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Effects of Expanded Polystyrene Beads and Printing Direction on Printable Epscrete Properties

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Abstract

This study investigates the effects of expanded polystyrene (EPS) beads and printing direction on the fresh and hardened properties of 3D printable lightweight concrete (epscrete) mixtures. In the experimental studies, control samples containing only sand, mixtures containing only EPS and sand-EPS mixtures with different ratios were prepared and various experiments such as workability, shape retention, unit weight, ultrasound transmission velocity, compressive strength, flexural strength and splitting tensile strength tests were performed on these specimens. In addition, the effects of printing and loading directions on the mechanical strength of epscrete mixtures were investigated. The results show that EPS beads improve the rheological properties of fresh concrete and increase workability, but cause a significant decrease in shape retention ability, especially at high EPS ratios. In terms of hardened concrete properties, it was determined that mechanical strength decreases as the EPS ratio increases, but sufficient load-bearing capacity can be provided with compressive strengths exceeding 30 MPa in all directions in mixtures containing 50% EPS. In addition, higher compressive strength is observed under loading perpendicular to the printing direction, while the strength is lower on the interlayer bonding surfaces. Microstructure analyses revealed that ettringite formations are intense in the transition zone between EPS and cement matrix and this increased porosity within the structure adversely affects the overall strength. These results show that lightweight concretes with EPS content, known for their advantages such as lightness and thermal insulation, have potential for 3D printable low-rise and lightweight building applications.

Keywords

EPS beads, 3D printable concrete, epscrete, anisotropic behavior, mechanical strength

1 Introduction

3D printing technology offers significant opportunities in the construction sector as well as in many areas such as medicine, food, aviation and home use. This technology provides fast construction opportunities without using molds in building production, reducing costs and providing flexibility in design. The construction of structures such as houses, bridges and offices with 3D concrete printers in China, the Netherlands, Slovenia and the United Arab Emirates and many other countries of the world reveals the developments in this field [1]. However, basic scientific studies on 3D concrete printing are not yet sufficient.

In this context, Ozalp has developed new mixtures with various mineral additives (silica fume, blast furnace slag, metakaolin) and fiber reinforcements (steel and synthetic) as a solution to problems such as the brittle structure of concrete, high cement requirement and strength differences depending on the directions. As a result of this study, the permeability of 3D printable concrete has been reduced and the workability has been enhanced; with steel fibers, fracture energy and ductility have increased by 36 and 22 times, respectively [2]. On the other hand, Yuan et al. [3] proposed a three-stage method for the production of 3D concrete containing coarse aggregates with a maximum size of 20 mm. In this method, the fresh, plastic and hardened states of the concrete were taken into account; both workability and strength properties were controlled with appropriate plasticizer additives (polycarboxylate ether superplasticizer and aluminum sulfate accelerator) [3]. In recent years, with the development of 3D concrete printing technology, the development of sustainable, lightweight and workable 3D printable concrete has come to the forefront in research. In this context, printable cement-based composites developed

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using different lightweight aggregates and waste materials give remarkable results in terms of both environmental and mechanical performance. Liu et al. [4] stated that 3D concretes prepared with diatomite additive reached the best printing and strength properties at 5–30% diatomite dosages. Cuevas et al. [5] showed that recycled glass aggregates and expanded thermoplastic microspheres increased printability by improving the pore structure. Yan et al. [6] reported that lightweight aggregate engineering cement composites stand out with high ductility and low carbon emission without reinforcement. Bodur et al. [7] emphasized that successful results were obtained in the production of lightweight cement composites produced with 3D printers by reinforcing waste tire aggregates with micro attapulgite and steel fibers. Deng et al. [8] reported that the printability increased and the matrix porosity decreased in lightweight aggregate cement mixtures produced with 3D printers obtained with clay ceramsite sand. Another study by Cuevas et al. [9] revealed that the combination of glass aggregate and expanded thermoplastic microspheres produced lightweight, environmentally friendly concretes by reducing density and thermal conductivity. Wang et al. [10] stated that reactive magnesium oxide cement composites containing cenospheres increased the printing quality. Gou et al. [11] showed that the lightweight and high-strength engineering cement composite developed using porous lightweight fine sand increased printability with excellent fluidity, consistency and fiber orientation. Rahul and Santhanam [12] and Araújo et al. [13] reported that expanded clay aggregate improves the behavior of fresh concrete by increasing the buildability and viscosity in printable concrete. Duan et al. [14] reported that mortars with fly ash cenosphere additives have positive effects on fluidity, adhesion and extrusion behavior. Rangel et al. [15] determined that cork aggregates improve printability and reduce density and thermal conductivity. Zandifaez et al. [16] showed that ultralight and thermally insulating 3D composites can be produced with a hybrid approach of chemical foaming and lightweight additives. Ma et al. [17] reported that the addition of aerogel provides thermal insulation and reduces strength, but is suitable for 3D printing. Falliano et al. [18] showed that 3D-printable lightweight foamed concrete offers better dimensional stability and mechanical strength than traditional foamed concrete. All these studies show that different lightweight aggregates and waste-based additives can be successfully used in 3D printable concretes, thus optimizing mechanical, thermal and environmental performances.

