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Full Length Research Paper

Blended cement and lightweight concrete using scoria: mix design, strength, durability and heat insulation characteristics

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This paper reports the results of an investigation on the potential industrial utilization of volcanic scoria. The scoria is assessed for its utilization as a cement additive. Pozzolanic activity of ground scoria is tested according to the Italian standards and found to be acceptable. X-Ray Diffraction (XRD) analysis and Differential Scanning Calorimetry (DSC) are conducted on finely ground scoria based blended cement paste and mortar for the characterization of hydration products. The strength activity index with Portland cement and the effectiveness of scoria admixture in controlling alkali-silica reactions and autoclave expansion are tested according to ASTM standards using different mixes. The results satisfy the ASTM requirements and confirm the viability of using ground scoria as a cement additive. The suitability of using scoria as both fine and coarse aggregate in lightweight concrete production is assessed and compared with other lightweight aggregates. The properties of scoria concrete (SC) are evaluated by conducting comprehensive series of tests on workability, air content, density, strength, drying shrinkage, and water permeability. Developed SC mixtures have attained required strength and density to be accepted as structural lightweight concrete. The utilization of scoria as a heat-insulating material is also tested and the results are also found to satisfy the ASTM requirements. Scoria concrete shows good heat-insulating characteristics and can be used in building construction as an energy saver.

Keywords: Scoria, Lightweight concrete; Pozzolanic activity; Alkali-silica reaction, Autoclave expansion, Drying shrinkage; Permeability; X-Ray Diffraction; Differential Scanning Calorimetry.

INTRODUCTION

Research has been conducted worldwide on a large number of natural or artificial lightweight aggregates such as volcanic pumice (VP), bamboo reinforced, oil palm shells (OPS), bottom ash, starch based aggregate, volcanic slag, sintered nodules known as ‘Lytag’, expanded perlite, crushed brick, expanded clay etc. to manufacture lightweight structural concrete (Ghavami, 1995; Topcu, 1997; Al-Khaiat and Haque, 1998; Nisnevich, 1998; Hossain, 1999; Glenn et al. 1999; Kohono et al. 1999; Basri et al. 1999; Jamal et al. 1999; Demirboga et al. 2001). 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. Structural lightweight concrete has its obvious advantages of higher strength/weight ratio, lower co-efficient of thermal expansion and superior heat and sound insulation characteristic due to air voids in the lightweight aggregate. Furthermore, the reduction in dead weight of a construction could result in a decrease in cross-section of structural members and steel reinforcement.

Pumice and scoria (S) are pyroclastic ejecta. Pumice is excessively cellular, glassy lava and has the same basic composition of rhyolite. Scoria is irregular in form and generally very vesicular and has the basic composition of basalt. Scoria is usually heavier, darker and more crystalline than pumice. Scoria is abundant in various parts of the world including Turkey, Papua New Guinea (PNG) (Hossain, 2000) and Saudi Arabia (Moufti et al. 2000). Scoria is formed of vesicular fine to coarse

Table 1. Chemical and physical properties of Portland cement (PC) and scoria (S).

Chemical Composition			Physical Properteis * finely ground scoria		
	Scoria (S)	PC			
Chemical compounds	**Mass %**	**Mass %**		**S***	**PC**
Calcium oxide (CaO)	5-8	60-67	Fineness, m^2/kg	290	320
Silica (SiO_2)	45-50	17-25	Passing 45µm sieve	85	94%
Alumina (Al_2O_3)	13-15	3-8	Residue on 75µm sieve	2%	0.1-1.5%
Iron oxide: Fe_2O_3	3-4	0.5-6.0	Residue on 150µm sieve	0.7%	-
FeO	4-6				
Sulphur trioxide (SO_3)	0.01-0.02	1-3	Specific gravity	2.15	3.15
Magnesia (MgO)	4-6	0.1-4.0			
Alakli: $Na_2O + K_2O$	4-6	0.5-1.3			
Free lime (CaO)	-	0.5-0.8			
Loss on ignition	1.25-1.50	1.22			

Figure 1. Scoria aggregates.

fragments, reddish or black in color and light in weight (Figure 1). Scoria can be utilized in several industrial applications including the manufacturing of lightweight concrete, as a source of pozzolan to manufacture Portland-pozzolan cement additive, as a heat insulating materials, in addition to other uses such as low cost fillers, filter materials, absorbents and other architectural applications.

Although there are numerous studies on using lightweight aggregates in concrete or block production, there are few published study on the use of scoria in structural lightweight concrete (Moufti et al. 2000). Particularly no research was conducted in the past to study the potential industrial utilization of scoria in PNG (Hossain 2000). Scoria is locally used in road construction as sub-base material and there are several quarries operating on scoria deposits in highland provinces. This research is the first detailed engineering investigation to explore the possible utilization of scoria in construction especially in the manufacture of blended cement and concrete (Hossain 2000). The use of scoria as a construction material will help conserve energy (as heat insulating material) and will provide low cost cement and lightweight concrete.

This paper presents the results of investigations on the use of scoria as pozzolanic, cement additive, lightweight aggregate and heat insulating materials.

