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The effect of expanded polystyrene beads (EPS) on the physical and mechanical properties of aerated concrete

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Abstract: There is a significant challenge to developing the strength and durability of the aerated concrete (AC) for structural applications, but to date, no researchers have focussed on the effect of expanded polystyrene beads (EPS) on the AC properties. EPS-AC consists of cement, sand, water and aluminium powder with commercially available spherical small, hollow and impermeable polystyrene beads. In this research, different contents of EPS from 0 to 4% by cement weight were added to create the AC with different densities. It is revealed that the greatest enhancements in the properties of EPS-AC were noticed when the EPS volume fraction was increased to 4%. The compressive, flexural strength and modulus of rupture were enhanced by 48, 37 and 125% respectively, whereas the density was raised slightly. Moreover, it was shown that all EPS-AC mixes could satisfy the requirements of structural lightweight concrete.

Keywords: aerated concrete, expanded polystyrene beads, modulus of elasticity, strength

1 Introduction

A decrease in the unit weight of concrete and affording suitable strength leads to an economic positive effect on the construction field. In this field, lightweight concrete (LWC) offers considerable features in terms of its lightweight compared to conventional concrete when the structure's weight is a major factor [1,2]. LWC can be divided into thermo insulating, low strength and structural LWC according to its density and strength.

Thermo-insulating LWC with a density range from 300 to 800 kg/m^3 and a strength of less than 7 MPa is used for insulating coating or filling material. It is used when concrete strength is inconsequential. However, low strength LWC has a strength range from 7 to 18 MPa and bulk density from 800 to 1,400 kg/m^3. Structural LWC has a density range from 1,400 to 2,000 kg/m^3 with a strength greater than 20 MPa [1]. LWC is considered an economical unit because of its low density and its cross-sectional (beam, column and plate) [3]. Accordingly, a decrease in dead load causes a reduction in structural elements size and steel fibres reinforcement [4]. Moreover, longer span, improved cyclic load response and smaller sections can be achieved by using LWC [5].

LWC can be produced by adding substances to create gasses and form pores in concrete or by utilising artificial or natural lightweight aggregate with high porosity. In this respect, normal aggregate is replaced totally or partially with expanded polystyrene beads (EPS). In recent years, a great interest in the use of EPS was noticed in the building industry [4]. EPS is a lightweight cellular plastic with 98% air and has small spherical-shaped particles with a density from 10 to 20 kg/m^3. In addition, it is an environmentally friendly material that can be recycled besides its components do not negatively affect the nature or ozone layer. Polystyrene beads are used in different applications due to their light rigid foam, high-impact resistance and suitable term thermal insulation [6]. It is utilised as lightweight aggregate, which can mix simply in mortar or concrete to produce LWC with EPS aggregate (EPS-LWC) with different densities. EPS-LWC with a density of 500–900 kg/m^3 can be used for non-structural applications, while it can be used as load

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bearing for structural purposes when its density ranges between 1,400 and 2,000 kg/m^3 [2].

Mohammad and Yasin [7] examined the influence of the EPS aggregate on self-compacted CLC properties. EPS with the range of 10, 15, 22.5 and 30% by volume was used. The results showed that the fresh density of SCCH (control) decreased by 30% with increasing EPS up to 30%. However, the tensile and compressive strength decreased by 45 and 64% respectively. The mechanical properties of the LWC with EPS were researched by Liu and Chen [8]. EPS with the range of 0, 30, 45 and 55 were used. The results revealed that when EPS increased up to 55%, dry density declined by 46%, while the compressive strength decreased by 68%. However, the splitting and flexural strength reduced by 52 and 39% respectively. The embodied energy for lightweight-foam concrete panels with 50% of recycled EPS was studied by Dissanayake et al. [9]. The results demonstrated that at 3.02 GJ/m^2 the cement sand blockhouse has better performance than the foam concrete precast panel. Nikbin and Golshekan [10] investigated the properties of LWC with varied EPS percentages up to 40%. The results indicated that the compressive and tensile strength dropped significantly by 73 and 71% respectively, with increasing the content of EPS up to 40%, while the dry density reduced by 33%. However, Ali et al. [1] experimented with the thermal resistant of LWC with EPS as coarse aggregates. The results illustrated a decrease in compressive strength, dry density, modulus of rupture and elastic module with increasing EPS volume due to the increase in harshness and a tendency to segregate because of the small content of cement with large lightweight aggregates volume.

