International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:6, 2016

Feasibility of a Biopolymer as Lightweight Aggregate in Perlite Concrete

Ali A. Sayadi, Thomas R. Neitzert, G. Charles Clifton

Abstract**—**Lightweight concrete is being used in the construction industry as a building material in its own right. Ultra-lightweight concrete can be applied as a filler and support material for the manufacturing of composite building materials. This paper is about the development of a stable and reproducible ultra-lightweight concrete with the inclusion of poly-lactic acid (PLA) beads and assessing the feasibility of PLA as a lightweight aggregate that will deliver advantages such as a more eco-friendly concrete and a non-petroleum polymer aggregate. In total, sixty-three samples were prepared and the effectiveness of mineral admixture, curing conditions, water-cement ratio, PLA ratio, EPS ratio and perlite ratio on compressive strength of perlite concrete are studied. The results show that PLA particles are sensitive to alkali environment of cement paste and considerably shrank and lost their strength. A higher compressive strength and a lower density was observed when expanded polystyrene (EPS) particles replaced PLA beads. In addition, a set of equations is proposed to estimate the water-cement ratio, cement content and compressive strength of perlite concrete.

Keywords**—**Perlite concrete, poly-lactic acid, expanded polystyrene, concrete.

I. Introduction

PERLITE is a siliceous volcanic glass containing 2-5% combined water. It can be expanded about 4-20 times by transforming chemically bound water (2-5%) to vapour when subjected to temperature within its softening range (above 870 °C). Expanded perlite is a high porosity aggregate with lower density, lower thermal conductivity value, and higher sound absorption. Expanded perlite is also classified as an artificial pozzolanic material due to its glassy structure along with a high silicon dioxide (SiO_2) and aluminium oxide (Al_2O_3) content [1].

Perlite is not technically used in concrete yet [2], [3]. A number of experimental and analytical studies have been conducted on the effectiveness of perlite on physical and mechanical properties of fresh and hardened concrete [1]-[11]. It has been reported that expanded perlite is a proper artificial aggregate with potential uses as coarse and fine aggregate to produce lightweight concrete with a density of lower that 800 kg/m^3 [4], [5]. Ozkan et al. [2] have concluded that thermal conductivity and unit weight of perlite concrete significantly decreased as the expanded perlite is replaced with natural aggregate. In addition, the same trend was observed in terms of compressive strength and elastic modulus as the content of expanded perlite enhanced [2]. Moreover, increasing the amount of expanded perlite significantly increased the water absorption and sorptivity. Gurhan et al. [6] have concluded that expanded perlite is capable of being used as a lightweight construction material. Additionally, the effect of expanded perlite and hydroxypropyl methylcellulose (HPMC) on hydration heat of concrete has been investigated by Lei et al. [7]. They have found that expanded perlite causes a significantly delayed hydration induction period and an acceleration period of cement pastes. Demirboga et al. [8] have found that thermal conductivity of concrete is a factor of porosity and increasing the expanded perlite percentage resultant in a lower thermal conductivity value due to the porous structure of the perlite. This trend is observed in another study about the influence of perlite on thermal conductivity [9]. They have found that perlite brings down the density and thermal conductivity value of the matrix. Yu et al. [10] found that the addition of perlite powder significantly improved the high-freeze-thaw resistance, fire resistance and causes an increase in the alkali silica reaction of the matrix due to the microcrystalline quartz (mostly chalcedony) content of perlite. Bekir et al. [3] have reported that the mechanical properties of concrete increased as the ratio of perlite decreased. Turkmen et al. [11] have found that slump flow is a factor of viscosity and the addition of silica fume increases the cohesiveness of the matrix due to an increase in the number of solid-to solid contact points. The addition of expanded perlite aggregate (EPA) remarkably decreased the unit weight of the matrix mainly due the fact that EPA has a lower specific gravity compared with normal aggregate. Moreover, they have concluded that the capillarity coefficient of concrete depends on curing time, curing conditions and EPA ratio. Kotwica et al. [1] have reported that waste perlite significantly decreased the calcium hydroxide content and increased the amount of hydration products within hardened pastes.

EPS is inert, hydrophobic and a stable low density foam which is obtained from styrene monomer. EPS has an excellent resistance to alkalis, methanol, ethanol silicone oils, halide acids, oxidizing and reducing agents and partial resistance to paraffin oil, vegetable oils, diesel fuel and Vaseline [12]. It has been reported [12] that toxicity levels of EPS are less than other ordinarily used materials. Compared with wood, polystyrene foam produces almost the same amount or less toxic gas, carbon monoxide and carbon dioxide when subjected to an ignition source. A wide range of lightweight concrete densities can be produced by

Ali A. Sayadi is with the Engineering Research Institute (ERI), Auckland University of Technology (AUT), Auckland, New Zealand (e-mail: asayadi@aut.ac.nz).
Thomas R. Neitzert is with the Engineering Research Institute (ERI), Auckland University of Technology (AUT), Auckland, New Zealand.
G. Charles Clifton is with the Department of Civil & Environmental Engineering, University of Auckland, Auckland, New Zealand.

incorporating and substituting of a certain ratio of natural aggregate with EPS beads [13], [14]. Research on EPS concrete and EPS aggregate traces back to 1973 [15]. The extremely low density and hydrophobic nature of EPS beads constrains the application of EPS concrete. In fact, beads tend to float (10-20 kg/m^3) when used as lightweight aggregate and cause serious segregation and poor mix distribution in the matrix. The bonding additives such as epoxy resin (aqueous dispersions of polyvinyl propionate), water-emulsified epoxies [15], [16], and chemically treated EPS [17] particles are used to increase the interfacial bonding strength between beads and matrix. It was reported that mineral admixtures such as silica fume [18], [19], fly ash [20], [21] and ground granulated blast furnace slag were used as bonding additives to increase the interfacial bonding strength between beads and the matrix and to improve dispersion of EPS beads in the cement matrix [13]. It has been confirmed and reported that the compressive strength of EPS concrete is reduced as a certain amount of EPS beads replaces natural aggregate [12]-[27]. Ravindrarjah et al. [17] have concluded that the water-cement ratio of EPS concrete should be retained as low as possible to obtain the highest compressive strength. Moreover, EPS concrete exhibited acceptable resistance to chemical attacks such as calcium hydroxide, sodium sulphate and ammonium sulphate solution, and its resistance to 5% hydrochloric acid enhanced as the water-cement ratio decreased. Schachow et al. [22] have investigated the differences between mechanical properties of EPS and vermiculite concrete and concluded that an air-entraining agent and the lightweight aggregate volume directly affect the compressive strength and density of concrete. Lower compressive strength and density is obtained as the volume of EPS and foam is enhanced [23]. This trend can be due to the fact that lightweight aggregate has lower specific unit weight along with near zero strength and the fact that the air-entraining agent increases the porosity of concrete which causes a considerable reduction in the compressive strength of the matrix. Furthermore, vermiculite concrete shows a lower thermal conductivity value than EPS concrete due to higher porosity of vermiculite. However, EPS concrete has advantages in terms of water absorption ratio (almost zero) and unit weight (lighter than vermiculite). Chen et al. [24] have indicated that the inclusion of foam substantially enhances the slump value of EPS concrete as a result of the fact that foam reduces the bulk density of the matrix and increases the volume of cement paste. In addition, the introduction of foam with its small spherical bubbles acts as ball bearings in the matrix and reduces the internal friction between particles. They have also found that an increase in the volume of foam causes a decrease in compressive strength of concrete. Moreover, they have concluded that thermal and mechanical properties of EPS foamed concrete is a factor of cement content and EPS volume. Madandoust et al. [25] have found that the slump flow enhanced, when the volume of EPS is increased. The slump flow increased as a result of lower internal friction between cement paste and particles due to spherical shape, smooth surface and hydrophobic nature of EPS. The addition of nano-SiO_2 decreased the slump flow due to the fact that nano-SiO_2 has a higher surface area and promotes the packing of particles. This trend causes higher internal friction between the particles of the matrix resultant in a lower slump flow. The influence of nano-SiO_2 is reduced as the volume of EPS particles increased. Kan et al. [26] have concluded that the density of lightweight concrete is more sensitive to the slump flow value than the water-cement ratio. A higher compressive strength and density is observed as the cement-EPS ratio is increased.