In this study, the aim was to use expanded polystyrene beads in obtaining printable lightweight concrete. Studies on the use of expanded polystyrene beads in concrete are aimed at improving the mechanical performance of concrete by reducing its density. In this context, the use of expanded polystyrene (EPS) beads, which attract attention with their low density (10–30 kg/m^3), closed cell structure and hydrophobic properties, has been increasing in recent years as lightweight aggregates in concrete production. EPS concretes are preferred in both structural and non-structural applications due to their advantages such as heat and sound insulation, superior workability, low density and environmental sustainability.

However, the addition of EPS generally tends to reduce the compressive and tensile strength of concrete; therefore, studies are carried out to improve the mechanical properties with additives such as fiber, silica fume and fly ash. In addition, durability properties of EPS concrete such as fire performance, freeze-thaw resistance, drying shrinkage and impact behavior have been investigated [19–21]. Bouvard et al. examined the microstructure and thermal-mechanical properties of EPS concretes with X-ray computed tomography (X-CT) and modeling techniques and showed that these properties can be predicted by Bruggeman and Gibson-Ashby models [22]. Miled et al. [23] investigated the effect of EPS particle size on compressive strength experimentally and revealed that smaller particles provide higher strength. Kathiravel et al. [24] analyzed the deterioration of concrete panels containing EPS due to moisture and heat using multi-scale modeling and stated that moisture entrapment at the EPS-mortar interface may lead to structural weakening. On the other hand, Prasittisopin et al. [25] drew attention to some sustainability issues such as toxic gas emission and waste management despite the environmental benefits of EPS use. In the study conducted by Dissanayake et al., [26] it was shown that foam concrete panels containing 50% recycled EPS are competitive compared to cement-sand blocks and clay bricks in terms of embodied energy, carbon emission, cost and natural resource use, and it was concluded that these panel systems can be a mainstream wall material in the construction sector thanks to their advantages such as fast construction process and low labor requirement. When previous studies were examined, it was seen that there was only one study in the literature on printable concrete produced with expanded polystyrene beads. In this study, Niu et al. [27] determined that EPS reduces the weight of the structure with its low density (10–60 kg/m^3), water-repellent structure and low water absorption rate and also increases thermal insulation. Concrete mixtures with unit weights of 500–1900 kg/m^3 were produced at volumetric EPS ratios between 0–100%; the mixture containing 40% EPS exhibited optimum performance in terms of rheology. The mixture became very light at 100% EPS and printing was only possible with a 40 mm nozzle. Although the mechanical compressive strength decreased from 30 MPa to 4 MPa, it was evaluated as sufficient for non-structural applications. X-CT analyses showed that EPS was homogeneously distributed in the mixture. In addition, the paste layer thickness was determined experimentally according to different aggregate types using the "excess paste" theory. Thus, it has been stated that it is possible to produce lightweight and sustainable 3D printed concrete with EPS. The difference of this cited publication from the current study is the examination of printing directions, determination of concrete behavior with different rheological tests, and evaluation of bending strength, which is important for beam elements. In addition, recent research by Thajeel et al. [28] examined the effects of metakaolin (MK) and silica fume (SF) on the fresh and hardened properties of 3D printed concrete, reporting that an optimum combination of 10% MK and 5% SF significantly enhanced shape retention, buildability, and directional strength uniformity. These findings further emphasize the importance of mixture optimization and printing direction in achieving high-performance 3D printable concretes. It has been seen that structural lightweight elements can be produced with printable epscrete.

2 Experimental study

2.1 Materials

In the production of 3D printable concrete, super white CEM I 52.5 R class cement produced by Cimsa cement factory was used as cement. The properties of this cement are given in Table 1.