Medher et al. [4] researched the effect of using EPS as a coarse aggregate to produce self-compacting LWC, reinforced with waste plastic fibre (WPF) with a content ranging from 0.25 to 1.25%. They had shown that the compressive and flexural strength of self-compacting LWC were improved with increasing WPF content up to 1%. Adeala and Soyemi [11] studied the possibility of using EPS in concrete as a sand replacement with a range from 0 to 30%. The results confirmed that the highest compressive strength (with 5% of EPS) was lower than the control specimen's strength by 16%. However, the tensile strength possessed an enhancement of 43% with increasing EPS content up to 10%. Yassin et al. [12] examined the curing conditions' influence on the properties of brick made of LWC with EPS. The sand was replaced by EPS by 0, 30 and 50% of the weight. It was confirmed that EPS had a major influence on brick properties, which were adversely affected by increasing EPS content.

The previous studies confirmed the possibility of using EPS as a coarse aggregate with a different percentage in LWC, even though the mechanical and physical properties of the EPS are different from the aggregate. LWC lowers the environmental pollution and improves the construction sustainability, besides its impact on the applied loads and thermal and sound insulation of buildings. Consequently, there is a significant challenge to develop the strength and durability of one type of LWC, the aerated concrete (AC). However, up to date, no research has been focused on the effect of EPS beads on the AC properties.

1.1 Research significance

It is of great importance to verify the suitability of using EPS to enhance the properties of AC to be used for structural applications. In this research, the commercially available EPS beads with the range from 0 to 4% were added to produce AC with different low densities, which leads to reducing dead load, structural members size and amount of cement used. For this purpose, different EPS-AC mixtures were produced using a combination of cement, sand, water, aluminium powder and spherical, small and hollow EPS beads. The research is intended to verify the significant influences of EPS on improving the compressive, flexural strength, modulus of rupture and dry density of EPS-AC.

2 Experimental details

2.1 Material properties for EPS-AC mix design

The EPS-AC mixes were prepared using CEM I/32.5R ordinary Portland cement according to IOS No. 5 [13] with natural sand according to IOS No. 45 [14]. The high range water reducer (HRWR) superplasticizer type (Glenium51) was used as an additive according to ASTM C494-05 [15]. A medium-fine aluminium flake (Al) (53–44 μm) was utilised as a pore-forming agent to produce AC samples. Spherical-shaped, commercially available EPS beads were added as aggregate. The beads were small, hollow and impermeable balls and about 2–3 mm diameter were added with different contents of cement weight. The physical and chemical properties of the cement are presented in Tables 1 and 2 respectively, while the properties of HRWR are demonstrated in Table 3.

2.2 Mixture proportions

EPS-AC mixes were designed with a sand/cement ratio equal to 2, using a cement content of 350 kg/m^3, with a w/c ratio of 0.55. Nine mixtures were prepared, one reference AC (with 0% EPS) besides eight EPS-AC mixtures. Different proportions of EPS beads (0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4%) by weight of cement were used. HRWR superplasticizer was added at a fixed content (0.3%) of total ingredients weight, while the content of medium-fine aluminium flake (Al) was 0.25% by cement weight. Mix proportions are presented in Table 4.

Table 1: Physical properties of the cement

Properties		Test result	I.Q.S. No.5-2019 limits
Setting time	Initial (min)	115	Min. 45
	Final (h)	2.55	Max. 10
Fineness (m^2/kg)		281	Min. 250
Compressive strength (N/mm^2)	2 days	14.5 MPa	Min. 10
	28 days	45 MPa	Min. 32.5
Soundness %		0.32	—

Table 2: Chemical properties of the cement

Component %	Test result	I.Q.S. No.5-2019 limits
SiO_2	20.63	—
Al_2O_3	5.68	—
Fe_2O_3	3.42	—
CaO	62.03	—
MgO	3.68	Max. 5.0
SO_3	2.47	Max. 2.8
Loss in ignition	1.46	Max. 4.0
Total	99.37	—
Insoluble residue	0.5	Max. 1.5

Table 3: Superplasticizer (Glenium51) properties

Properties	Test result
Polycarboxylic ether	Type A and F
Density	1.06–1.08 g/cm^3 (at 20°C)

2.3 Mixing process

For mix preparation, EPS beads were mixed with one-half of the water content to let EPS absorbs water for 1 min. After that, cement, sand and medium fine aluminium flake (Al) were added and mixing was continued for another one minute. Then, ESP with the remaining water was added and mixed for 3 min. Next, the moulds were filled with the fresh EPS-AC. The specimens were demoulded after 24 h. The specimens were cured in a water tank for 27 days and then tested for physical and mechanical properties.