INVESTIGATION ON SCORIA AS A CEMENT ADDITIVE

Materials and properties

Scoria (S) used in this investigation was collected from a quarry near the town of Goroka in the highland province of Papua New Guinea. Chemical properties of scoria are compared with those of ASTM Type I Portland cement (PC) in Table 1. Chemical analysis indicates that scoria is principally composed of silica (45-50%); while the main oxide component of PC is calcium oxide (60-67%). However, scoria also has calcium oxide, alumina and iron oxide (25-33%). The contents of oxides of sodium and potassium known as ‘alkalis’ is found to be higher in scoria (4-6%) than those in PC (2.6% maximum).

Scoria samples were tested for their loss on ignition (LI) according to ASTM C 311. The LI ranges between 1.25 and 1.51% with an average of 1.35% (Table 1). The LI is assumed to represent the total moisture and CO_2 content in the scoria. The average value of the measured moisture content is 0.71%. Therefore, the average CO_2 lost by ignition is 0.80%.

Scoria has the potential to be used as an additive to PC for the manufacture of blended cement like other pozzolanic materials such as fly ash and volcanic ash. Several tests were conducted to study the suitability of finely ground scoria as a pozzolanic material. The

Table 2. Potential phase composition of cementing materials from X-Ray diffraction

Phase	PC	Blended scoria cement **
C_3S	68.1	55.6
C_2S	14.1	9.1
C_3A	5.9	5.3
C_4AF	9.2	6.9
Other	2.4	7.6
Total	99.7	84.5
Glassy fraction*	0.3	15.5

* Glassy fraction ** PC blended with 20% ground scoria

physical properties such as Blaine fineness and specific gravity of finely ground scoria are presented in Table 1. The fineness of ground scoria was 290 m^2/kg compared to 320 m^2/kg of PC and can be controlled by the user during grinding process. Ground scoria with a specific gravity of 2.36 was also lighter than PC.

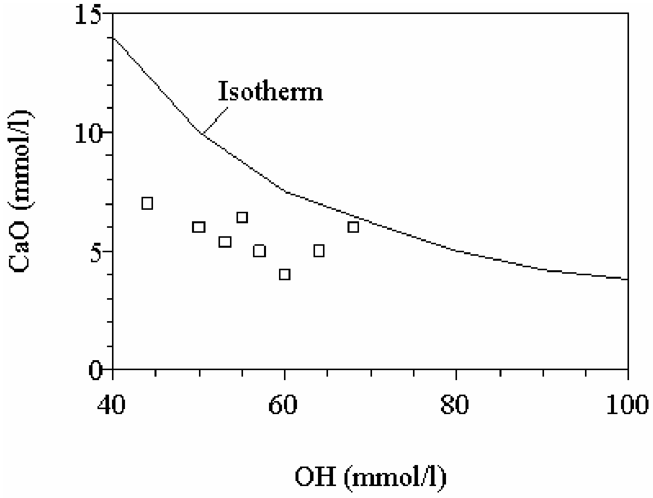

Figure 2. Pozzolanic activity test of ground scoria.

X-Ray Diffraction (XRD) analysis of PC and scoria based blended cement

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 69% CaO in the cement analysis 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. Similarly, the scoria does not have the oxide content listed (Table 1) present as oxides- most likely are primarily glass. Quantitative XRD analysis of PC and blended cements with 20% ground scoria as cement replacement, provided valuable information on this aspect. The phase composition of these materials is presented in Table 2.

Pozzolanic activity and hydration product characterization

The pozzolanic activity was tested according to the Italian Standards (Italian chemical society 1954) where ground scoria 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 (Figure 2). The results indicate that all scoria samples fall below the lime solubility isotherm and are therefore, pozzolanically active. Being pozzolanically active, scoria has a cementitious characteristic and can economically be used as a cement additive to manufacture blended cement.

Cylindrical mortar specimens having 50 mm diameter and 100 mm in height were cast for microstructure and hydration product characterization. River sand (Table 3 and 4) having a specific gravity of 2.65 and water absorption of 0.6% percent with ordinary drinking water were used to prepare mortar mixes with W/B of 0.55. Scoria replacement percentages of 20% and 40% by mass were used in mortar mixes. In addition, control specimens were prepared without scoria (0%). The ratio of binder (B) to sand was 1:3 by mass. Table 5 shows mixture proportions of mortars. After casting, mortar specimens were cured for 91 days in the saturated calcium hydroxide solution. The differential scanning calorimetry (DSC) was conducted on samples taken from mortar specimens. The samples weighted around 60 mg were heated at a constant heating rate of 10 °C per minute 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 show peaks due to endothermic (heat absorbing) and exothermic (heat releasing) reactions.

Table 3. Grading of aggregates.

Sieve opening (mm)	Coarse aggregate (% finer)			Fine aggregate (% finer)		
	Lightweight		Normal weight	Lightweight		Normal
	SA	ASTM C-330	GA	SA	ASTM C-330	River sand
25	100	95-100	100			
19	90	-	94			
12.5	40	25-60	50			
9.5	20	-	28	100	100	100
4.75	5	0-10	10	92	85-100	93
2.36				74	-	70
1.18				65	40-80	51
0.30				15	10-35	20
0.15				6	5-25	15

Table 4. Properties of aggregates.