Masterglenium 51, a new generation super plasticizer additive from BASF, was used as a water reducer and plasticizer (NGSP). Walocel mkx 4000 pf 01 type hydroxypropyl methylcellulose (HPMC) was used as a viscosity modifier. The properties of these materials are given in Table 2.

Table 1 Cement properties

Chemical Content, %								
CaO	SiO	Al	Fe	Na	MgO	SO	K	LOI
65.7	21.6	4.05	0.26	0.3	1.3	3.5	0.35	3.5
Density, kg/dm^3		Blain, cm^2/g		Setting time, min		Compressive Strength, MPa		
				Initial	Final	7. day	28. day	
3.06		4600		100	130	50	60	

Table 2 Admixtures properties

NGSP	structure	colour	density, kg/dm	chlorine, %	alkaline, %
	poly carboxylic ether	brown	1.1	<0.1	<3
HPMC	form	solubility	viscosity, mPa·s	pH	moisture
	powder	water soluble	<5000	netural	<7

Expanded polystyrene beads used instead of aggregate are a granulated expanded polystyrene based material and its properties are given in Table 3.

Washed 0–2 mm river sand was used as aggregate. Sand was supplied from Sakarya River Bilecik/Turkey region. Its granulometry and properties are given in Table 4.

The mixing water used in this study was obtained from the water supply system of the university campus, not from municipal tap water. Therefore, its chemical composition was analyzed and presented in Table 5 to confirm according to EN 1008:2002. [30]

2.2 Method and tests

In order to provide lightness in printable concrete, EPS beads were used instead of aggregate. However, in order to determine the change in mechanical properties, mixtures were also prepared using sand as a reference. In addition, new mixtures were produced by taking equal amounts of these two aggregates in terms of volume to determine the usability of both sand and EPS beads together.

Table 3 Properties of expanded polystyrene beads

Spesific unit weight, kg/m	Compressive Strength, kPa	Grain size, mm	Water absorbtion, %
20	90	0.5–2	4

Table 4 Granulometry and physical properties of sand

Sieve size, mm	2	1	0.5	0.25	0.125	Specific unit weight, kg/dm^3
Granulometry, %	100	67.8	47.4	16.6	2	2.65

Table 5 Properties of mix water

Chemical Content, %							
SO_4	NO_3	NH_4	P	Al	Fe	NO_2	Mn
80	11.1	0.06	0.06	0.043	0.007	0.005	0.015
Conductivity, µS/cm	Hardness, Fd°		pH		Turbidity, NTU		
628	30.11		7.35		0.25		

In concrete mixtures, the values obtained as a result of initial trial productions were used for the weight of additives and water/cement ratios. Concrete mixture proportions are given in Table 6. The appearance of the extruded concrete layers of these mixtures is shown in Fig. 1. The photographs on the left and middle illustrate the first trial prints made to determine the appropriate mixture proportions and printing parameters. These mixtures are called epscrete as stated in the literature [21].

2.2.1 Determination of rheological properties of mixtures

In order to determine the effect of EPS on rheological behavior, the spreading index and buildability were determined. A spreading test was performed to determine the flowability index. As can be seen from Eq. (1), the spreading index is obtained by dividing the result obtained by subtracting the square of the mold inner diameter (d_0) from the product of the spreading diameters (d_1, d_2) by the square of the mold inner diameter (d_0). Buildability, which is determined using the shape retention values, is found by determining the final height obtained as a result of the collapse resulting from a static load of 600 g [29]. These tests, shown in Fig. 2, were repeated at certain time intervals and the rheological properties were examined.

$$\Gamma = \frac{d_1 d_2 - d_0^2}{d_0^2} \quad (1)$$

Table 6 Mixture proportions of printable concrete

water/ cement	sand/ cement	EPS/ cement	sand/EPS, (by vol.)	HPMC/ cement	NGSP/ cement
0.32	1.5	0	1/0	0.002	0.01
0.32	0.75	0.014	0.5/0.5	0.002	0.01
0.32	0	0.028	0/1	0.002	0.01

Fig. 1 Extrusion of printable concrete containing EPS

Fig. 2 Schematic representation of flow table test and buildability test

2.2.2 Determination of properties of printable epscrete mixtures

In order to perform mechanical tests, appropriate nozzle size (it was used to obtain a printed sample equivalent to the casted sample) was selected and surface smoothness was ensured by cutting the 2-layer extruded samples before setting. Thus, prismatic and cube shaped samples were obtained. Standard 4 × 4 × 16 cm prismatic casted samples were used as reference samples. All samples were kept in standard 20 °C ± 2 water cure conditions. Bending strengths were determined by performing 3-point loading tests on these samples. Compressive strength tests were performed on cube samples. In order to determine the adhesion strength between concrete layers, the load applied to the contact surfaces. Thus, splitting tensile strengths were determined. The test results of these samples were compared with the splitting tensile strengths of the reference samples and the effect of EPS on the interlayer adhesion strength was determined. Fig. 3 shows the images of the test setups used to determine the flexural strength, compressive strength and splitting tensile strength of the samples in various loading directions.

