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Influence of Foundry Sand and Natural Pozzolans on the Mechanical, Durability and Micro-structural Properties of Lightweight Concrete

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Authors' contributions

This work was carried out in collaboration between both authors. Author KMAH planned/designed the study, supervised the research, managed literature review, involved in experimental data analyses and prepared the final manuscript for submission. Author MSA carried out the experimental investigation, performed data analyses, did literature review and wrote the first draft of the manuscript. Both authors read and approved the final manuscript.

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ABSTRACT

This paper presents the results of an experimental investigation on the use of waste foundry sand as fine aggregate replacement to produce lightweight concrete (LWC) with Portland volcanic ash based blended cement (PVC) and coarse pumice aggregate. The effect of foundry sand as replacement of river sand (from 0 to 30%) on fresh (slump and air content), mechanical (density, compressive/tensile strength, and modulus of elasticity), durability (drying shrinkage, water permeability, rapid chloride permeability and carbonation) and micro-structural (porosity, pore size distribution, micro-hardness, interfacial transition zone) properties is described. Other variables in the study include: water-to-binder ratio (W/B) by mass, aggregate-to-binder ratio (A/B) by mass, total binder content and cement types (ASTM type I cement and PVAC). The properties of LWC is influenced by water to binder ratio (W/B), binder content, foundry sand content and the presence of

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volcanic ash in blended Portland cement. The investigation leads to the production of foundry sand based LWCs for structural applications having satisfactory strength and durability characteristics. The foundry sand induces the beneficial effect of reducing drying shrinkage and water permeability as well as refinement of pore structures and better interfacial transition zone (ITZ). Results have indicated that foundry sand has potential for being used as fine aggregate in producing durable concrete. The utilization of natural pozzolan (volcanic ash) and waste (foundry sand) not only makes LWC economical, but also do help in reducing disposal problems and promote sustainable construction.

Keywords: Pozzolans; foundry sand; lightweight concrete; strength; durability; microstructure.

1. INTRODUCTION

Lightweight aggregates have been used worldwide to manufacture concrete over the decades. The use of natural lightweight aggregates instead of processed artificial aggregates can significantly reduce the cost of such concretes [1-8]. Utilization of natural resources and industrial wastes is becoming widespread and their use as construction materials can lead to low-cost and sustainable construction. Volcanic materials such as pumice and volcanic ash (VA) and other industrial wastes (such as foundry sand, fly ash, slag etc) are used in the production of concrete materials [9-15]. Foundry sand is high quality silica sand which is a by-product of ferrous and non-ferrous metal casting industries where sand has been used for centuries as a molding material. In modern foundry practice, sand is typically recycled and reused through many production cycles. Foundries successfully recycle and reuse the sand many times. When the sand can no longer be reused in the foundry, it is removed from the foundry and disposed [14,15].

Research, over the last few years, lead to the development of blended Portland volcanic ash cement (PVAC) with maximum replacement of up to 20% [9]. Strength, durability and fire resistance of PVAC-based normal weight concrete as well as lightweight concrete with pumice aggregate have been investigated [9-13,16]. The use of comparatively finer foundry sand as replacement of normal sand in such lightweight concretes can improve strength, durability and micro-structural properties in addition to producing green products through consuming industrial wastes. Limited research has been conducted on the use of foundry sand in combination with naturally available pozzolanic volcanic materials (such as ash and pumice) to produce lightweight concrete with no investigation on micro-structural characteristics and long-term durability [17]. Some mechanical and short-term durability properties of such lightweight concrete mixes (such as strength, water permeability, drying shrinkage and carbonation) are reported to prove the viability of using foundry sand [17]. However, it is important to investigate the combined influence of fine aggregate (foundry sand and commonly used river sand), cementitious materials (blended cement with volcanic ash) and lightweight pumice coarse aggregate on micro-structural properties to characterise interfacial transition zone 'ITZ', porosity/pore size distribution and pozzolanic activities (through differential scanning calorimetry 'DSC').

This paper presents the results of a comprehensive experimental investigation that has been conducted over the past few years [17] on the use of waste foundry sand as replacement of fine aggregate (river sand) to produce lightweight concrete (LWC) with VA based blended cement and coarse pumice aggregate. The effect of foundry sand content on strength and long-term durability (up to one year) as well as micro-structural characteristics of LWCs is described. The long term durability and micro-structural properties of foundry sand based LWCs are new contributions of the paper to the existing technology. The recommendations of this research will surely benefit engineers, designers, and concrete manufacturing/construction industries interested in green sustainable lightweight concretes produced from wastes and natural pozzolans.