Materials	Bulk density (kg/m^3) SSD	Oven dry	Loss Angeles abrasion (%)	Absorption (24 hour) (%)
GA (Coarse agg.)	2540	2470	20	2.86
River sand	2660	2610	-	2.04
SA (Coarse agg.)	1556	1150	30	35.6
SA (Fine agg.)	1885	1545	-	22.2

Table 5. Mortar mix proportions.

Mix	W/(C+S) W/B	Water (W) kg	Cement (C) kg	Scoria (S) kg	Sand kg
0%S (control)	0.55	0.55	1	0	3
20%S	0.55	0.55	0.80	0.20	3
40%S	0.55	0.55	0.60	0.40	3

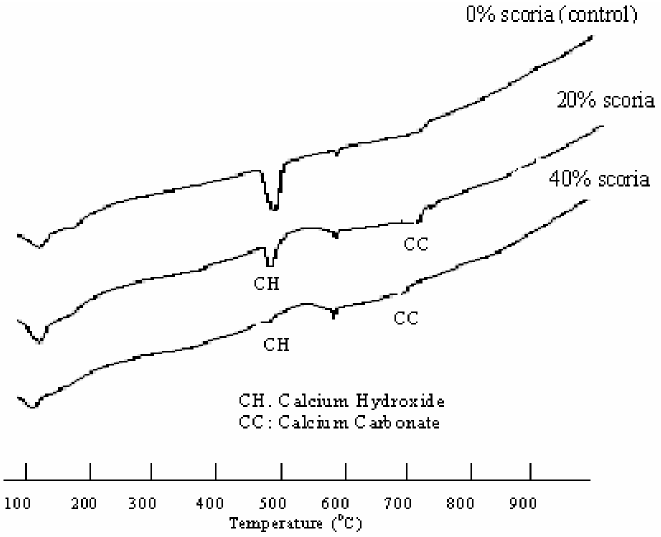

Figure 3. Typical DSC curves.

Figure 3 shows typical DSC curves, of samples taken from mortar specimens. It is found that the $Ca(OH)_2$ content (which is equivalent to the area under the endothermic peak around 450 °C of scoria blended specimens, is lower than control specimens. It is an indication that the pozzolanic reactivity of scoria consumed $Ca(OH)_2$ resulting from the hydration of cement.

Study on alkali-silica reaction

Tests were performed to determine the effect of ground scoria on the expansion caused by the alkali-silica reactions. The test was performed, with some modification, according to ASTM C 311, 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 mix on the other hand, used Portland cement (ASTM type I), clean silica sand instead

Table 6. Effect of scoria on the alkali-silica reaction and autoclave expansion.

Scoria content (%)	Alkali silica reaction		Autoclave Expansion (%)
	Length change (mm)	Expansion (%)	
0 (control mix)	0.089	-	0.40
10	0.111	125	0.24
20	0.102	115	0.20
30	0.088	99	0.16
40	0.079	82	0.13

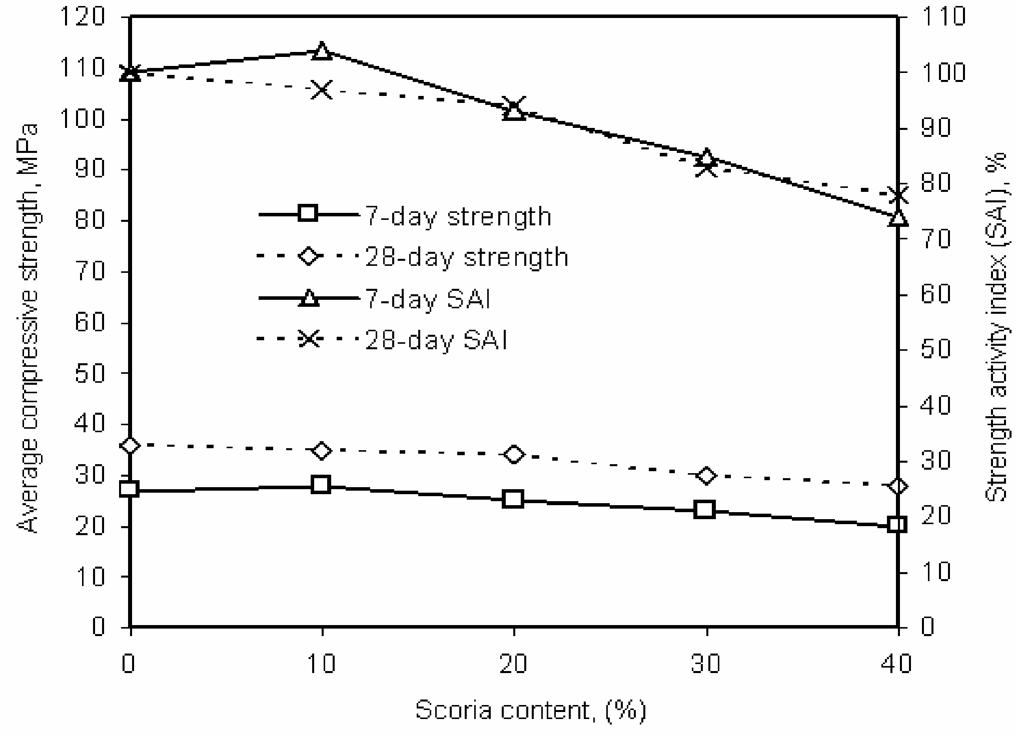

Figure 4. Influence of scoria content on the strength activity index (SAI).

of borosilicate glass (which was not available and also expansive) and finely ground scoria passing through 45 µm sieve. The scoria replaced the Portland cement by 10, 20, 30 and 40% (by mass) in four different mixes. Mortar cubes, 50 x 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 6. The ASTM C 618 requires that, for the effectiveness in the alkali-silica reactions, the reduction in 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 with 10% scoria content showed the maximum length change and the highest reduction in length value. Mixes with 30 and 40% scoria content, on the other hand, satisfy the ASTM C 618 requirement.