The mechanical properties of chemically treated EPS lightweight concrete have been investigated by Ravindrarajah et al. [17]. They have concluded that a higher compressive strength and tensile strength is obtained with a lower water-cement ratio. In addition, the higher shrinkage value observed by inclusion of EPS aggregate is mainly due to the lower resistance of EPS particles, because of their smooth surface and spherical shape, to the shrinkage of the cement paste. Furthermore, polystyrene aggregate is a stable aggregate when subjected to calcium hydroxide, sulphate solutions and ammonium sulphate solutions. Xu et al. [27] have found that mechanical properties of EPS lightweight concrete are a factor of EPS volume, water-cement ratio, cement content and sand content. However, EPS volume and cement/sand content are the most and least important factors in design of EPS concrete. The lower degree of compaction and workability obtained with an increase in EPS volume is mainly due to the compressible nature and low unit weight of EPS. Compared with normal concrete, the failure mode of EPS concrete was more gradual. The stress-strain diagram of EPS concrete was almost the same as normal concrete. However, the length of the elastic segment and the slope of the stress-stain curve increased as the volume of EPS decreased.

One of the main problems associated with the use of polystyrene (such as EPS) is the environmental impact of this material. Millions of tons of waste polystyrene are produced by the packing industries. European countries prohibited EPS from landfills and manufacturing companies are responsible for collection and recycling of EPS in these countries [28]. As a matter of fact, EPS is non-biodegradable, resistant to photolysis and derived from non-renewable petroleum resources (according to EN 13432). In addition, pentane emission during the manufacturing of polystyrene products is another problem which considerably affects the environment. It has been stated [30], [31] that estimated volatile organic compounds (VOCs) escaping into to the atmosphere is about 250000 to 300000 tons/year. Moreover, increases in oil prices considerably affect polymer products prices as the polymers used in foams are mainly obtained from petroleum. Thus, the parameters such as environmental concerns, fluctuation of crude oil prices along with natural gas pricing on polymer markets causes a growing interest in developing materials with more environmentally friendly characteristics [28]-[32]. In order to eliminate the influence of petroleum polymer on the environment, and to replace non-renewable oil derived polymers with renewable bio-based resources, several bio-polymer materials were developed with non-petroleum materials. From all the available bio-polymers, PLA is one of the readily available and a more cost-competitive bio-plastics which is progressively preferred as alternative for petroleum polymers (i.e. polyethylene, polypropylene and polystyrene) due to its eco-friendly profile and performance features. PLA is being introduced as foamed packing for food applications due to its advantages such as excellent insulation properties, good mechanical properties and its characteristics in terms of heat resistance or flame retardancy [12], [25]. Based on European standard EN 13432, PLA is considered and categorized as a sustainable and compostable polymer. PLA is produced through ring-opening polymerization of lactide and a dimer of lactic acid, which is derived from fermented corn starch. Moreover, carbon dioxide (CO_2) as an eco-friendly blowing agent is used for expansion of PLA polymer [28]-[32].

The paper aims to assess the feasibility of expanded poly-lactic acid (EPLA) lightweight aggregate as a proper substitution for petroleum polymer such as EPS and to produce a more economical and environmentally friendly ultra-lightweight concrete. In addition, no information is available on the performance of PLA concrete and its contribution as lightweight aggregate.

TABLE I
CHEMICAL COMPOSITION OF CEMENT AND SILICA FUME

Composite (%)	Ordinary Portland Cement (OPC)	Silica Fume (SF)
Silicon dioxide (SiO_2)	22.8	94.7
Aluminium oxide (Al_2O_3)	4.20	0.80
Iron oxide (Fe_2O_3)	2.30	0.50
Calcium oxide (CaO)	64.8	0.91
Magnesium oxide (MgO)	1.00	0.27
Sodium Oxide (Na_2O)	0.19	-
Potassium oxide (K_2O)	0.49	-
Sulphur trioxide (SO_3)	0.42	-
Loss on ignition	0.76	2.00

TABLE II
COMPARING THE RESULTS OF TABLE OF INPRO AND PROPOSED EQUATION

Density	Provided Table (INPRO)			Proposed equation		
	w/c*	P/C*	Cement Content	w/c*	P/C*	Cement Content
576	0.79	1/4	376	0.79	1/4	376
488	0.96	1/5	301	0.95	1/5	300.5
432	1.07	1/6	252	1.10	1/6	252
352	1.43	1/8	188	1.42	1/8	189

w/c is water-cement ratio, P/C is perlite-cement ratio.

II. EXPERIMENTAL PROCEDURE

A. Materials

Portland cement type GP as per NZS3122:2009 with a 28-day compressive strength of 45.0 MPa is used as the main binding material for all the mixtures. Silica fume (with a SiO_2 content of 94.7%) replaces 15% of the cement content to increase the cohesiveness of the matrix, reduce the segregation and improve the compressive strength. It is worth mentioning that mineral admixtures, i.e. fly ash, silica fume and micro silica, reduce the porosity of concrete and improve the strength of the interfacial zone between the cement matrix and aggregates [20], [21], [33]-[36]. Three types of lightweight aggregate viz. EPLA, EPS, expanded perlite (EP) are used. The EP with a nominal size of 0-4 mm (SiO_2 content of 74%) is used as fine aggregate in this study. EPLA beads with a bulk density of 35 kg/m^3 and an average diameter of 5 mm was obtained from Scion (a crown research institute in New Zealand). A commercially available spherical EPS with bulk density and average diameter of 10 kg/m^3 and 5 mm is used as a comparison for PLA particles. In order to decrease the unit weight of light weight concrete and to reduce the shrinkage of perlite aggregate an air entraining agent (Sika air mix) from Sika.NZ is used with the dosage of 30-150 ml/m^3 of concrete weight. The chemical composition of cementitious materials is provided in Table I.