2. EXPERIMENTAL INVESTIGATION

Volcanic ash and pumice (P) used in this investigation were collected from the Rabaul area of the East New Britain province of Papua New Guinea (PNG) and the source was a volcano called Mount Tavurvur. Waste foundry sand was supplied by a local industry situated in the city of Lae, PNG. Portland VA based blended cement (PVAC) was produced by blending

ASTM Type I Portland cement (C) with 20% VA. Table 1 presents the chemical properties of VA, cement and waste foundry sand. The phase composition of Type I cement and PVAC as per quantitative XRD analyses is also presented in Table 1. The grading of 12.5-mm maximum size coarse volcanic pumice aggregate (VPA) and the local river sand conformed to ASTM C-330. The foundry sand had lower fineness modulus than the river sand. For foundry sand, the size corresponding to 50% passing was around 35µm and average diameter of the particle was around 31µm. Clean drinking water was used to produce the concrete mixtures. The properties of aggregates and foundry sand determined as per ASTM Standards are summarized in Table 2.

2.1 Mix Design of Lightweight Concretes (LWCs)

Mix proportioning was conducted according to ACI 213R-03 [18]. Two series of LWC mixtures (Series A and Series B) were developed [17]. Series A had water to binder ratio (W/B) of 0.45 and binder content of 400 kg/m^3 while Series B had water to binder ratio of 0.37 and binder content of 480 kg/m^3. For each series, four different mixes were developed with foundry sand (used as replacement of river sand) varying from 0 to 30% keeping all other parameters constant. Overall considering both series, variables in the study were aggregate (A) to binder (B) ratio (A/B) by mass (1.8 to 2.4), W/B ratio (0.37 to 0.45), binder content (400 kg/m^3 to 480 kg/m^3) and PVAC content (80 kg/m^3 to 96 kg/m^3). Mix designs of LWC mixtures are presented in Table 3. Numeric in the mix ID represents % of foundry sand as replacement of river sand.

2.2 Concrete Mixing, Test Specimens, Curing Conditions and Testing Details

All eight concrete mixtures were prepared in a laboratory counter-current mixer where the mixing sequence consisted of 5 minutes of mixing the aggregates with water followed by

Table 1. Chemical and other properties of volcanic ash, pumice, foundry sand and cement

	VA	Cement (C)	Foundry sand	Potential phase composition from X-ray diffraction (%)		
Chemical Compounds	Mass, %	Mass, %	Mass, %	Phase	C	PVAC (C + 20%VA)
Calcium oxide (CaO)	6.3	64.6	1.91	C_3S	65.9	55.2
Silica (SiO_2)	59.5	21.2	79.11	C_2S	13.2	9.1
Alumina (Al_2O_3)	17.8	5.6	7.21	C_3A	7.9	5.4
Iron oxide (Fe_2O_3)	6.9	3.4	5.21	C_4AF	9.9	7.6
Sulphur trioxide (SO_3)	0.6	2.1	0.04	Other	2.4	7.4
Magnesia (MgO)	2.5	2.1	2.12	Total	99.3	84.7
Sodium oxide (Na_2O)	3.1	0.5	0.13	Glassy fraction	0.7	15.3
Potassium oxide (K_2O)	3.3	0.5	0.15			
Loss on ignition	0.8	1.1	3.21			
Free lime (CaO)	-	0.6	-			
Physical properties						
Blain fineness, m^2/kg	292	318				
Unit mass, kg/m^3	2450	3150				

Table 2. Properties of aggregates

Aggregates	Specific gravity	Bulk density, kg/m^3 ASTM C 29		Fineness modulus	Water absorption 24 hour (%)
	Oven dry	Loose oven dry	Rodded oven dry		
12.5 mm maximum size VPA	ASTM C 127 0.98	680	750		ASTM C 127 26.7
	ASTM C 128				ASTM C 128
River sand	2.61	-	-	2.92	2.0
Foundry sand	2.62	-	-	1.67	2.2

additional 5 minutes of mixing with blended cement. Due to the high water absorption capacity, the VP aggregates were pre-soaked for a minimum of 48 hours and then saturated surface dry aggregates (SSD) were used [17]. Tests on fresh, mechanical, durability and micro-structural properties of concrete mixtures were conducted.

The slump of fresh concrete was determined as per ASTM C 143. Air content of LWC mixtures was determined as per ASTM C173/173M, respectively. 28-day compressive (f'_c) and indirect tensile (f_t), strengths were determined by using 100 x 200-mm cylinders as per ASTM C-39 and ASTM C 496, respectively. 100 x 200 mm cylinders were also used for modulus of elasticity (E) and density.