Study on 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. 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 scoria 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. Cubes, 25 mm x 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 6. The autoclave expansion of the paste mixes is decreased with the increase of scoria content. All the mixes containing up to 40% scoria, satisfy the ASTM C 618 requirement of 0.8% maximum.

Study on strength activity index (SAI).

The strength activity index test was performed on the scoria material using a slightly modified form of ASTM C 311 which calls for the replacement of the cement in the mortar mix by 20% of scoria. 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 scoria 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 x 50 mm in dimensions, were prepared from these mixes and stored in a saturated lime water solution until tested for their uniaxial compressive strengths at 7 and 28 days. The results are presented in Figure 4. It is found that the compressive strength generally decreases with the increase in the scoria 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 for the results of samples at 7 and 28 days. The SAI values ranges between 74 and 104% at 7 days and between 78 and 97% at 28 days (Figure 4). The SAI values are more than 75% as required by ASTM C 618 for mixes with 10, 20 and 30% scoria content.

DISCUSSION

The effect of scoria in controlling the alkali-silica reaction shows that the value for 10% scoria mix is much higher than the value of 100% required as per ASTM C618. Only 40% scoria mix satisfies this requirement. The SAI value for 40% scoria mix, on the other hand, does not satisfy the ASTM C 618 requirement. It is then safe to conclude that mixes with 10% and 40% scoria can not be recommended as additives. The compressive strength values of mixes with 30% and 40% scoria are significantly reduced because of the presence of scoria. The mix with 20% scoria content compromises all the required criteria. It shows a relatively reasonable expansion value and a reasonable compressive strength value. As recommended by the ASTM C 618, this study also recommends the use of 20% scoria as a cement additive.

USE OF SCORIA TO PRODUCE LIGHTWEIGHT CONCRETE

Materials and properties

Scoria collected from PNG sources consisted of lumps of various sizes ranging from 2 mm to 64 mm but bigger blocks were also available. Crushed scoria aggregate (SA) of various grading could be produced from these sources. In this study, scoria was used as both coarse and fine aggregates in the manufacture of scoria concrete (SC). Scoria was also used as replacement of crushed gravel aggregate (GA) in the production of SC. The aggregates used were 20 mm maximum size crushed gravel, 20 mm maximum size scoria and local river sand.

The properties of GA are compared with those of SA in Table 4. Both crushed GA and SA were angular in shapes but SA was found to be honeycombed compared with rough GA. The bulk density results suggested that the SA was much lighter than GA. The oven dry bulk density of SA was around 1150 kg/m^3. Bulk densities of lightweight pumice, OPS and volcanic slag aggregates used in the manufacture of lightweight concrete are around 760 kg/m^3, 590 kg/m^3 and 1330 kg/m^3, respectively (Hossain, 1999; Basri et al. 1999; Topcu, 1997). The bulk dry density of VP based commercial 'Vac-Lite' aggregate, widely used in USA, ranges between 400 and 450 kg/m^3 (http://www.clppumice.com/engineering.html). The density of expanded shale and clay aggregates may range from 300 to 900 kg/m^3 while the bulk density of sintered nodules known as 'Lytag' is around 1000 kg/m^3 (Neville, 1995). As per ASTM C 330, SA satisfied the requirement of lightweight aggregate for structural concrete as the oven dry density fell closely within the range of 560 to 1120 kg/m^3. However, the water absorption of SA was higher (36%) than the range of 5% to 20% as normally occurred in other lightweight aggregates (Kostmatka et al. 2002). One hour water absorption of 'Vac-Lite' aggregate ranges between 18 and 22% (http://www.clppumice.com/engineering.html). On the other hand 24-hour water absorptions of pumice, OPS, volcanic slag, expanded clay and brick aggregates were reported to be around 37%, 24%, 14-20%, 28 and 47% respectively (Hossain, 1999; Basri et al. 1999; Topcu, 1997; Jamal et al. 1999). High water absorption also indicated high degree of porosity in SA like other lightweight aggregates. The high abrasion value as per BS 812-Part 113 of SA compared with GA indicated the low strength of SA (Table 4).

The particle size distributions of aggregates were performed according to ASTM C 136 and presented in Table 3. Grading of both coarse and fine meet the requirement of lightweight aggregate for structural concrete as per ASTM C 330. The overall clay lumps content in the SA was determined according to ASTM C

Table 7. Scoria concrete (SC) mix details and properties (Series A).