B. The Logic of the Mix Design

Design of lightweight concrete is complex due to the variation on lightweight aggregate properties. Normal concrete is mostly designed based on the water-cement ratio, while lightweight concrete is affected by specific absorption rates of lightweight aggregate and its bulk density. The ACI 211.2 standard [37] recommended two different methods for designing lightweight concrete. The weight method is used for concrete containing lightweight coarse aggregate and normal fine aggregate, while concrete containing coarse and fine lightweight aggregate or a combination of normal and the lightweight aggregate can be designed as per the volumetric method. However, the provided methods, relevant tables and guidelines are limited to a compressive strength of greater 20.7 MPa, which is much higher than compressive strengths of insulating ultra-lightweight concrete, which can be less than 2.0 MPa. In order to find an optimum mix ratio and to obtain a more practical mix ratio for insulating concrete such as perlite concrete, the following equations are proposed to estimate the water-cement ratio (1) and cement content (2) of perlite concrete by knowing the required density.

$$\frac{w}{c} = a = \frac{0.76\gamma^{0.0001\gamma}}{0.0001\gamma.\gamma^{0.5}} \tag{1}$$

$$\begin{cases} 1000 = \dfrac{(\frac{\gamma}{a})^{0.5}}{RD_c.RD_p}C + \dfrac{123a(\frac{a}{\gamma})^{0.5}}{RD_p}C + 10aV_p \\ \gamma = \gamma^{\frac{1}{10a}}C + aC + RD_pV_p \end{cases} \tag{2}$$

where, γ is density of concrete (kg/m^3), a is water-cement ratio, C is cement content (kg/m^3), RD_C is relative density of cement, RD_p is relative density of perlite, V_p is perlite volume (m^3).

Provided table by Industrial Processors Limited (INPRO) New Zealand for mix proportions of perlite concrete and the results from proposed equations are compared in Table II. The results indicate that the proposed equation for mix design of perlite concrete provides a reliable estimate.

C. Mix Proportions

The mix proportions and target density values of the proposed concrete are shown in Table III. The sample with 100% perlite (100P0S1/4 and 100P0S1/6) is used as a reference for PLA perlite and EPS perlite concrete. However, the mechanical properties of bio-polymer perlite concrete (PLA perlite) are compared with EPS perlite concrete to assess the differences between petroleum and bio polymer aggregate when used as lightweight aggregate in concrete. A total number of 63 samples with differences in water-cement ratio, PLA ratio, EPS ratio, perlite ratio, cement content, silica fume content and density are prepared. In addition, EP is used in the place of natural sand to reduce the unit weight of concrete.

TABLE III
MIX PROPORTIONS OF PERLITE, EPS PERLITE AND PLA PERLITE CONCRETE

P/C*	Target density (kg/m^3)	Specimen	Cement (kg/m^3)	Water (kg/m^3)	Perlite (kg/m^3)	PLA (kg/m^3)	EPS (kg/m^3)	Silica Fume (kg/m^3)	Air-Entraining (m^3)
1/4	576	100P0S1/4	376.0	300.0	185.0	0	0	0	0.0041
		75P25E0S1/4	376.0	275.0	138.7	0	2.5	0	0.0041
		75P25PL0S1/4	376.0	275.0	138.7	9.0	0	0	0.0041
		50P50E0S1/4	376.0	250.0	92.5	0	5.0	0	0.0041
		50P50PL0S1/4	376.0	250.0	92.5	18.0	0	0	0.0041
		25P75E0S1/4	376.0	225.0	46.2	0	7.5	0	0.0041
		25P75PL0S1/4	376.0	225.0	46.2	27.0	0	0	0.0041
1/6	432	100P0S1/6	252.0	270.0	185.0	0	0	0	0.0041
		100 P15S1/6	214.2	270.0	185.0	0	0	37.8	0.0041
		75P25E0S1/6	252.0	245.0	138.7	0	2.5	0	0.0041
		75P25E15S1/6	214.2	245.0	138.7	0	2.5	37.8	0.0041
		75P25PL0S1/6	252.0	245.0	138.7	9.0	0	0	0.0041
		75P25PL15S1/6	214.2	245.0	138.7	9.0	0	37.8	0.0041
		50P50E0S1/6	252.0	225.0	92.5	0	5.0	0	0.0041
		50P50E15S1/6	214.2	225.0	92.5	0	5.0	37.8	0.0041
		50P50PL0S1/6	252.0	225.0	92.5	18.0	0	0	0.0041
		50P50PL15S1/6	214.2	225.0	92.5	18.0	0	37.8	0.0041
		25P75E0S1/6	252.0	200.0	46.2	0	7.5	0	0.0041
		25P75E15S1/6	214.2	200.0	46.2	0	7.5	37.8	0.0041
		25P75PL0S1/6	252.0	200.0	46.2	27.0	0	0	0.0041
		25P75PL15S1/6	214.2	200.0	46.2	27.0	0	37.8	0.0041

P/C is perlite-cement ratio; w/c is water-cement ratio.

D. Test Methods and Curing Conditions

The perlite and cement were blended in a rotary mixer for about 1 min. Before adding water, an appropriate amount of air entraining agent was mixed with the required amount of water and then 70% of the mixed water (water + air entraining agent) were added to the perlite/cement mixture and mixed for 3 min. The remaining water was added to the mixture and mixing continued for about 5 min. The density and compressive strength tests were carried out on 100x200mm (diameter x height) standard cylinders as per ASTM C567 [38] and ASTM C495 [39], respectively. The cylinders were demoulded after 24±2 h. Two types of curing regimes, namely moist curing and air curing were chosen to assess the effect of the curing environment on mechanical properties of PLA perlite concrete. In the case of moist curing, the specimens were kept in water curing at 20 ºC for the whole curing period and then oven dried at 110±5 ºC for 24 h a day before the scheduled date of test (28 days), while air cured samples were kept in a laboratory environment for the whole curing period after demoulding.