The drying shrinkage (DS) of 75 x 75 x 285-mm specimens were monitored according to ASTM C-157 every week for a total of 52 weeks (for series A) and 12 weeks (for series B). The 12-week water permeability (α) was determined (after 1 day of moist and remaining days of air curing of 100 x 200 mm cylinder specimens) by applying 1.4 MPa of water pressure in a hydraulic permeability apparatus. The top and bottom of the specimen were sand blasted to remove the surface layer of cement paste. The sides were coated with two coats of a 70:30 by weight mixture of paraffin and rosin applied hot using a paint-brush. The cylinder specimens were then installed in the chamber to carry out the test. The water permeability calculations were based upon an application of Darcy's law for unidirectional flow at constant head [17].

100 mm x 200 mm cylindrical specimens were used to measure 12-week and 52-week carbonation depth using phenolphthalein indicator as per RILEM CPC-18 [19]. The specimens wrapped in plastic sheets were cured at room temperature for 24 hours followed by 28 days of water curing and then, air cured until tested at 12-week and 52-week.

The specimens were split at date of testing and the cleaned freshly split surface was sprayed with a phenolphthalein pH indicator. Immediately after spraying the indicator, the average depth (x) of the colorless phenolphthalein region was measured from three points, perpendicular to the two edges of the split face [17].

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

Rapid chloride permeability test (RCPT) was conducted as per ASTM C1202-97 on 100 (diameter) x 50-mm concrete slices (prepared from concrete cylinders) to determine permeability and resistance to chloride ion penetration. The chloride ion resistance of

Table 3. Mix designs and fresh state properties of LWC

Mix ID	FS %	A/B	W/B	Binder (B) kg/m^3 PVAC		Aggregate, kg/m^3		
						Coarse	Fine	
				C	VA	VPA	Sand	FS
Series A								
A-FS0	0	2.4	0.45	320	80	364	581	0
A-FS10	10	2.4	0.45	320	80	364	501	58
A-FS20	20	2.4	0.45	320	80	364	465	116
A-FS30	30	2.4	0.45	320	80	364	407	174
Series B								
B-FS0	0	1.8	0.37	384	96	369	507	0
B-FS10	10	1.8	0.37	384	96	369	456	51
B-FS20	20	1.8	0.37	384	96	369	405	102
B-FS30	30	1.8	0.37	384	96	369	354	153

A: Total aggregate; C: Portland cement; W = Water; VPA: Volcanic pumice aggregate; FS: Foundry sand concrete gives an indirect measure of its permeability and internal pore structure, as more current passes through a more permeable concrete.

The differential scanning calorimetry (DSC) test was performed on the hardened mortar samples taken from the crushed concrete cubes (at 25°C) after 56 days of curing to determine the quantity of $Ca(OH)_2$ formed in the mortars. The 60 mg samples were heated at a constant heating rate of 10°C per minute to 1100-1200°C, in a dynamic helium atmosphere. DSC thermograms showed peaks due to endothermic (heat absorbing) and exothermic (heat releasing) reactions. The $Ca(OH)_2$ content was equivalent to the area (enthalpy) under the respective endothermic peaks. The size of the area under the curve was related to the quantity of the material in the sample.

Based on the ASTM E384-99 testing method, a Vickers indenter was used to determine the microhardness in bulk pastes and in the transition zone between aggregates and hcp. Slices cut from the middle of the cylinders were polished with 600# paper then 1500# paper to obtain an adequate surface with a minimum of damage. Slices were then carefully sealed to avoid carbonation which might lead to larger measured hardness values. As the typical width of the interfacial transition zone (ITZ) is about 50 µm, the applied load in the microhardness test was determined to be 0.05 N so that the spacing between indentation points should be at least two times the diagonal of the indentation while ensuring a sufficient number of points was taken to map the ITZ. The measured range was up to 250 µm away from the surface of aggregates although the actual width of the transition zone can be far smaller than 50 µm. Six determinations were performed on the surface of each sample, and the profiles of microhardness from the average values were derived.

3. RESULTS AND DISCUSSION

3.1 Fresh State Properties of LWCs

The fresh state properties of concrete mixtures are presented in Table 4 [17]. The slump of concrete mixtures slightly decreased with the increase of foundry sand from 0 to 30%. This can be attributed to the higher water demand of the finer foundry sand particles [9,10,17]. Slump value ranges between 68 mm and 73 mm for Series A while for Series B, it ranges between 59 mm and 65 mm. Lightweight concrete slumps less compared to normal aggregate concrete due to lower density of aggregate [7,8]. However, all concrete mixtures were found workable and showed no segregation. Series A mixtures slumped higher compared to Series B, possibly due to higher W/B. The air content of LWC mixtures decreased with the increase of foundry sand in both Series A and B as observed in other research studies [9,10]. The air content of LWC mixtures ranged between 2.5% and 3.1%.

3.2 Mechanical Properties of LWCs

The mechanical properties such as density, compressive/tensile strength and modulus of elasticity of concrete mixtures are summarized in Table 4 [17].