Mix desig.	SA kg/m^3	GA kg/m^3	% SA*	Ratio**	Slump mm	Air content %	Dry density kg/m^3	28 day compressive strength, MPa f_{cy} (f_{cu})
Cement (C) = 490 kg/m^3 ; W/C = 0.45; Sand = 615 kg/m^3								
A-100	456	0	42.6	2.19	64	4.0	1845	24 (28)
A-90	411	98	36.5	2.29	68	3.6	1963	26 (30)
A-75	342	245	28.5	2.45	72	3.4	2022	28 (32)
A-50	228	490	17.1	2.72	78	3.2	2135	30 (35)
A-0$^+$	0	980	0	3.26	82	2.8	2520	35 (40)

$^+$control concrete * % of SA of total aggregate by weight
**Total aggregate cement ratio by weight

142. The percentage of clay lumps ranges between 0 and
1.6% with an average of 0.55% not exceeding the 2% maximum acceptable limit according to ASTM C 330 for lightweight aggregate for structural concrete.

Tables 3 and 4 present particle size distribution and properties of river sand, also used as fine aggregate. The locally manufactured ASTM Type I Portland cement and clean drinking water were used.

Investigation on scoria concrete (SC)

Tests were conducted in two series namely Series A and Series B to study fresh, hardened and durability properties of scoria concrete mixtures.

Series A: SC mix design, testing and properties

Mix design and testing procedures

In Series A, tests were performed to investigate the effect of different percentages of SA as replacement of GA (by volume) on strength and durability properties of SC. The coarse aggregate consisted of 20-mm maximum crushed gravel (GA) and SA with river sand as fine aggregate. The coarse aggregates were washed, dried and then made saturated surface dry (SSD) by immersing under water for 24 hours before casting of concrete. This was very important for SA as it had higher absorption rate. The mix parameters and some characteristics of the fresh concrete are presented in Table 7. The letter in the mix designation represents Series and the numeric represents % of SA of total coarse aggregate by volume The water-to-cement ratio (W/C) of all mixes was kept constant at 0.45 by mass.

The effect of SA on the workability of different fresh SC mixtures was studied by conducting slump tests as per ASTM C 143. The slump values and air content of fresh concrete mixes are presented in Table 7. The air content ranged between 2.8% and 4.1%.

The test specimens were 100 mm cubes as per BS1881-part 116 and 150 mm x 300 mm cylinders as per ASTM C-39 for compressive strength. Total 4 cubes and 6 cylinders were cast for each mix.

Three 75 x 75 x 285 mm shrinkage specimens and two cylinders (100 x 200 mm) for permeability tests were also cast for each sub mix.

All specimens were compacted by external vibration using a table vibrator. The specimens were removed from the moulds after 24 hours of 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 percent relative humidity room where the shrinkage was monitored using a vertical length comparator according to ASTM C-157 at 7, 14, 28, 56 and 91 days.

The 91-day water permeability of the 100 x 200 mm cylinder specimens was determined after 1 day of moist and 90 days of air curing by applying 1.4 MPa of water pressure in a hydraulic permeability test apparatus (Kostmatka et al. 2002).

Four cubes and three cylinders for compressive strength were tested at an age of 28 day. All strength results (mean values) are included in Table 7.

Results and discussion on fresh properties

The slump values for SC mixes with similar W/C of 0.45 were found to decrease (82-mm to 64-mm) with the increase of % SA from 0 to 100%. The lighter the mix, the less was the slump value. The reason for this was that the work done by gravity was lower in the case of lighter SA. Due to lower aggregate density, structural low-density concrete does not slump as much as normal density concrete with the same workability. For 100% SC, a slump of 55 to 64 mm represented satisfactory workability compared to 80-82 mm slump of control concrete (0% SA). However, to make SC with 50% to

100% SA having satisfactory workability, the range of slump values should be between 60 and 80 mm. The SC mixtures developed in this study showed no segregation or excessive surface water or bleeding. Commercial 'Vac-Lite' pumice concrete (with a W/C of 0.53) with a slump value of 82 mm, shows no segregation and bleeding (http://www.clppumice.com/engineering.html). 80 to 90 mm slump was found to be satisfactory for lightweight concrete with Lytag aggregate (Al-Khaiat and Haque 1998). Lightweight crushed brick and expanded clay concrete generally showed very good workability and compatibility when slump varied between 80 and 100 mm (Jamal et al. 1999).

Results and discussion on compressive strength

The compressive strength decreased with the increase of % SA as shown in Table 7. This was due to the replacement of GA by relatively weak SA. The 28-day cylinder strength (f_{cy}) of SC decreased from 35 to 24 MPa while the cube strength (f_{cu}) decreased from 40 to 28 MPa when SA content varied from 0% to 100% by volume. Commercial 'Vac-Lite' pumice concrete mixtures are available with a target compressive strength from as low as 7 MPa to an excess of 30 MPa (http://www.clppumice.com/engineering.html). The compressive strength of volcanic slag concrete was decreased from 35 to 6 MPa when the slag content was increased from 0 to 60% by volume (Topcu, 1997). The 28-day f_{cu} of expanded clay aggregate concrete ranged between 15 and 21 MPa (f_{cy} ranged between 11 and 18 MPa) while those of crushed brick aggregate ranged between 13 and 21 MPa (f_{cy} ranged between 11 and 15 MPa) (Jamal et al. 1999). The compression failure pattern in SC indicated that SA governed the failure as observed from broken cubes and cylinders. Higher air content of about 4.1% (Table 7) in fresh SC compared to control concrete (0% SC) might be a feature of the aggregate porosity and the degree of compaction of the concrete.