2.4 Testing procedure

The compressive strength of the EPS-AC was measured using a 100 mm cube according to BS EN 12390-3 [16]. A standard modulus of elasticity test was performed for a cylinder (100 × 200) mm according to BS EN 1352 [17], whereas flexural strength was measured using a beam (100 × 100 × 400) mm according to BS EN 12390-5 [18]. Moreover, the dry density was measured for a cylinder (33 × 70 ± 5) mm height according to BS EN 12350-6: ref. [19]. The average value for the results of three specimens was adopted for each of the above-mentioned tests.

3 Results and discussion

3.1 Compressive strength

The compressive strength improvement of EPS-AC mixtures with increasing EPS content is presented in Figure 1. The control mixture (0% EPS) shows a relatively lower strength of about 18.9 MPa. For the specimens with 0.5% EPS of cement content, the strength increased by about 9%. However, with increasing EPS content to 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 and 0.4%, the compressive strength enhanced by 17.5, 27, 36, 42, 43, 47 and 48% respectively. It was noticed that AC strengths were raised significantly with increasing EPS content up to 0.35% of cement weight, after that no considerable change was noticed in the results. Also, all EPS-AC mixes satisfy the requirements of structural LWC strength (higher than 20 MPa at 28 days) [20]. However, other researchers use the EPS as a sand replacement with different percentages [12,21].

Table 4: Mix details of EPS-AC

Mix group	Mix ID	Material (kg/m^3)					
		Cement	Sand	Water	EPS	Al	HRWR
Mix 1	EPS-LWAC	350	700	192	0	0.875	4.2
Mix 2	EPS-LWAC 0.5	350	700	192	1.75	0.875	4.2
Mix 3	EPS-LWAC 0.1	350	700	192	3.5	0.875	4.2
Mix 4	EPS-LWAC 0.15	350	700	192	5.25	0.875	4.2
Mix 5	EPS-LWAC 0.2	350	700	192	7	0.875	4.2
Mix 6	EPS-LWAC 0.25	350	700	192	8.75	0.875	4.2
Mix 7	EPS-LWAC 0.3	350	700	192	10.5	0.875	4.2
Mix 8	EPS-LWAC 0.35	350	700	192	12.25	0.875	4.2
Mix 9	EPS-LWAC 0.4	350	700	192	14	0.875	4.2

They observed that compressive strength of the LWC decreased with increasing the EPS content. They justified the results due to the existence of EPS with lower strength than sand. However, in this research, the EPS beads were not used as a sand substitution, but different contents of the beads were added to the mix. Therefore, it could be expected that the inclusion of EPS may affect the microstructure of AC by reducing capillary pore volume-enhancing AC strength [22]. Furthermore, in this work, the amount of water had not been changed with the addition of EPS; thus, the beads worked to adsorb part of the mixing water leading to lowering the w/c ratio, which enhances the compressive strength of EPS-AC.

3.2 Flexural strength

Similar to compressive strength, the bending strength of the EPS-AC was enhanced gradually with increasing EPS percentage as indicated in Figure 2. The major reason for strength improvement is that the presence of the EPS beads could reduce bleeding and shrinkage, which are the main causes of lowering of bond strength [22]. Consequently, the flexural strength that is considerably affected by bond characteristics was improved. The results show that the strength of AC with 0% ESP was 3.06 MPa, which was developed by 37% with increasing the content of ESP up to 0.4%. These conclusions are in contrast with previous studies [8,10] where the EPS was used as a coarse aggregate causing a decrease in the flexural strength of AC. It was stated in those studies that the decrease in the strength was mainly caused by the reduction of invalid stress area (in concrete section) with increasing volume fraction of EPS, whereas the dry density has little effect on the flexural strength. This phenomenon was not encountered in this research.