The 28-day density increased slightly with the increase of foundry sand content (Fig. 1). The 28-day compressive strength also increased (by

Table 4. Fresh state and mechanical properties

Mix ID	Fresh state properties		Mechanical properties (28-day)			
	Slump mm	Air content %	Density$^+$ kg/m^3	f'_c MPa	f_t MPa	E GPa
Series A: W/B = 0.45; A/B = 2.4						
A-FS0	73	3.1	1799	20	1.9	9.5
A-FS10	70	2.9	1799	20	1.9	9.6
A-FS20	71	2.7	1801	22	2.0	9.6
A-FS30	68	2.6	1802	23	2.1	9.7
Series B: W/B = 0.37; A/B = 1.8						
B-FS0	65	2.8	1806	28	2.4	11.9
B-FS10	65	2.8	1807	29	2.4	11.9
B-FS20	62	2.6	1808	30	2.5	12.0
B-FS30	59	2.5	1810	31	2.6	12.1

f'c: Compressive strength; f_t : Tensile strength; E: Modulus of elasticity; +structural lightweight concrete (f'c > 15 MPa; density < 1850 kg/m^3)

15% for series A and 11% for series B mixes) with the increase of foundry sand from 0 to 30% (Fig. 1). The increase in strength can be attributed to the resulting denser concrete due to replacement of coarser river sand by the finer foundry sand leading to better packing of the matrix [9,10].

As per Table 4, all LWCs (Series A and Series B) developed compressive strength ranging between 20 MPa and 31 MPa (>15 MPa) with an air dry density ranging between 1799 kg/m^3 and 1810 kg/m^3 (<1850 kg/m^3) to satisfy the criteria for lightweight structural concrete [8].

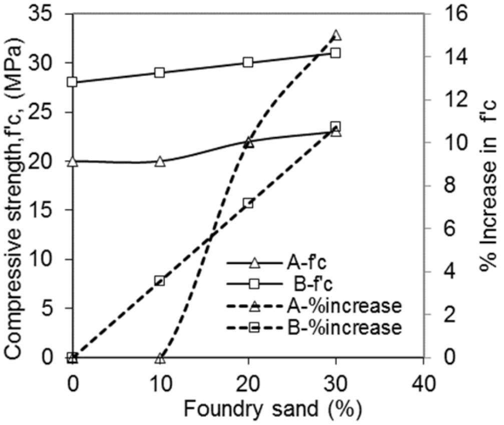

Fig. 1. Effect of foundry sand on 28-day compressive strength

The 28-day tensile strength also increased (by 11% for series A and 8% for series B mixes) with the increase of foundry sand content from 0 to 30% (Fig. 2). The 28-day tensile strength of LWC mixes ranged between 1.9 MPa and 2.6 MPa (Table 4). The 28-day elastic modulus also slightly increased with the increase of foundry sand from 0 to 30% and ranged between 9.5 GPa and 12.1 GPa (Table 4). Series B concretes showed higher compressive/tensile strength than those of Series A due to lower W/B, higher binder content and lower aggregate to binder ratio (A/B).

Fig. 3 shows good correlations between tensile strength (f_t) and compressive strength (f'_c) as well as between modulus of elasticity (E) and compressive strength (f'_c).

3.3 Durability Properties of LWCs

The durability properties in terms of drying shrinkage, water permeability, rapid chloride permeability (RCP) and carbonation resistance of concrete mixtures are summarized in Table 5.

3.3.1 Drying shrinkage

Figs. 4 and 5 show the variation of drying shrinkage with age for Series A and Series B concrete mixes, respectively. For all concrete mixes, drying shrinkage increased at faster rate up to the age of 14 days - mixes containing 30% FS showed higher rate of increase (Figs. 4 and 5).

Table 5 summarizes the 12-week drying shrinkage of concrete mixtures. The 12-week drying shrinkage of Series A mixtures ranges between 570 and 583 microstrain compared to between 560 and 572 microstrain of Series B (Table 5). The 52-week drying shrinkage of Series A mixtures also remained below 600 microstrain (Fig. 4). Generally, drying shrinkage increases with the increase of W/B, and hence, Series A mixes showed higher shrinkage than Series B. The drying shrinkage increased (by 13% and 15% for Series A and Series B mixes, respectively) with the increase of foundry sand from 0 to 30% (Fig. 6).