The density of SC decreased with the increase of % SA (Table 7). This was due to the replacement of comparatively heavier 20-mm GA by lighter SA. The 100% SC was about 25% lighter than control concrete (0% SC).

All SCs using a SA replacement within the range of 50% and 100% of coarse aggregate by volume developed strength in excess of 15 MPa and had an air dry density of between 1850 and 2150 kg/m^3, satisfied the criteria for semi-lightweight structural concrete as per CSA Standard (CSA 23.3-94, 1994). However, the density of 100% SC (100% SA aggregate) mixes seemed to satisfy closely the criteria for structural low-density (lightweight) concrete having a density of less than 1850 kg/m^3. They also satisfied the criteria of structural lightweight concrete as per ASTM C 330, which requires minimum 28-day cylinder compressive strength of 17 MPa and maximum dry density of 1850 kg/m^3. Dry density of commercial 'Vac-Lite' pumice concrete ranges between 960 and 1920 kg/m^3 (http://www.clppumice.com /engineering.html) while dry density of volcanic slag concrete was around 1900 kg/m^3 (Topcu, 1997). The dry density of expanded clay concrete varied from 1470 to 1520 kg/m^3 while that of crushed lightweight bricks concrete from 1560 to 1670 kg/m (Glenn et al. 1999; Jamal et al. 1999).

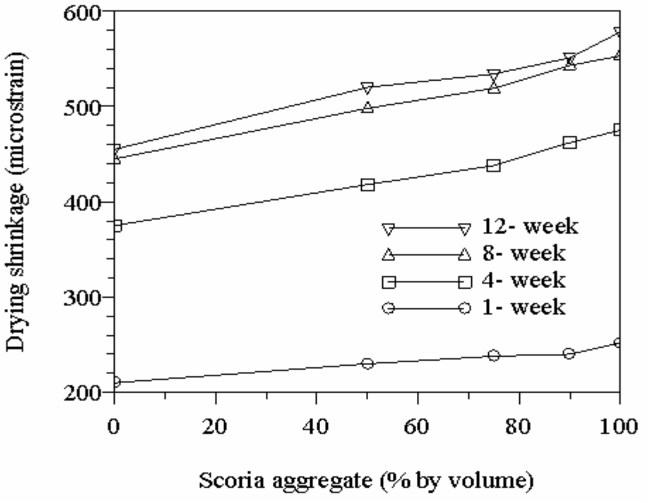

Figure 5. Drying shrinkage of SC

Results and discussion on drying shrinkage

The variation of drying shrinkage with different percentages of SA is presented in Figure 5. Aggregates with high absorption properties are associated with high shrinkage in concrete (Neville, 1995) as confirmed from the increase in shrinkage with the increase of the amount SA in SC (Figure 5). The cement and fine aggregate (sandy fraction) content in all mixes were constant. The percentage of SA was increased from 0 to 100% by volume or 0 to 47% by weight and consequently, the shrinkage was higher in concrete specimens having higher SA content.

The shrinkage in 100% SC over the age of 12 weeks was found to be approximately 27% higher than those in the control concrete (0% SA). The 12-week drying shrinkage in 100% SC was about 578 microstrain compared to about 450 microstrain in control concrete. As per ASTM C-330, the drying shrinkage of concrete specimens with lightweight concrete should not exceed 700 microstrain. It is also reported that the shrinkage of lightweight concrete can be 50% greater than the normal weight concrete (FIP, 1983). Concrete made with lightweight aggregates having open textured and irregular surface can produce a shrinkage of 1000 microstrain . The 5-week drying shrinkage of 'Vac-Lite'

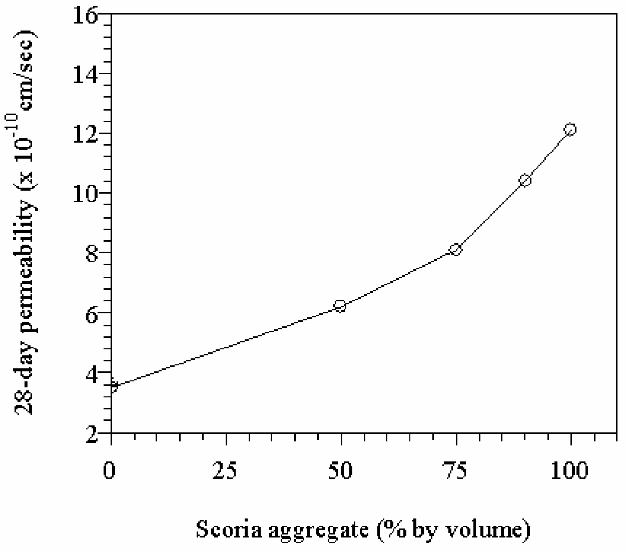

Figure 6. Permeability of SC.

pumice concrete was reported to be around 550 microstrain (http://www.clppumice.com/engineering.html), rotary kiln expanded clay concrete was around 2500 microstrain (Neville, 1995), and 90-day drying shrinkage of Lytag concrete was found to be more than 600 microstrain (Al-Khaiat and Haque 1998). The 28-day drying shrinkage strain of expanded clay concrete ranged from 93 to 193 microstrain, while those of crushed lightweight brick concrete varied from 113 to 212 microstrain (Jamal et al. 1999).