III. TEST RESULTS AND DISCUSSION

A. Density

Density of lightweight concrete mostly depends on the bulk density of lightweight aggregate and the cement content. As expected, the density and strength of perlite concrete was reduced with an increase in PLA and EPS. In total four density ranges were obtained by replacing perlite aggregate with certain percentages of PLA and EPS aggregate. The density of dry concrete was varied from 532.5 kg/m^3 to 374.4 kg/m^3 and 439.3 kg/m^3 to 266.5 kg/m^3 for specimens with the perlite-cement (p/c) ratio of 1/4 and 1/6, respectively. Compressive strength tests (after 28 days) were carried out on air-dried samples. The unit weights of specimens in wet and dry conditions are shown in Table IV. The experimental results show that factors such as volume of perlite, water absorption ratio and PLA/EPS volume significantly affect the unit weight of concrete in the dried and fresh state. In the case of the 100% perlite sample, the unit weight was decreased from 645.2 kg/m^3 to 532.5 kg/m^3 and 542.0 kg/m^3 to 439.3 kg/m^3 for the concrete with p/c ratio of 1/4 and 1/6, respectively. The unit weight reduction was 99.6 kg/m^3, 102.1 kg/m^3, 85.5 kg/m^3, 88.9 kg/m^3, 75.7 and 75.5 kg/m^3 in concretes containing 25% EPS, 25% PLA, 50% EPS, 50% PLA, 75% EPS and 75% PLA, respectively. Thus, the decline of unit weight in the dried state is an indication of a higher amount of open pores in the perlite structure. The PLA concretes were 3%, 15% and 27% lighter than perlite concretes, while an even higher reduction was observed in EPS concretes due to the lower unit weight of EPS beads.

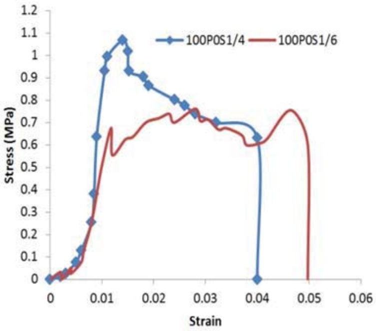
TABLE IV
FRESH AND DRY DENSITY OF PERLITE, PLA PERLITE AND EPS PERLITE CONCRETE

P/C*		Target density (kg/m³)	Actual density (kg/m³)						
			100P	75P25E	75P25PL	50P50E	50P50PL	25P75E	25P75PL
1/4	Fresh	-	645.2	565.5	574.3	519.4	536.9	450.1	467.2
	Dry	576	532.5	487.5	472.2	433.9	448.0	374.4	391.7
1/6	Fresh	-	542.0	457.2	469.7	409.1	412.7	322.3	351.1
	Dry	432	439.3	359.1	385.6	323.9	332.5	266.5	290.4

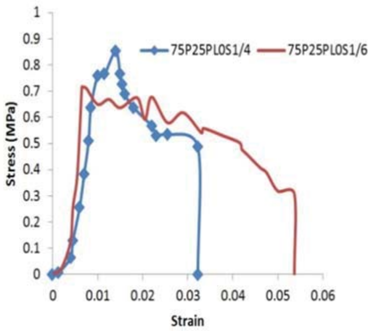
P/C is perlite-cement ratio.

B. Compressive Strength

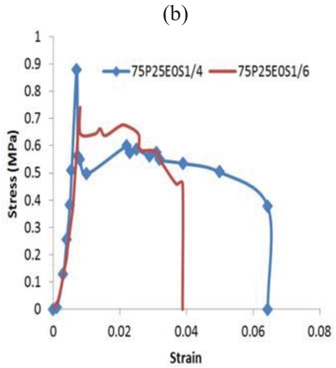
1. Influence of Perlite-Cement Ratio



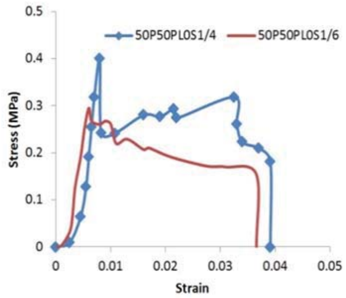
(a)



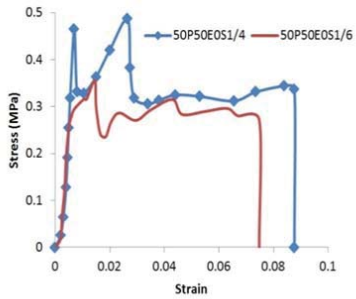
(b)



(c)



(d)



(e)

Fig. 1 Effects of perlite-cement content on compressive strength; (a) 100% Perlite, (b) 75% Perlite-25% PLA, (c) 75% Perlite-25% EPS, (d) 50% perlite-50% PLA, (e) 50% perlite-50% EPS

The experimental results show that there is a direct relation between perlite-cement (p/c) ratio and compressive strength of concrete (Fig. 1). A substantial improvement in compressive strength (about 72%) of perlite concrete containing 100% perlite was achieved with the inclusion of a higher cement content (from 252 kg/m^3 to 376 kg/m^3). The rate of increase was much lower in the presence of EPS and PLA particles. The increases were about 32% in concrete with 25% EPS and 37% in concrete containing 50% EPS. However, this trend was a bit lower for PLA concrete. The samples with 25% and 50% PLA were showing increases of 30% and 35% when the cement content was enhanced from 252 kg/m^3 to 376 kg/m^3. The experimental results show that the influence of the perlite-cement ratio on compressive strength mostly depends on aggregate characteristics and interfacial bond strength between components of the matrix. The interfacial zone between the aggregate and the paste significantly affects the stress-strain response of concrete under a uniaxial compression load. As a matter of fact, the micro cracks are initially starting to propagate at the interfacial zone which causes an increment in strain rate rather than applied stress. This resulted in discontinuity of the interconnected network of matrix and aggregate, and thus a failure of the matrix. However, compared with normal concrete, the failure modes of lightweight concrete are considerably different. This can be attributed to the porous structure of lightweight aggregate and lower strength. The penetration of fresh cement into the open pores of lightweight aggregate resulted in higher interfacial bond between the components of the matrix. Moreover, the applied stress and micro cracks can propagate in the structure of aggregates and cause a higher deformability and strength. It is worth noting compressive strength of normal concrete is a factor of aggregate strength, while lightweight aggregate concrete mostly depends on the strength of cement and the interfacial zone of the matrix. In the case of polymer materials, the presence of hydrophobic aggregates such as PLA and EPS causes a lower compressive strength and lower interfacial bond. In addition, the compressible behaviour of PLA/EPS aggregate accelerates the propagation of micro carks and de-bonding failure of aggregates. Compared with EPS particles, the interfacial bond between PLA and the matrix was much lower due to the shrinkage of aggregate and alkali reactivity with cement paste during the hydration process (Fig. 2).