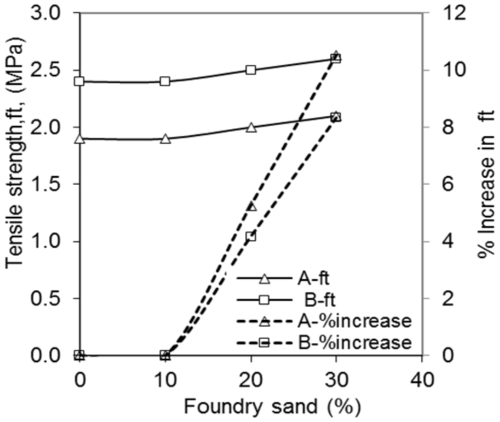

Fig. 2. Effect of foundry sand on 28-day tensile strength

The shrinkage of lightweight concrete can be 50% greater than normal weight concrete because of high absorption capacities of aggregates [20]. High initial drying shrinkage and comparatively low tensile strength may lead to the danger of shrinkage cracking in LWC mixes. However, all LWC mixtures showed a 12-week drying shrinkage of less than 600 microstrain. The drying shrinkage of PVAC concrete mixtures in previous research studies was found to be lower compared to those with Portland cement similar to that observed in fly ash concrete [11,13,20]. Hence, the increased drying shrinkage due to the presence of foundry sand may be compensated by the use of PVAC in the developed LWC mixtures. It reflects the beneficial effect of using combination of PVAC and foundry sand in the developed LWCs.

3.3.2 Water and rapid chloride permeability

The 12-week water permeability of LWCs decreased from 5.82 x 10^{-10} cm/s (highest value) to around 5.61 x 10^{-10} cm/s for Series A and from 5.52 x 10^{-10} cm/s to around 5.19 x 10^{-10} cm/s for Series B when foundry sand content was increased from 0 to 30% by weight (Table 5). A maximum decrease of about 6% was observed in the study [17].

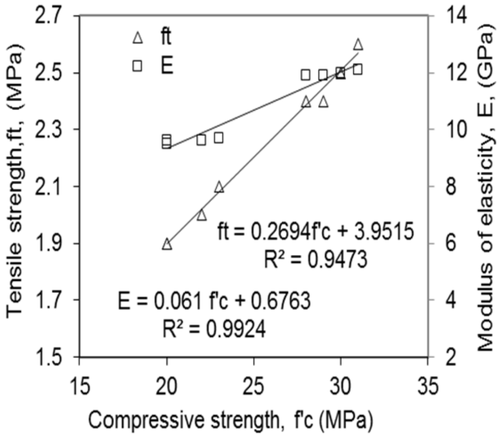

Fig. 3. Correlations between compressive strength and tensile strength/modulus of elasticity

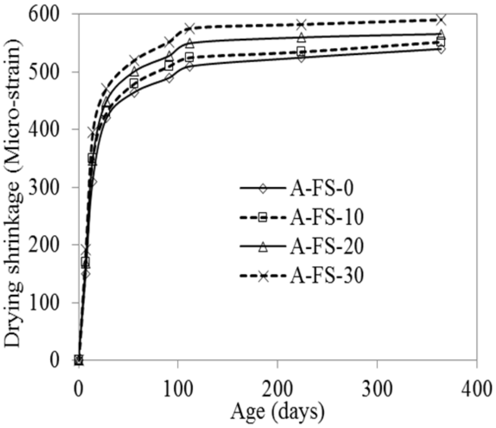

Fig. 4. Influence of foundry sand content and age on drying shrinkage (Series A)

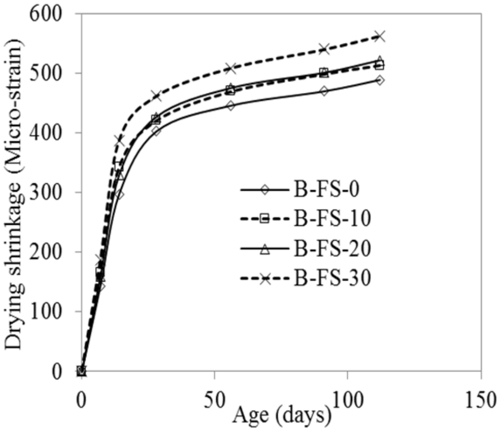

Fig. 5. Influence of foundry sand content and age on drying shrinkage (Series B)

Table 5. Summary of durability and micro-structural properties

Mix ID	Durability Properties			MIP		DSC*	Lowest micro-hardness at ITZ
	12-week (52-week) DS Microstrain	56-day RCPT Coulomb	12-week water permeability x 10^{-10}cm/s	Porosity % v/v	Avg. pore diameter µm	$Ca(OH)_2$ J/g	x10^{-2} GPa
Series A: W/B = 0.45; A/B = 2.4							
A-FS0	510 (540)	2552	5.82	5.98	0.0389	565	40.3
A-FS10	525 (552)	2493	5.75	5.83	0.0369	567	41.5
A-FS20	550 (566)	2254	5.71	5.81	0.0354	566	43.5
A-FS30	575 (590)	2121	5.61	5.75	0.0344	571	44.5
Series B: W/B = 0.37; A/B = 1.8							
B-FS0	490	2367	5.52	5.37	0.0324	568	36.0
B-FS10	515	2221	5.45	5.26	0.0318	571	37.5
B-FS20	523	2154	5.31	5.20	0.0311	573	39.5
B-FS30	564	2045	5.19	5.17	0.0307	574	41.1