It was noticed during the flexural tests that the samples were not divided into pieces signifying that the failure was more gradual, which refers to the role of EPS in increasing the toughness of AC. It can be stated

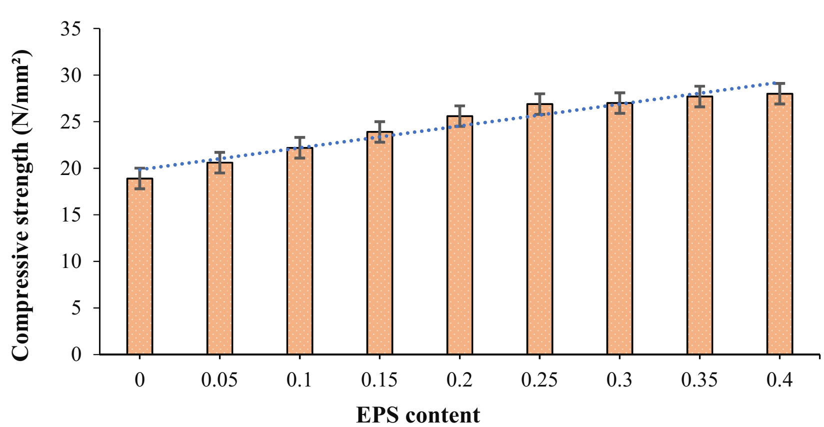

Figure 1: Compressive strength at 28 days of EPS-AC with different EPS content.

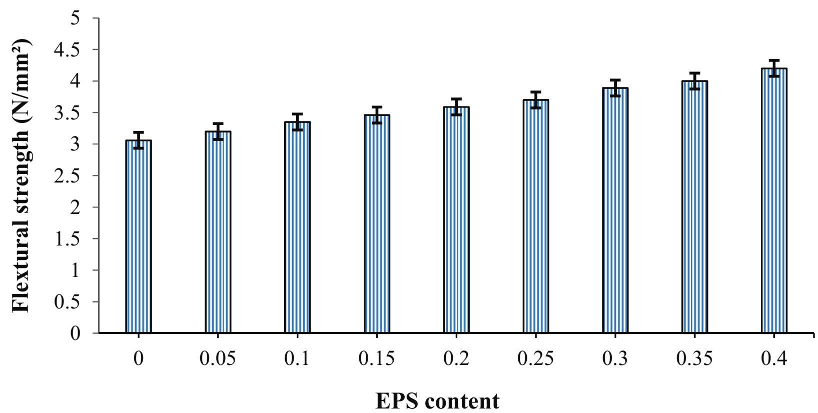

Figure 2: EPS-AC flexural strength versus EPS content.

that EPS beads worked to arrest internal cracks leading to a change in the mode of failure being almost gradual [22]. Furthermore, it is proposed the role of EPS in increasing the probability of plastic failure of the EPS-AC.

3.3 Static modulus of elasticity

The modulus of elasticity of different EPS-AC samples is illustrated in Figure 3. The modulus of elasticity was improved by 18% compared with control specimens by adding 0.05% EPS of the weight of cement, followed by improvements of 34 and 51, 67, 82 and 96% of the reference specimen's modulus value for the AC with 0.1, 0.5, 0.1, 0.15, 0,2 and 0.25% EPS respectively. However, the maximum percentage of increase in elasticity modulus was observed in the case of using 0.4% EPS where the enhancement reached 125% of the control specimen modulus. These results could be attributed to the fact that the stiffness of the materials has a major role in the elasticity modulus of concrete. Although the EPS beads have negligible stiffness, the beads fill the large pores in the hydration products structure of AC [22]. Consequently, the modulus of elasticity of the AC is increased by raising the EPS content. Furthermore, the same justifications about the effects of EPS beads on the lowering shrinkage and bleeding of concrete and the mechanism of strength enhancement referred to in the above played the same role in the static modulus of elasticity of EPS-AC.