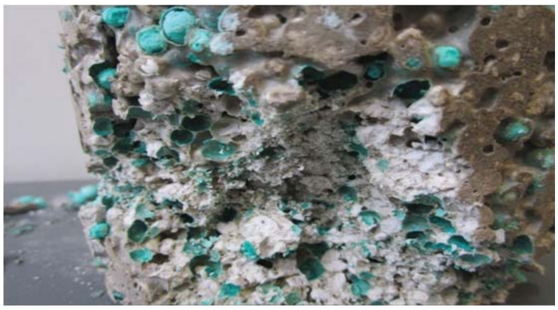


Fig. 2 Effect of alkaline environment on PLA aggregate

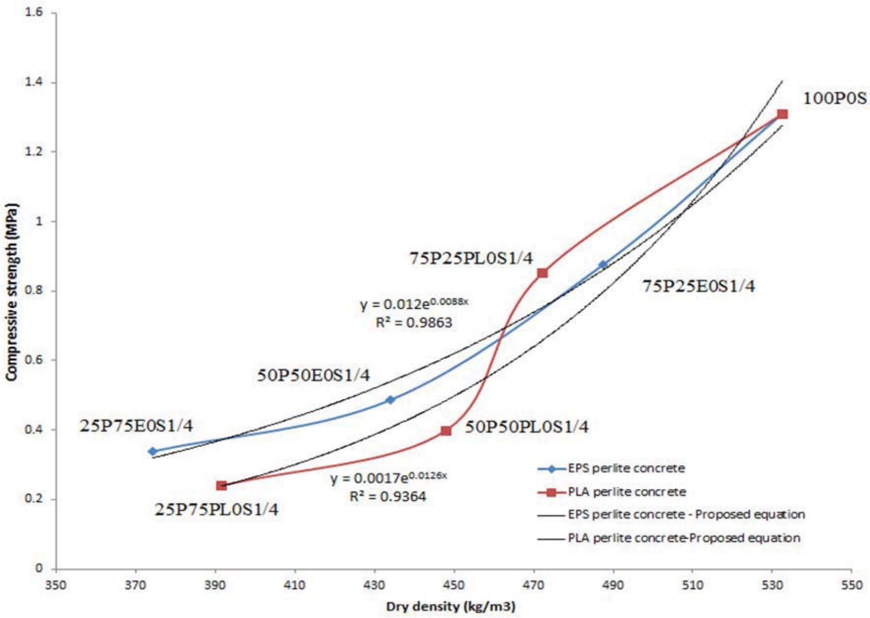


Fig. 3 Influence of EPS and PLA ratio on compressive strength of concrete

2. Influence of PLA and EPS Ratio

The variation of compressive strength with differences in perlite, PLA and EPS ratios is shown in Fig. 3. The results indicate that the strength of concrete was reduced with an increase in the PLA and EPS ratio. The compressive strength of the sample containing 25% PLA was 0.85 MPa, which was approximately 54% lower than the control sample (100% perlite). A further reduction in compressive strength was obtained with an increase in the PLA ratio. The compressive strength of 0.41 MPa and 0.22 MPa was obtained as 50% and 75% of perlite aggregate was replaced with PLA particles. This trend shows a considerable reduction of 219% and 495% in compressive strength of perlite concrete. In addition, most of the PLA beads easily de-bonded from the matrix due to close to zero interfacial bonds at the interface area of bead and paste. A lower reduction rate of 50%, 172% and 309% was observed in samples containing 25%, 50% and 75% EPS aggregate, respectively. This trend can be attributed to the proper interfacial bond between EPS beads and the matrix. Thus, the bond strength of the interfacial zone plays a significant role in the compressive strength of the matrix. The interfacial bond strength increased the compressive strength of concrete by 2%, 17% and 45% as the 25%, 50% and 75% of PLA aggregate was replaced with EPS aggregate. Moreover, samples containing PLA and EPS beads exhibited different behaviour and failure modes. In the case of EPS concrete, the failure mode was more gradual with the ability to retain the load after failure due to the compressible behaviour of EPS

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:10, No:6, 2016

beads. Contrary, a sudden disintegration was observed for PLA concrete, due to the close to zero interfacial bond strength between matrix and PLA beads through its alkaline reactivity with cement (Fig. 4). It can be noted EPS beads were sheared off along the failure plane due to proper interfacial bonds between EPS and the matrix, while all of the PLA beads were de-bonded from the matrix and collapsed suddenly. The following equation is proposed to estimate the compressive strength of EPS perlite (3) and PLA perlite concrete (4).

$$f'_{cEPS} = 0.012e^{0.0088\gamma} \quad (3)$$

$$f'_{cPLA} = 0.0017e^{0.0126\gamma} \quad (4)$$

where, f'_{cEPS} is compressive strength of EPS concrete, f'_{cPLA} is compressive strength of PLA concrete, γ is density of concrete.

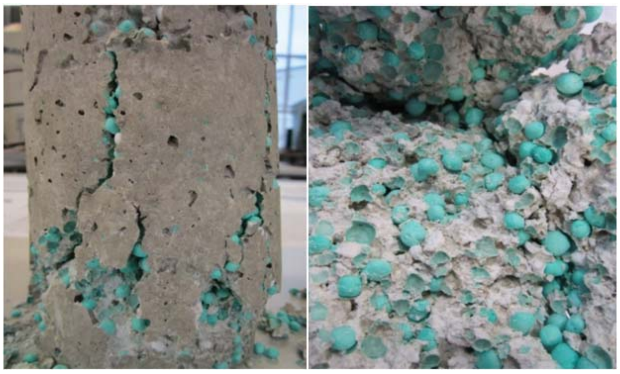
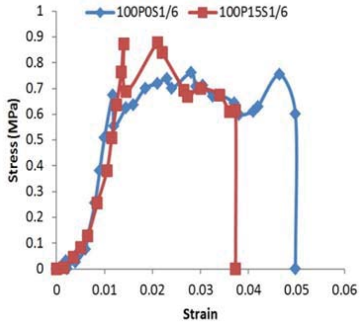