Like hydration of cement, drying shrinkage is a long lasting process that depends on W/C, degree of hydration, curing temperature, relative humidity, duration of drying, aggregate properties, admixture and cement composition (Neville, 1995). The drying shrinkage is affected by twin influences of aggregate cement and water cement ratios. Shrinkage increases with the increase of W/C and decreases with the increase of aggregate cement ratio of concrete (Neville, 1995). Higher water absorption and porosity in lightweight aggregates result in a higher demand for mixing water and an increased W/C, both contributing to higher drying shrinkage strains. Previous study showed that for each 1% increase in mixing water, concrete shrinkage was increased by about 2% (Carlson 1938). For the current series of tests on SC (W/C was kept constant at 0.45), as the percentage of SA was increased from 0 to 100% by volume, the aggregate-cement ratio was decreased from 3.26 to 2.19 by weight. As a consequence, the decrease in shrinkage with the increase of SA was justified.

Results and discussion on permeability

The permeability values obtained were mainly comparative under similar condition of tests for different SC mixes. The effect of % of SA on the permeability of SC at the age of 91 day is shown in Figure 6. The permeability increased from approximately 3.5 x 10^{-10} cm/s to around 13 x 10^{-10} cm/s when SA content was increased from 0 to 100% by volume. Compared to control concrete, the permeability of SC with 100 % SA was about 3.5 times higher. The increase in permeability with the increase of SA content was due to the replacement of GA by comparatively porous SA.

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 (Whiting, 1989). Higher water permeability of lightweight expanded clay and brick aggregate concrete at the age of 28-day was also reported (Jamal et al. 1999). The 28-day permeability of lightweight pumice concrete was around 12.5 x 10^{-10} cm/s (Hossain and Uy, 1999).

Series B: SC mix design, testing and results

In Series A, only the coarse fraction of the total aggregate was replaced by SA and river sand was used as fine aggregate. Much lighter SC could be obtained by partial or total replacement of fine aggregate as well as full replacement of coarse aggregate by using combined fine and coarse SA following the grading requirement suggested by ASTM C 330. Mix design characteristics of concrete mixture in Series B are presented in Table 8. Based on the experience of Series A, two concrete mixes (B-1 and B-3) were prepared with different percentages of SA as coarse aggregate and river sand as fine aggregate. On the other hand, mix B-2 was prepared with SA as both coarse and fine aggregate. Casting and curing of concrete cubes (100 mm x 100 mm) and cylinders (150 mm x 300 mm) as well as testing for slump, air content and strength were similar to Series A.

The air content of SCs ranges between 4.2 % and 4.8%. The SC with SA as both coarse and fine aggregate (B-2) shows higher air content than those of the other two mixes (B-1 and B-3). The average compressive strength of SC cubes at 28 days varies between 24 and 32 MPa depending on the contents of cement, type of fine aggregate either sand or SA and amount of coarse SA (Table 8 and Table 9). The use of SA as fine aggregate in place of river sand (as in mix B-2) reduces the compressive strength to 24 MPa compared to 32 MPa in mix B-1. The average density of SC is also reduced to 1710 kg/m^3 (in mix B-2) compared to 1920 kg/m^3 in mix B-1. This is due to the replacement of fine aggregate (river sand) by relatively weak and lightweight SA. The increase in the quantity of lightweight and weak SA as

Table 8. Mix design of SC (Series B).

Mix desig.	Water kg/m^3	Cement kg/m^3	Coarse Aggregate kg/m^3	Fine Aggregate kg/m^3
B-1**	250	500	410 (SA)	625 (Sand)
B-2*	250	500	410 (SA)	370 (SA)
B-3**	210	420	510 (SA)	560 (Sand)

* all lightweight SA; ** sand/lightweight SA.

Table 9. Properties of SC (Series B).

Mix desig.	Slump mm	Air content %	Average density kg/m^3	Average compressive strength, MPa Cube (Cylinder)	Average thermal conductivity W m^{-1} K^{-1}
B-1**	70	4.2	1920	32 (27)	0.252
B-2*	64	4.8	1710	24 (20)	0.174
B-3**	66	4.4	1860	27 (24)	0.223

* all lightweight aggregate; ** sand/lightweight aggregate.

coarse aggregate also reduces both compressive strength and density of SC as observed in mix B-3.

All SCs develop strength in excess of 15 MPa and have air dry densities ranging between 1850 and 2150 kg/m^3 and satisfy the criteria for semi-lightweight structural concrete according to CSA Standard (CSA 23.3-94, 1994). However, the density of SC (made with 100% fine and coarse SA) in mix B-2 satisfies the criteria for structural low-density (lightweight) concrete per ASTM C 330 and CSA Standard (CSA 23.3 - 94, 1994).