*DS: Drying shrinkage (microstrain); ITZ: Interfacial transition zone; MIP: Mercury intrusion porosimetry; DSC: Differential scanning calorimetry; * endothermic peak area*

The 56-day rapid chloride permeability (RCP) of LWCs decreased from 2552 Coulomb to 2121 coulomb for Series A and from 2367 Coulomb to 2045 Coulomb for Series B when foundry sand content was increased from 0 to 30% by weight (Table 5). A maximum decrease of about 17% was observed in the study. As per ASTM C1202, rapid chloride permeability of LWCs can be classified as 'Moderate' (ranging between 2000 and 4000 coulombs).

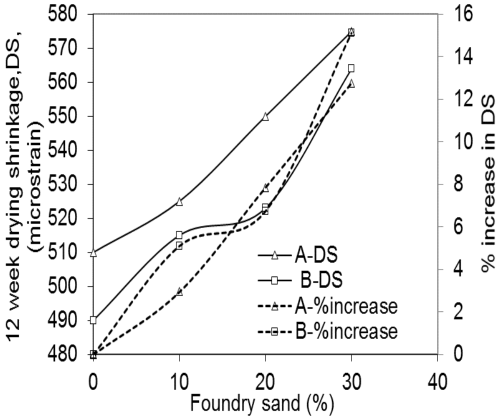

Fig. 6. Influence of foundry sand content on 12-week drying shrinkage

Permeability of concrete depends on the permeability of paste/aggregate, gradation of aggregate, paste-aggregate transition zone, paste to aggregate proportion and W/B. Permeability increases with the increase of W/B (as confirmed from the higher permeability of Series A, LWC mixtures) and initial curing conditions [21]. The resulting denser LWC with the increase foundry sand should exhibit lower permeability (as confirmed from this study). The reduction of permeability may have beneficial effect of improving the long-term corrosion resistance of foundry sand based LWCs. The drop in permeability with age had been reported in fly ash concrete and volcanic ash concrete [13,22]. So combination of PVAC and foundry sand has the beneficial effect of reducing water permeability of concrete. Previous investigations also showed that lightweight concrete had equal or lower permeability than its normal weight counterpart despite wide variations in concrete strengths [18,23].

3.3.3 Carbonation resistance

The relation between carbonation depth (x) in mm and the period of exposure (t) in month can be correlated through carbonation coefficient (c) as shown in Eq. 1 [17,24]:

$$x = ct^{0.5} \tag{1}$$

Fig. 7 and Fig. 8 compare the variation of 12-week and 52-week carbonation depth and carbonation coefficient with foundry sand content, respectively. Carbonation depth is found to increase with the increase of foundry sand from 0 to 30% similar to that observed in other research studies [14]. Series A mixes with higher W/B showed higher carbonation depth. However, maximum carbonation depth at 12-week and 52-week were 0.93 mm and 1.08 mm, which is far less than the cover of reinforcing bar to cause corrosion. Lower carbonation depth of the LWC mixtures can also be attributed to the presence of volcanic ash in blended cement [25]. The 12-week and 52-week carbonation coefficient (c) also increased with the increase of foundry sand content. However, carbonation coefficient of far less than 1.5 represents good concrete as per Fig. 8 [26].

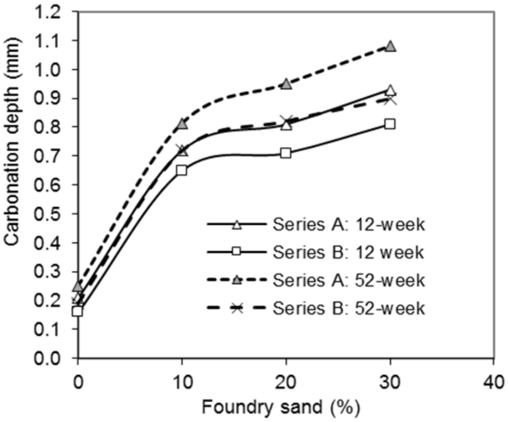

Fig. 7. Variation of carbonation depth

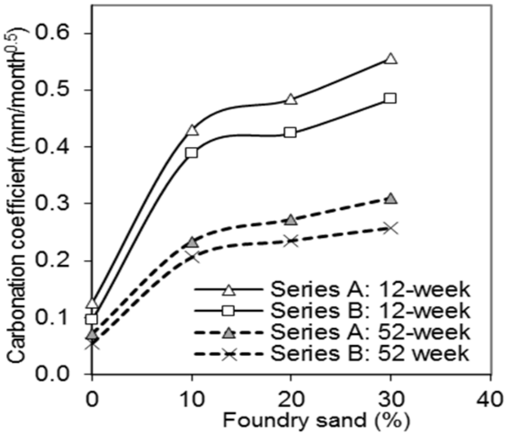

Fig. 8. Variation of carbonation coefficient

3.4 Micro-structural Properties

Micro-structural properties of LWC mixtures in terms porosity, average pore diameter, DSC parameter and microhardness at interfacial transition zone (ITZ) are summarized in Table 4.