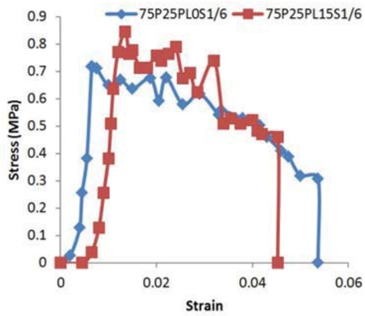
Fig. 4 Failure modes of PLA concrete

3. Influence of Silica Fume

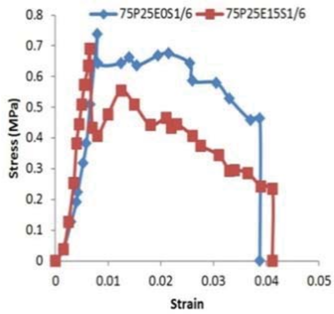
In order to solve the problem associated with the hydrophobic natures of PLA and EPS aggregate and to improve the cohesiveness of the matrix and the interfacial bond, a certain amount of silica fume (15%) was used in specimens with a perlite-cement ratio of 1/6 (Fig. 5). In the case of 100% perlite aggregate (control specimens), the compressive strength of concrete was increased by 15% with the inclusion of silica fume (Fig. 5 (a)). However, the substitution of mineral admixture imposes an inverse effect on compressive strength of EPS and PLA concrete. A decline of 6% and 64% was observed in compressive strength of sample containing 25% and 50% EPS aggregate (Figs. 5 (c) and (e)). This phenomenon can be attributed to the fact that the thermal resistivity of EPS particles and the inclusion of silica fume (SF) accelerate the hydration heat and the absence of adequate moisture at the initial stage of curing results in an incomplete hydration process and lower strength. This trend was different in PLA concrete. A considerable development in compressive strength (38%) was observed in a sample containing 25% PLA (Fig. 5 (b)), whereas the addition of SF imposes an inverse effect on concrete with a PLA volume of 50% (49% reduction, Fig. 5 (d)). It can be concluded that the alkaline reactivity of PLA and its sensitiveness to the alkaline environment accelerates its reaction in the presence of SF. However, there is no evidence available on the reactivity of PLA with SF of the matrix yet.



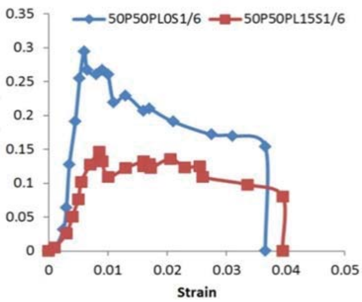
(a)



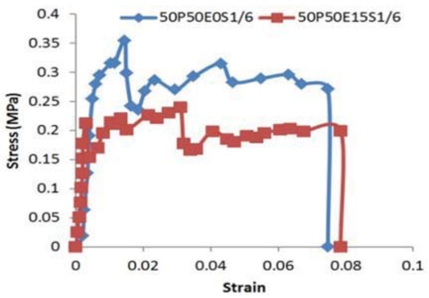
(b)



(c)



(d)

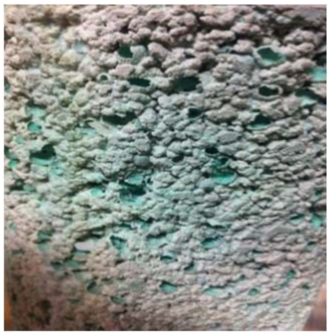


(e)

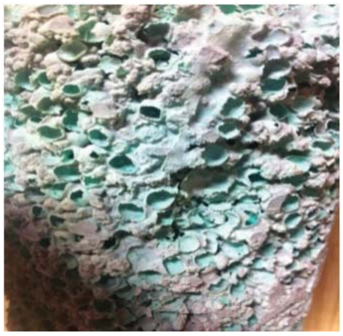
Fig. 5 Effects of silica fume on compressive strength; (a) 100% Perlite, (b) 75% Perlite-25% PLA, (c) 75% Perlite-25% EPS, (d) 50% perlite-50% PLA, (e) 50% perlite-50% EPS.

4. Influence of Curing Regimes

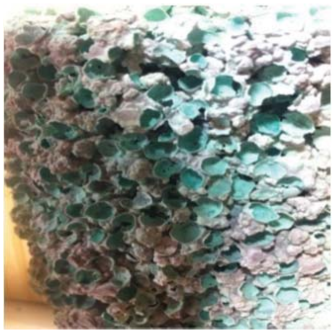
The curing of concrete plays a significant role in the performance and strength development of concrete. ACI-318 [40] has suggested that the concrete should be kept in a moist environment for at least the first seven days. The experimental results show that the compressive strength of perlite concrete after 28 days was decreased by 8% as the curing method was changed from air curing to moist curing. This trend can be attributed to the higher water absorption characteristics of perlite and the fact that sufficient water for an appropriate curing was held in the interior pore structure of perlite aggregate and the additional moisture affects the chemical interaction with the cement. In the case of aired cured samples, the pressure differences between voids of EP and cement is the main factor affecting the release of stored water. This free stored water eases the hydration reaction in air curing conditions. The results show that the inclusion of 25% EPS causes an increase in compressive strength from 0.87MPa to 0.90MPa as the curing method changed from air curing to moist curing. Whereas, a lower compressive strength (10% reduction) was observed in specimens made with 25% PLA. The influence of the curing method was more noticeable when the volume of PLA was increased (Fig. 6). The moist curing reduced the compressive strength of specimens with 50% and 75% PLA by 53% and 48%, respectively. An explanation might be the alkaline-reactivity of PLA with cement causes an expansion and increases the absorption ratio of PLA particles. After expansion, PLA particles were more sensitive to the moist environment and shrank up to three times of their original size. This reduces the formability of concrete and the holes around the PLA beads cause a stress concentration in this area. In contrast, the rate of reduction in compressive strength is much lower for concrete containing EPS particles. The effectiveness of moist curing was observed in specimens with 75% EPS particles as the compressive strength increased from 0.39MPa to 0.49MPa due to the thermal properties of EPS and better interfacial bond strength. Thus, PLA particles are sensitive to the alkaline environment of the cement paste and considerably shrank and lost their strength and moist curing becomes an inappropriate method for concrete containing PLA beads. In addition, a special curing is required for PLA concrete to obtain better durability. Finally, due to the sensitivity of PLA particles to a moist environment, it is recommended that perlite aggregate with its high water absorption ratio is used as a base aggregate for PLA concrete.



(a)



(b)



(c)

Fig. 6 Effect of moist curing on PLA perlite concrete; (a) contains 25% PLA, (b) contains 50% PLA, (c) contains 75% PLA