Investigation on the Use of scoria as heat insulating material

Test procedure

The low density and the good heat insulation properties of scoria make it highly resistant to heat flow and thus can be used in the manufacture of heat-insulating building blocks. Concrete discs of about 20 mm in thickness and 150 mm diameter were prepared from the SC mixes of Series B as given in Table 8. The discs were tested in Lees' apparatus, which is used for measuring the thermal conductivity of bad conductors. The concrete discs were placed between the two brass discs of the apparatus. The discs set was then suspended in the air by non-conducting strings attached to the lower brass disc. The top brass disc was heated by water vapor supplied from a steam heater through rubber tubing. The test started by heating the upper brass disc and measuring the temperature in the two discs by digital thermometers mounted in them until the temperature reached at a steady state.

The heat conductivity value of the tested concrete discs is a function of the rate of flow of heat of the brass disc, the cross sectional area of the sample and the temperature gradient between the upper brass disc and lower brass disc. Eq. 1 was used to calculate the heat conductivity (k):

$$k = \frac{H_f}{AT_g} = \frac{m\alpha T_{rf}}{A\left[\frac{T_1 - T_2}{t}\right]} \qquad \text{Eq.1}$$

where A = The area of cross section of the concrete samples; H_f = m. α. T_{rf} = Rate of flow of heat = Rate at which heat is emitted from the lower brass disc; m = Mass of the lower brass disc = 1.9 kg; α = The specific heat of brass = 380 J kg^{-1} K^{-1}; T_{rf} = Rate of fall of temperature (^{0}C s^{-1}) calculated from the cooling curve of the lower brass disc; T_g = (T_1-T_2)/t = Temperature gradient; T_1 = Temperature of the upper disc at the steady state; T_2 = Temperature of the lower disc at the steady state and t = Thickness of the concrete disc.

RESULTS AND DISCUSSION

Table 9 presents the thermal conductivity test results of SC samples. The ASTM C 332 specification for insulating concrete expects a range of thermal conductivity values ranging between 0.15 and 0.43 W m^{-1} K^{-1} depending on the density of the concrete. For the tested concrete samples of dry densities in excess of

1440 kg/m^3, the maximum average thermal conductivity should be 0.43 W m^{-1} K^{-1}. The average thermal conductivity of the concrete samples ranges between 0.15 and 0.22 W m^{-1} K^{-1}. The thermal conductivity of SC decreases with the increase of the percentage of fine scoria in the mix. This also implies that the heat gradient increases with the increase in scoria content. All of the obtained values satisfy the requirements of insulating concrete as per ASTM C 332. The thermal conductivity values of 0.93 and 1.16 were reported for concrete manufactured with 26 and 47% quartz sand with densities of 1800 and 2000 kg/m^3 respectively (FIP, 1983). It is obvious that SC can insulate heat five to seven times better than the quartz sand concrete. Structures built with heat-insulating concrete or building blocks manufactured with scoria material will therefore, result in substantial savings in energy consumption.

CONCLUSION

This paper describes the potential use of volcanic scoria as a construction material to manufacture blended cement and lightweight heat-insulating concrete. The following conclusions are drawn from the study:

The pozzolanic activity tests indicate that finely ground scoria is pozzolanically active and has cementitious characteristics to be used as cement additive. The study recommends the use of 20% scoria as a cement additive in blended cement production.

Tests as per ASTM C 311 (to assess the expansion caused by the alkali-silica reactions) confirm that mortar mixes with 30 and 40% ground scoria content satisfy the ASTM C 618 requirement.

Tests conducted as per ASTM C 151 shows that the autoclave expansion of paste mixes containing up to 40% scoria, satisfy the ASTM C 618 requirement of 0.8% maximum.

The strength activity index (SAI) values as per ASTM C 311 are more than 75% as required by ASTM C 618 for mortar mixes with 10, 20 and 30% scoria content.

Scoria satisfied the requirements of lightweight aggregate for structural concrete as per ASTM C 330.

To make scoria concrete (SC) with 50% to 100% scoria aggregate (SA) as replacement of coarse crushed gravel aggregate (GA) by volume, a range of slump between 60 and 80 mm would provide satisfactory workability.

SC with 50 to 100% SA as replacement of crushed gravel aggregate satisfied the criteria for semi-lightweight structural concrete. SC made with 100% fine and coarse SA satisfies the criteria for lightweight structural concrete.

The 12-week drying shrinkage in 100% SC was about 578 microstrain and seemed to satisfy the criteria of not exceeding 700 microstrain as per ASTM C 330. The permeability of SC was increased from approximately 3.5 x 10^{-10} cm/s to around 13 x 10^{-10} cm/s when SA content was increased from 0 to 100% by volume. Higher permeability of SC may be harmful for long-term durability and can enhance corrosion of reinforcement needing special protection.

The thermal conductivity values of all SC mixes, satisfy the requirements of insulating concrete as per ASTM C 332 and SC can insulate heat five to seven times better than the quartz sand concrete. The scoria is therefore, suitable as a thermal insulating material and has the potential to be utilized in manufacturing heat-insulating concrete and building blocks having strength and durability characteristics comparable to other lightweight aggregates.

Investigations are in progress to develop blended cements and concrete incorporating different combinations of natural pozolans such as scoria, volcanic ash and pumice as these materials can be simultaneuously available in many parts of the world which is the case for Papua New Guinea.

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