which shows a decrease of about 42%.
5. The compressive strength (cylinder and cube) of VPC with 100% VPA is approximately 40–45% lower than control concrete with 0% VPA.
6. The splitting tensile strength of VPC with of 100% VPA varies from 3.7 to 3.4 MPa compared with 2.6 to 2.2 MPa of control concrete with 0% VPA.
7. VPC has higher degree of porosity than the control concrete as indicated by higher air content of about 4.5% in fresh VPC compared to control concrete.
8. VPC with 100% VPA satisfies the criteria of structural lightweight concrete [20].
9. The shrinkage in 100% VPC over the age of 12 weeks is found to be approximately 22% (mean value) higher than those in the representative control concrete (0% VPA).
10. The permeability of VPC is increased from approximately 3.6×10^{-10} cm/s to around 13×10^{-10} cm/s when VPA content is increased from 0% to 100% by volume. The initial surface absorption of 100% VPC is approximately 35% higher than that of control concrete (0% VPA).
11. VPC design mixes presented in this study can be used as guidelines for the mix design of VPC for similar condition and type of mix. The design mixes are now in use in the volcanic areas of Papua New Guinea. Papua New Guinea Halla cement factory is now manufacturing blended PVPC in accordance with the research recommendation.

Acknowledgements

The author is grateful to the Papua New Guinea University of Technology 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. Assistances of The PNG Halla Cement Factory, The PNG Department of Works, PNG Ready Mixed Concrete and Gazella Restoration Authority are appreciated.

References

[1] A.M. Nevile, Properties of Concrete, 4th ed., Longman, Harlow, England, 1995.
[2] N. Jackson, Civil Engineering Materials, 3rd ed., Macmillan Press, Hong Kong, 1983.
[3] M. Al-Ani, B. Hughes, Pulverized-fuel ash and its uses in concrete, Mag. Concr. Res. 41 (147) (1989) 55–63.
[4] P.K. Mehta, Properties of blended cements made from rice husk ash, J. Am. Concr. Inst. 74 (1979) 440–442.
[5] R.N. Swamy, Cement Replacement Materials, Concrete Technology and Design, vol. 3, Surrey Univ. Press, Great Britain, 1986.
[6] R.N. Swamy, New Concrete Materials, Concrete Technology and Design, vol. 2, Surrey Univ. Press, Great Britain, 1983.
[7] E.E. Berry, V.M. Malhotra, Fly ash for use in concrete—a critical review, J. Am. Concr. Inst. 77 (8) (1980) 59–73.
[8] A. Bilodeau, V.M. Malhotra, High volume fly ash system: the concrete solution for sustainable development, Compilation of papers, Three day CANMET/ACI Symposium on Sustainable Development of the Cement and Concrete Industry, October 21–23, Ottawa, 1998, pp. 193–214.
[9] R.D. Hooton, Canadian use of ground granulated blast-furnace slag as a supplementary cementing material for enhanced performance of concrete, Can. J. Civ. Eng. 27 (2000) 754–760.
[10] ASTM C 612-97, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Concrete, 1997.
[11] ASTM C 989-95, Standard Specification for Blast Furnace Slag for Use in Concrete and Mortars, 1995.
[12] ASTM C 1240-97, Standard Specification for Silica Fume for use as a Mineral Admixture in Hydraulic-Cement Concrete, Mortar and Grout, 1997.
[13] A. Jamal, A. Khalid, M.N. Haque, E. Khalid, Lightweight concrete in hot coastal areas, Cem. Concr. Compos. 21 (5–6) (1999) 453–458.
[14] M. Nisnevich, Improving lightweight concrete with bottom ash, Fuel Energy Abstr. 39 (3) (1998) 191.
[15] G.M. Glenn, G.M. Gray, W.J. Orts, D.W. Wood, Starch-based lightweight concrete: effect of starch source, processing method, and aggregate geometry, Ind. Crops Prod. 9 (4) (1999) 133–144.
[16] K. Kohono, T. Okamoto, Y. Isikawa, T. Sibata, H. Mori, Effects of artificial lightweight aggregate on autogenous shrinkage of concrete, Cem. Concr. Res. 29 (4) (1999) 611–614.
[17] H.B. Basri, M.A. Mannan, M.F.M. Zain, Concrete using waste oil palm shells as aggregate, Cem. Concr. Res. 29 (4) (1999) 619–622.
[18] K. Ghavami, Ultimate load behaviour of Bamboo-reinforced lightweight concrete beams, Cem. Concr. Compos. 17 (4) (1995) 281–288.
[19] Blong-Aislabe, The Impact of Volcanic Hazards at Rabaul, PNG, Institute of National Affairs, Paper No. 33, Papua New Guinea, 1988.
[20] ASTM C330-00: Specification for lightweight aggregates for structural concrete, Annual Book of ASTM Standards, Philadelphia, USA.
[21] S.H. Kostmatka, B. Kerkhoff, W.C. Panarese, N.F. Macleod, R.J. McGrath, Design and control of concrete mixtures, 7th Canadian ed., Engineering Bulletin, vol. 101, Cement Association of Canada, Ottawa, Ontario, 2002.
[22] AS 1289.C6.1, Australian Standard, Standards Association of Australia, Sydney, 1977.
[23] ASTM C136-01, Standard test method for sieve analysis of fine and coarse aggregate, Annual Book of ASTM Standards, Philadelphia, USA.