5. Stress-Strain Analysis

The stress-strain response is used as an indicator for material characteristics. It was reported that the stress-strain response of lightweight concrete with lightweight aggregate is typically linear until 90% of peak stress, while this value is around 30% to 45% for normal concrete. The factors such as maximum stress, (known as compressive strength, elastic modulus, peak and ultimate strength significantly affect the stress-strain response of concrete. Fig. 7 presents the stress-strain curve for perlite, EPS and PLA concrete with density ranges of 487 to 276 kg/m^3. The results indicate that the stress-strain relationship of the proposed concrete was almost linear until the peak point of stress. Compared with the stress-strain response of perlite concrete, PLA/EPS concretes show different responses in terms of higher deformability and compressibility. The stress-strain response of concrete can be divided into four stages of stiffness namely; elastic platform, elastic stage, strengthening stage and descending stage [41]. The slow rate of increment in strain and corresponding stress normally takes place in the elastic region mainly due to a collapse and compaction of the pore structure of the matrix and lightweight aggregate. The steepness of the elastic region was increased with compacting of more collapsed pores. The results show that an increase in EPS/PLA volume results in lower compaction stress due to the higher compactibility of PLA/EPS beads. A higher compaction stress was observed in perlite concrete, while this value was much lower in specimens with 75% EPS/PLA beads. The second, elastic stage, of stiffness is the linear part of the stress-strain response. The results show that the gradient and yield strength of the elastic segment significantly depends on the PLA/EPS ratio. However, a higher steepness is observed in specimens with PLA aggregate as a result of de-bonding in the interfacial area between matrix and PLA beads. All specimens show an oscillating manner in the strengthening stage due to the higher porosity of concrete, encapsulating of PLA/EPS beads along with generating of micro cracks at the interface of the matrix and particles. The stress was decreased and levelled off to a plateau at the descending stage. At this stage, the stress remains at an almost constant value, while the increment of strain can be seen. The fluctuation during the descending stage was due to the compressible behaviour of PLA/EPS beads, crashing and collapsing of remaining pores. Strain values of 0.008, 0.007, 0.014, 0.026, 0.08, 0.019 and 0.007 were obtained for specimens 100P0S, 75P25E0S, 75P25PL0S, 50P50E0S, 50P50PL0S, 25P75E0S and 25P75PL0S at the peak stress, respectively. The results indicate that a considerable increment in strain was observed when the volume of PLA/EPS increased. However, the strain of PLA concrete was much higher than EPS concrete. The higher strain (0.08) was observed in specimens with 50% perlite and 50% PLA. Whereas, an inverse effect on strain capacity was obtained as the volume of PLA enhanced from 50% to 75%. This decline can be attributed to the interfacial bond problem of PLA particles. Thus, the introduction of PLA/EPS aggregates improves the ductility and energy absorption capacity of concrete. However, a full disintegration after the descending segment and lower ductile behaviour was observed in concrete containing PLA particle.

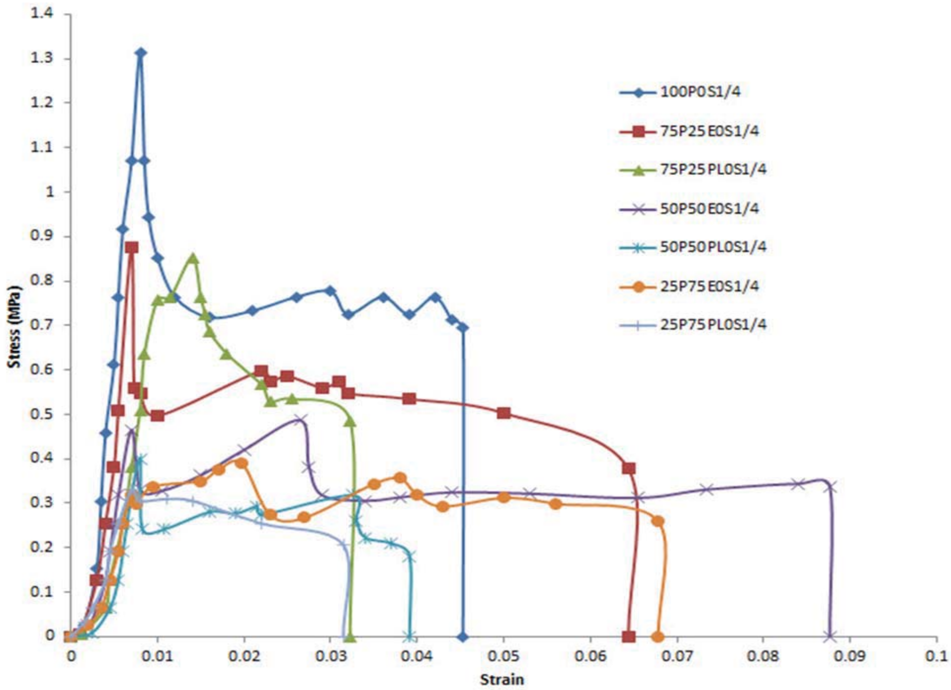


Fig. 7 Stress-strain response of perlite, EPS perlite and PLA perlite concrete

IV. Conclusions

Based on the experimental results from density, compressive strength and curing conditions of perlite, PLA perlite and EPS perlite concrete the following conclusions can be drawn:

1- The substitution of cement with 15% silica fume imposes an inverse effect on compressive strength of PLA and EPS concrete.
2- The density and strength of perlite concrete reduced with an increase in PLA and EPS.

3- The interfacial bond strength between PLA and EPS particles remarkably affect the stress-strain response of concrete.
4- Density ranges of 260 kg/m^3 and 290 kg/m^3 were obtained as 75% of perlite aggregate volume was replaced with EPS and PLA particles, respectively.
5- The cement content ratio and interfacial bond strength between matrix and lightweight aggregate directly affect the strength of lightweight concrete.
6- A considerable increment in strain was observed when the volume of PLA/EPS increased.

Comparison between PLA and EPS concrete can be summarized as:

1- The interfacial bond between PLA and the matrix was much lower.
2- PLA particles are sensitive to the alkaline environment of cement paste and considerably shrank and lost their strength.
3- Moist curing is an inappropriate method for concrete containing PLA beads.
4- The failure modes of PLA concrete were more brittle due to interfacial bond problems.

Acknowledgment

The authors would like to acknowledge the financial support of the New Zealand Ministry for Business, Innovation and Employment under contract number UOAX819. The support of the Auckland University of Technology (AUT), New Zealand, is also acknowledged.