3.4 Density

By adding EPS beads to the AC with different volume fractions, various densities can be achieved. Figure 4 represents the EPS-AC dry density at 28 days for various EPS volume fractions. Based on these results, the dry density was enhanced by increasing the content of EPS, reaching a maximum value at 0.4% of cement weight, where the density was enhanced by 29% of its control

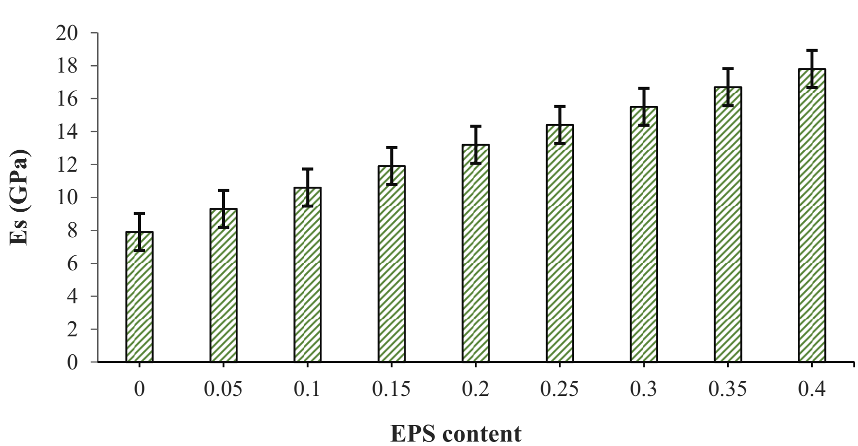

Figure 3: The elastic modulus of EPS-AC versus the EPS content.

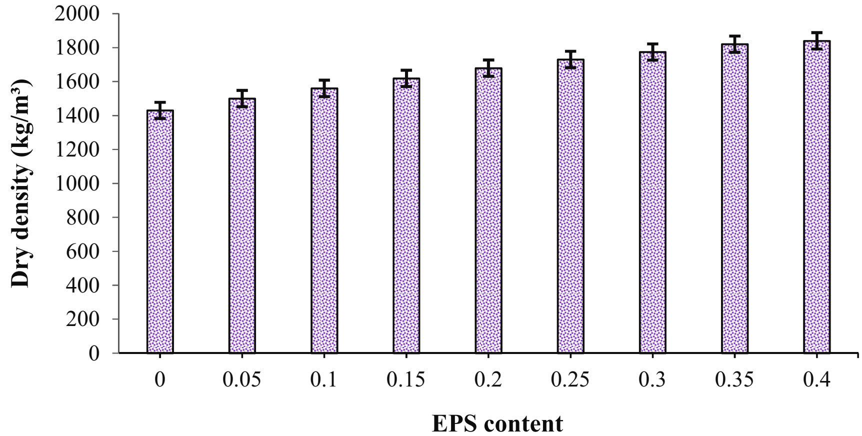

Figure 4: Effect of EPS on the dry density of varied AC mixes.

value. The effect of increasing EPS on the AC density can almost be compared to the influence of EPS on other characteristics (compressive, flexural strength and dry density) of AC. As seen, increasing the EPS content to 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 and 0.4% resulted in about 5, 9, 13, 17, 21, 24, 27 and 29% increase in concrete dry density. The EPS-AC mixtures with varying densities can be categorised as structural LWC. However, Allahverdi et al. and Yassin et al. [12,23] obtained opposite results using different contents of EPS as a coarse aggregate in AC mixtures. Their results indicated that the density decreased exponentially with increasing EPS content. They explained that the decrease in EPS-AC density could be due to the coarse structure of EPS compared to that of cement. However, the results of this research indicating the effect of adding EPS beads in the improvement of AC density could be interpreted by the role of the beads in reducing the overall pore volume of the cement paste. Therefore, it could be expected that the density of AC would be enhanced with increasing EPS volume fraction.

4 Conclusions

1. The research results verified the feasibility of using EPS beads to develop the mechanical properties of the AC.
2. In contrast to previous findings, the results indicated an improvement in compressive, flexural strength, density and modulus of elasticity of AC, with the addition of EPS. The greatest enhancements in the properties of EPS-AC were obtained when the EPS volume fraction was increased to 4%.
3. EPS can be added in different quantities to produce AC with different densities and strengths.
4. It was shown that all EPS-AC mixes could satisfy the requirements of structural LWC. EPS-AC with a dry density of 1,840 kg/m^3 and a compressive strength of around 28 MPa at 28 days was effectively achieved, which realised the integration of function and structure.
5. Further research is recommended about the effect of increasing EPS content in the concrete mix on increasing the probability of plastic failure of the EPS-AC.

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