3.4.1 Porosity, pore size distribution and DSC test results

The porosity and average pore diameter (as measured by MIP) for the LWC mixtures decreased with the increase of foundry sand content in both series A and B mixes (Table 5). Porosity decreased by about 4% while average pore diameter decreased by 14% (for series A) and 6% (for series B) when foundry sand content was increased from 0 to 30%.

The beneficial effect of the addition of foundry sand can also be identified from the lower volume of pores (larger than 0.01 μm) in LWCs with 30% FS compared to control LWSC (with 0% FS) for both Series A and B mixes (Fig. 9). The lower volume of pores (larger than 0.01 μm) in (A-FS-30 and B-FS-30) confirms the refinement of pore structures in presence of FS.

As per DSC test results (Table 5), the quantity of $Ca(OH)_2$ in concrete mixes was not affected due to the increase of foundry sand content from 0 to 30% which confirmed the non-pozzolanic behaviour of foundry sand. Previous research studies [11,13] have confirmed significant decrease in porosity, average pore diameter and the quantity of $Ca(OH)_2$ in concretes mixes (associated with refinement of pore structure) made with PVAC (compared with Portland cement). The pozzolanic reactivity of VA in PVAC consumed $Ca(OH)_2$ resulting from the hydration of cement as confirmed from the lowering of $Ca(OH)_2$. Such pozzolanic reaction was attributed to the decrease of pore size with subsequent refinement of pore structure, denser concrete and increased long-term impermeability [11,13]. The drop in long-term permeability had also been reported in fly ash cement paste and concrete [22]. The combination of foundry sand and pozzolanic volcanic ash (present in PVAC) has shown cumulative benefit of reducing permeability, porosity and average pore diameter which can improve the long-term corrosion resistance of PVAC based LWCs.

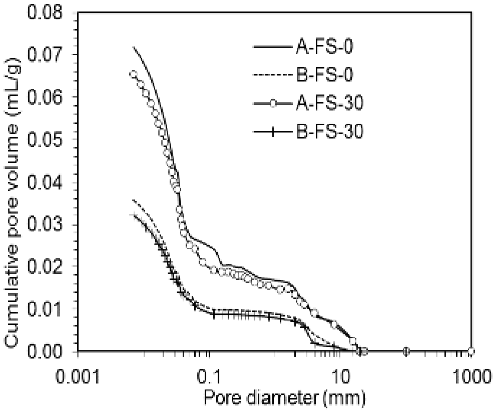

Fig. 9. Effect of foundry sand on pore size distribution in LWCs

3.4.2 Microhardness at interfacial transition zone (ITZ)

Microhardness testing was applied to characterize the influence of PVAC, foundry sand and coarse VPA on the ITZ of LWCs around the aggregates. Figs. 10 and 11 show the variation of ITZ ranges of all LWC mixtures. Higher microhardness values in the vicinity of the aggregate due to the presence of stiff inclusions in the excited range around the indentation were observed in all specimens similar to previous research studies [27]. Microhardness test showed lower Vickers Hardness Numbers (Hv) in ITZ than those in the middle of the hardened bulk cement pastes. The extent of the weak zone (ITZ range) was about 40 μm and seemed to be not affected by the increase for foundry sand.