2.2.3 Extrusion of printable epscrete beam elements and tests

3D printable concrete can be used to produce structurally large-scale beam elements. However, in this case, it is important to know the behavior of beam elements under bending. Separations may occur on the contact surfaces of the printing layers on these elements due to tensile stresses. In order to perform bending tests on these beam elements, tests were performed on 10 × 10 × 50 cm prismatic samples prepared by cutting the samples extruded in 2 rows and 4 floors high before the concrete set. In addition, compressive strength and splitting tensile strength tests were performed on 10 × 10 × 10 cm cube samples prepared with the same method. Before testing, the top and bottom surfaces of the printed specimens were leveled and smoothed to ensure

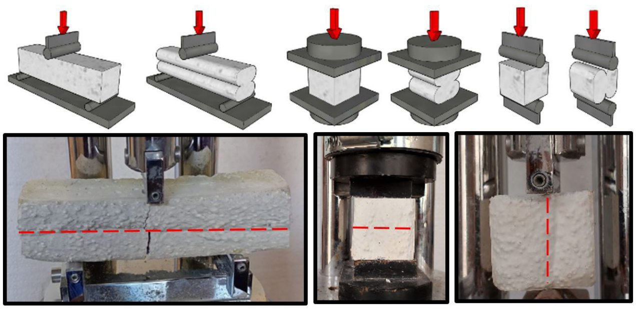

Fig. 3 Mechanical tests of 3D printed epscrete specimens

uniform load distribution and proper contact with the testing machine platens. Fig. 4 presents the bending, compression and splitting tensile test images performed on these prepared samples.

2.2.4 Determination of printing orientations and tests

Unlike conventional concretes, the properties of 3D printable concretes can change significantly depending on the direction. In 3D concrete technique, the direction in which the loads are applied is extremely important. Studies on the anisotropic behavior of 3D concrete are constantly ongoing. Structures are generally exposed to vertical loads. In this case, tests are carried out by applying loading perpendicular to the printing direction. However, concrete elements are expected to show sufficient resistance against horizontal loads, especially in structures that may be affected by earthquakes. In order to determine this effect, loading tests are carried out on 3D printable concrete samples in a direction parallel to the printing direction. In this study, tests were carried out for both vertical and horizontal loading. For this purpose, 15 × 15 × 15 cm cube-shaped samples were obtained by cutting the concrete before it set from the samples extruded in 3 rows and 6 layers side by side. In addition, the compressive strengths of the samples were investigated in two different printing directions with the scenario of producing 3D printable lightweight concrete as an alternative to lightweight blocks such as aerated concrete. The schematic drawings of the loading type and printing directions and the codes of the samples used in the study are given in the Fig. 5. The samples given as 90 degrees in Fig. 5 show samples printed with one layer in the parallel direction and one layer perpendicular to the lower layers.

2.2.5 Microstructural analysis

Microstructural analyses were performed on the samples using a Hitachi Regulus 8230 FE-SEM field-emission scanning electron microscope. In addition, Energy-Dispersive X-ray Spectroscopy (EDS) was employed to confirm the elemental composition at the EPS–cement interface and to distinguish between polymeric EPS regions and the surrounding cementitious matrix based on their characteristic chemical elements. The electron gun was operated in the 10 kV voltage range and images were obtained at 100×, 500×, 2000× magnification values.