References

[1] Łukasz Kotwica, Waldemar Pichór, Wiesława Nocuń-Wczelik (2015). "Study of pozzolanic action of ground waste expanded perlite by means of thermal methods." Journal of Thermal Analysis and Calorimetry 123(1): 607-613.
[2] Ozkan Sengul, Senem Azizi, Filiz Karaosmanoglu, Mehmet Ali Tasdemir (2011). "Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete." Energy and Buildings 43(2–3): 671-676.
[3] İlker Bekir Topçu, Burak Işıkdağ (2008). "Effect of expanded perlite aggregate on the properties of lightweight concrete." Journal of Materials Processing Technology 204(1–3): 34-38.
[4] ASTM Standard (2009). "ASTM C330/330M, Standard specification for Lightweight Aggregates for structural concrete." ASTM International.
[5] ASTM Standard (2009). "ASTM C 332, Standard Specification for lightweight aggregates for insulating concrete." ASTM International.
[6] Atila Gurhan Celik, Ahmet Mahmut Kilic, Gaye Ozgur Cakal. (2013). "Expanded perlite aggregate characterization for use as a lightweight construction raw material." Physicochemical Problems of Mineral Processing 49(2): 689-700.
[7] Su lei, Ma Baoguo, Jian Shouwei, Zhao Zhiguang, Liu Min (2013). "Hydration heat effect of cement pastes modified with hydroxypropyl methyl cellulose ether and expanded perlite." Journal of Wuhan University of Technology-Mater. Sci. Ed. 28(1): 122-126.
[8] Ramazan Demirboğa, Rüstem Gül (2003). "The effects of expanded perlite aggregate, silica fume and fly ash on the thermal conductivity of lightweight concrete." Cement and Concrete Research 33(5): 723-727.
[9] Abhijeet S. Gandage, V.R. Vinayaka Rao, M.V.N. Sivakumar, A. Vasan, M. Venu, A.B. Yaswanth (2013). "Effect of Perlite on Thermal Conductivity of Self Compacting Concrete." Procedia - Social and Behavioral Sciences 104: 188-197.
[10] L.-H Yu , H Ou, L.-L Lee (2003). "Investigation on pozzolanic effect of perlite powder in concrete." Cement and Concrete Research 33(1): 73-76.
[11] İbrahim Türkmen, Abdulhamit Kantarcı (2007). "Effects of expanded perlite aggregate and different curing conditions on the physical and mechanical properties of self-compacting concrete." Building and Environment 42(6): 2378-2383.
[12] L., T. F. and Subhan (2006). "Lightweight high strength concrete with expanded polystyrene beads." Mektek 7: 9-15.
[13] Chen, B. and J. Liu (2004). "Properties of lightweight expanded polystyrene concrete reinforced with steel fiber." Cement and Concrete Research 34(7): 1259-1263.
[14] Cook, D. J. (1983). "Expanded polystyrene concrete, concrete technology and design." New Concrete Materials, Surrey Univ. Press, London: 41-69.
[15] Cook, D. J. (1973). "Expanded polystyrene beads as lightweight aggregate for concrete." Precast Concrete 4: 691-693.
[16] Babu, K. G. and D. S. Babu (2003). "Behaviour of lightweight expanded polystyrene concrete containing silica fume." Cement and Concrete Research 33(5): 755-762.
[17] Sri Ravindrarajah, R. and A. J. Tuck (1994). "Properties of hardened concrete containing treated expanded polystyrene beads." Cement and Concrete Composites 16(4): 273-277.
[18] Bing Chen, Long-zhu Chen (2010). "Experimental study of lightweight expanded polystyrene aggregate concrete containing silica fume and polypropylene fibers." Journal of Shanghai Jiaotong University (Science) 15(2): 129-137.
[19] A. Sadrmomtazi, J. Sobhani, M.A. Mirgozar, M. Najimi (2012). "Properties of multi-strength grade EPS concrete containing silica fume and rice husk ash." Construction and Building Materials 35: 211-219.
[20] Ganesh Babu, K. and D. Saradhi Babu (2004). "Performance of fly ash concretes containing lightweight EPS aggregates." Cement and Concrete Composites 26(6): 605-611.
[21] Jamal M Khatib, El-Sayed Negim (2013). "Lightweight Concrete Made from Waste Polystyrene and Fly Ash " World Applied Sciences Journal 21(9): 1356-1360.
[22] Adilson Schackow, Carmeane Effting, Marilena V. Folgueras, Saulo Güths, Gabriela A. Mendes (2014). "Mechanical and thermal properties of lightweight concretes with vermiculite and EPS using air-entraining agent." Construction and Building Materials 57: 190-197.
[23] Ali A. Sayadi, Juan V. Tapia, Thomas R. Neitzert, G. Charles Clifton (2016). "Effects of expanded polystyrene (EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete." Construction and Building Materials 112: 716–724.
[24] Chen, B. and N. Liu (2013). "A novel lightweight concrete-fabrication and its thermal and mechanical properties." Construction and Building Materials 44: 691-698.
[25] Rahmat Madandoust, Malek Muhammad Ranjbar, S. Yasin Mousavi (2011). "An investigation on the fresh properties of self-compacted lightweight concrete containing expanded polystyrene." Construction and Building Materials 25(9): 3721-3731.
[26] Kan, A. and R. Demirboğa (2007). "Effect of cement and EPS beads ratios on compressive strength and density of lightweight concrete." Indian Journal of Engineering & Materials Sciences 14: 158-162.
[27] Yi Xu, Linhua Jiang, Jinxia Xu, Yang Li (2012). "Mechanical properties of expanded polystyrene lightweight aggregate concrete and brick." Construction and Building Materials 27(1): 32-38.
[28] Kate Parker, Jean-Philippe Garancher, Samir Shah and Alan Fernyhough (2011). "Expanded polylactic acid –an eco-friendly alternative to polystyrene foam." Journal of Cellular Plastics 47(3): 233-243.
[29] Garancher, J.-P. and A. Fernyhough (2012). "Crystallinity effects in polylactic acid-based foams." Journal of Cellular Plastics 48(5): 387-397.
[30] Jean-Philippe Garancher, Kate Parker, Samir Shah, Alan Fernyhough (2010). "Expanded Polylactide (E-PLA): A Realistic Approach to Expanded Polystyrene." Society of Plastics Engineers (SPE).
[31] Kate Parker, Jean-Philippe Garancher, Samir Shah and Alan Fernyhough (2011). "Polylactic Acid (PLA) Foams for Packaging Applications". Handbook of Bioplastics and Biocomposites Engineering Applications, John Wiley & Sons, Inc.: 161-175.
[32] Stephanie Weal (2011). "Heat Stability of PLA-Based Foams and its Measurement " BIOFOAMS 2011 Conference.
[33] J.M. Chi, R. Huang, C.C. Yang, J.J. Chang (2003). "Effect of aggregate properties on the strength and stiffness of lightweight concrete." Cement and Concrete Composites 25(2): 197-205.
[34] Kearsley, E. P. and P. J. Wainwright (2001). "The effect of high fly ash content on the compressive strength of foamed concrete." Cement and Concrete Research 31(1): 105-112.

[35] Kearsley, E. P. and P. J. Wainwright (2002). "Ash content for optimum strength of foamed concrete." Cement and Concrete Research 32(2): 241-246.
[36] D. Saradhi Babua, T, K. Ganesh Babub , T.H. Wee (2005). "Properties of lightweight expanded polystyrene aggregate concretes containing fly ash." Cement and Concrete Research 35(6): 1218-1223.
[37] ACI Committee (2004). "ACI 211.2, Standard Practice for Selecting Proportions for Structural Lightweight Concrete " American Concrete Institute (ACI): 1-20.
[38] ASTM Standard (1999). "ASTM C567, Test method for density of structural lightweight concrete." ASTM International.
[39] ASTM Standard (2012). "ASTM C495, Standard Test Method for Compressive Strength of Lightweight Insulating Concrete." ASTM International.
[40] ACI Committee (2011). "ACI 318, Building Code Requirements for Structural Concrete and Commentary." American Concrete Institute (ACI).
[41] Jeffrey W. Bullard, Hamlin M. Jennings, Richard A. Livingston, Andre Nonat, George W. Scherer, Jeffrey S. Schweitzer, Karen L. Scrivener, Jeffrey J. Thomas (2011). "Mechanisms of cement hydration." Cement and Concrete Research 41(12): 1208-1223.