[24] AS 2350.3, Australian Standard, Standards Association of Australia, Sydney, 1980.
[25] AS 2350.6, Australian Standard, Standards Association of Australia, Sydney, 1980.
[26] ASTM C 143-00, Standard test method for slump of hydraulic cement concrete, Annual Book of ASTM Standards, Philadelphia, USA.
[27] ASTM C 231-97, Test method for air content for freshly mixed concrete by pressure method, Annual Book of ASTM Standards, Philadelphia, USA.
[28] BS 1881. Part 116, Method for determination of compressive strength of concrete cubes, British Standard Institution, London.
[29] ASTM C39-01: Standard test method for compressive strength of cylindrical concrete specimens, Annual Book of ASTM Standards, Philadelphia, USA.
[30] ASTM C496-96, Standard test method for splitting tensile strength of cylindrical concrete specimens, Annual Book of ASTM Standards, Philadelphia, USA.
[31] AS1012, Part 13, 1970, Australian Standard, Standards Association of Australia, Sydney, Australia.
[32] ASTM C157-99, Standard test method for length change of hardened hydraulic cement, mortar, and concrete, Annual Book of ASTM Standards, Philadelphia, USA.
[33] BS 1881, Part 5, Methods of testing hardened concrete for other than strength, British Standard Institution, London.
[34] ASTM C 469-87a, Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression, Annual Book of ASTM Standards, Philadelphia, USA.
[35] P.B. Bamforth, In situ measurement of the effect of partial Portland cement replacement using either fly ash or ground granulated blast-furnace slag on the performance of mass concrete, Proc. Inst. Civ. Eng. 69 (2) (1980) 777–800.
[36] K.M.A. Hossain, Performance of volcanic ash concrete in marine environment, Proceedings of 24th OWICS Conference, "21st Century Concrete and Structures", 25–26 August, Singapore, vol. XVIII, 1999, pp. 209–214.
[37] J.J. Shideler, Lightweight aggregate concrete for structural use, J. Am. Concr. Inst. 54 (1957) 299–328.
[38] CSA 23.3-94: Design of Concrete structures, Canadian Standard Association, http://www.csa.ca.
[39] ACI 221R-89, ACI Committee 221 Report, American Concrete Institute, Farmington Hills, MI, 1989.
[40] FIP, FIP Manual of Lightweight Aggregate Concrete, 2nd ed., Surrey Univ. Press, London, 1983.
[41] S. Mindess, J.F. Young, Concrete, Prentice-Hall, Englewood Cliffs, NJ, 1981.
[42] A.M. Brandt, Cement Based Composites: Materials, Mechanical Properties and Performance, E & FN SPON, London, 1995.
[43] R.W. Carlson, Drying shrinkage of concrete as affected by many factors, Proceedings of the 41st Annual Meeting of the ASTM, Philadelphia, vol. 38 (Part II), 1938, pp. 419–440.
[44] D. Whiting, Permeability of selected concretes, Permeability of Concrete, SP108, American Concrete Institute, Farmington Hills, MI, 1989, pp. 195–222.
[45] ACI Committee 301, Specifications for structural concrete for buildings, J. Am. Concr. Inst. 72 (7) (1975) 361–362.
[46] R.D. Browne, P.L. Domone, Permeability and fatigue properties of structural marine concrete at continental shelf depths, Proceedings of the International Conference on Underwater Construction Technology, University of Wales, College of Cardiff, Cardiff, April, 1975, p. 39.
[47] D.F. Orchard, Concrete Technology, vol. 2, Applied Science Publishers, London, 1979.
[48] AS1317, Australian Standard, Standards Association of Australia, Sydney, 1982.
[49] AS1315, Australian Standard, Standards Association of Australia, Sydney, 1982.
[50] AS2350.8; Australian Standard, Standards Association of Australia, Sydney.
[51] AS2350.9, Australian Standard, Standards Association of Australia, Sydney.
[52] ASTM C618-91, Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in Portland cement concrete, Annual Book of ASTM Standards, Philadelphia, USA.
[53] ASTM C595-00, Standard specification for blended hydraulic cements, Annual Book of ASTM Standards, Philadelphia, USA.