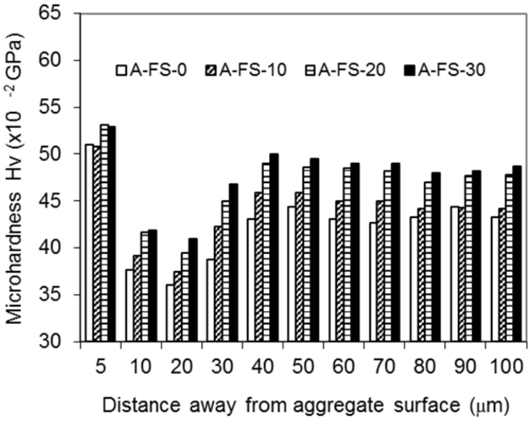

Fig. 10. Microhardness characteristics at ITZ for Series A mixes

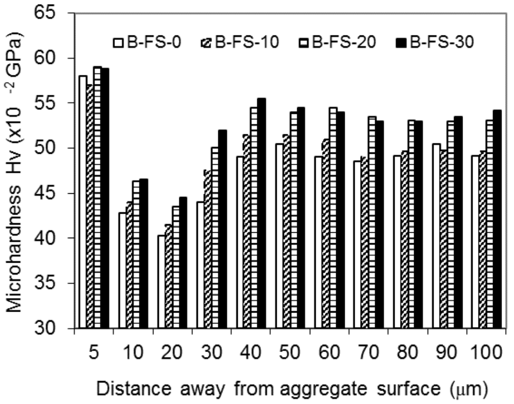

Fig. 11. Microhardness characteristics at ITZ for Series B mixes

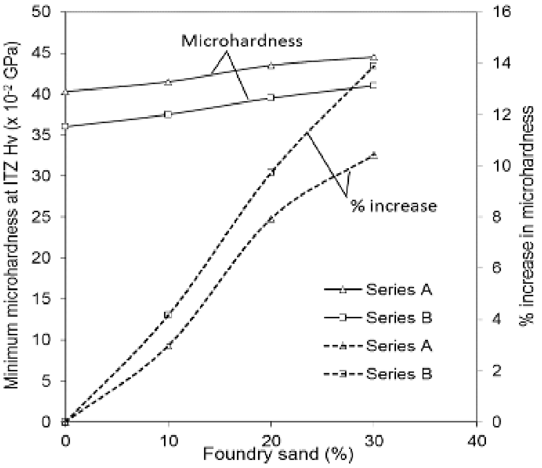

Fig. 12. Influence of foundry sand on microhardness

Table 5 shows an increase of minimum microhardness at ITZ with the increase of foundry sand content (from 0 to 30%) and increase of about 14% and 10% were observed for Series B and series A mixes, respectively (above Fig. 12). The higher values of microhardness (within the ITZ) confirmed the superior (stronger) ITZ in foundry sand based LWCs compared to control mixes. Microhardness values of Series A mixes were found to be higher compared to those based on Series B (followed the trend of compressive strength which was higher for mixes in Series A). Paste aggregate transition zone can also be improved in the long term as a result of extended period of moist curing (internal curing) due to the availability of absorbed pore water in the lightweight aggregate. This may be the reason for series B mixes (with higher W/B) showing higher % increase in ITZ microhardness compared to those of Series A. Superior ITZ characteristics were also observed in concretes (both normal weight and lightweight) made with PVAC and pumice aggregate [11-13]. The addition of foundry sand has the beneficial effect of further enhancing ITZ characteristics of LWCs made with PVAC. The lower water permeability of developed foundry sand based LWCs is attributed to the development of increased transition zone microhardness (as observed in this study) at the surface of the lightweight aggregate producing superior contact zone that enhances bond between the aggregate and the continuous matrix phase.

4. CONCLUSIONS

The fresh and mechanical properties as well as durability and microstructural characteristics of lightweight concrete (LWC) incorporating volcanic ash based blended cement (PVAC), volcanic pumice aggregate (VPA) and foundry sand as replacement of fine aggregate are described. The following conclusions are drawn from the study:

1. The 28-day density, compressive/tensile strength and modulus of elasticity increase with the increase of % foundry sand as replacement of river sand. Developed LWC mixtures with varying aggregate-to-binder ratio, water-to-binder ratio and foundry sand content have satisfied the requirement of lightweight structural concrete (strength in excess of 15 MPa and density of less than 1850 kg/m^3). Good correlations exist between compresssive strength and tensile strength/modulus of elasticity.
2. The 12-week water permeability of LWC mixtures decreases with the increase foundry sand from 0 to 30% by mass. The 12-week/52 week drying shrinkage of LWC mixtures increases with the increase of foundry sand. Such LWCs may be prone to cracking due to higher drying shrinkage and comparatively lower tensile strength. However, the danger of shrinkage cracking can be compensated by the lower modulus of elasticity. In addition, the increased drying shrinkage due to the presence of foundry sand is compensated by the use of PVAC.
3. Although carbonation depth increases with the increase of foundry sand from 0 to

30%, maximum carbonation depths at 12 week and 52 week were far less than the cover of reinforcing bar to cause corrosion. Lower carbonation depth of the LWC mixtures can also be attributed to the presence of volcanic ash. In terms of carbonation resistance, developed LWCs can be classified as good.

4. The combination of foundry sand and pozzolanic volcanic ash based blended cement has shown cumulative benefit of reducing permeability, porosity and average pore diameter as well as enhancing microhardness characteristics at ITZ which illustrates superior long-term durability and corrosion resistance of developed LWCs.
5. Overall, this research confirms the viability of using combination of PVAC and foundry sand in the production of LWCs having satisfactory mechanical, durability and microstructural properties.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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