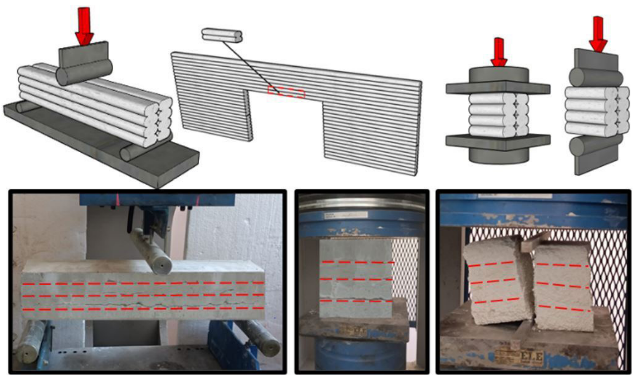

Fig. 4 Mechanical tests of epscrete beam specimens

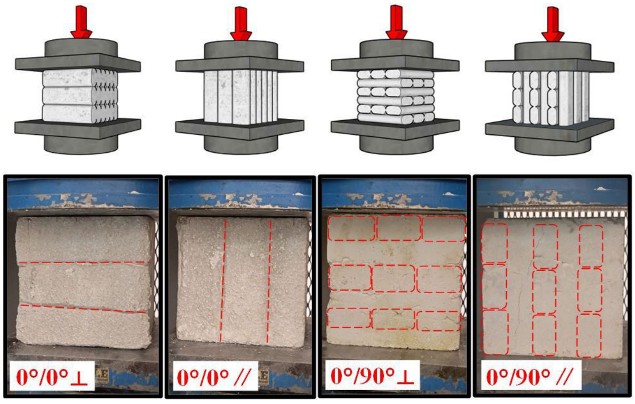

Fig. 5 Compressive strength tests according to different loading and printing directions

3 Discussion

3.1 Effect of expanded polystyrene beads on rheological properties

The flowability indexes of epscrete mixtures depending on the open time are shown in Fig. 6. Open time refers to the period during which the printable concrete maintains adequate workability and extrudability before significant loss of flowability occurs due to ongoing hydration or thixotropic stiffening. When Fig. 6 is examined, the flowability index decreased as the open time increased. This decrease was 84.1% in control mixtures without EPS at the end of 60 min, while it was 84% in mixtures containing 50% EPS and 57.1% in mixtures containing 100% EPS at the end of

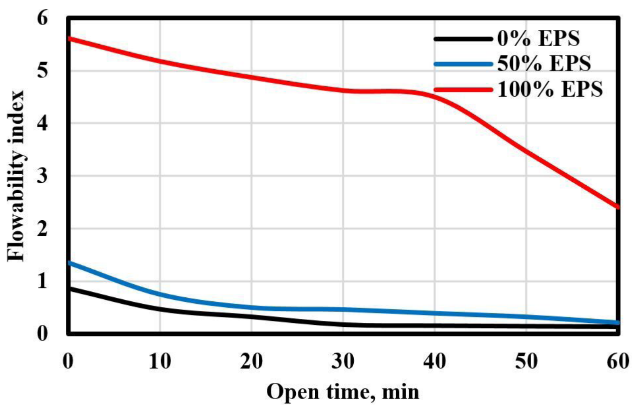

Fig. 6 Effect of expanded polystyrene beads on the flowability index

the same time. The lightness of EPS beads and their rounded surface facilitated the workability by increasing the fluidity. It was understood that this advantage disappears when used with sand material. However, it can be stated that the use of 100% EPS increases the open time.

The changes in the buildability with open time of printable epscretes containing different ratios of expanded polystyrene beads are given in Fig. 7. When Fig. 7 is examined, it is determined that shape retention under load decreases by 24.7% in mixtures containing 50% EPS and 61.7% in mixtures containing 100% EPS compared to control concretes at the beginning ($t = 0$ min), i.e. as soon as the mixture is prepared. Shape retention increases over time and the effective period is 40 minutes in control mixtures without EPS and 70 minutes in mixtures containing 50% EPS. In mixtures containing 100% EPS, shape retention ability increases significantly especially after 80 minutes and reaches the highest value at 130 minutes. Although mixtures containing 100% EPS have better flowability, the fact that shape retention capacity is low in terms of buildability reveals that concrete printing speeds should not be high along the layers in such concretes. However, the applied load here is the same value for comparison purposes in mixtures containing and not containing EPS. However, the fact that epscrete is much lighter than conventional concrete will also reduce the weight of the upper layers by up to 50%. Since most of the loads on the vertical plane of the structures are the self-weight of the concrete, it is necessary to take this into account in the evaluations.

3.2 Properties of printable epscrete containing different proportions of expanded polystyrene beads

The unit weight values of the samples depending on the EPS content are given in Fig. 8. When Fig. 8 is examined, it is determined that the unit weights vary between 1039–2093 kg/m³. While the unit weight values of the samples decrease by rates reaching 23% when the EPS content is 50%, it is determined that they decrease by rates reaching

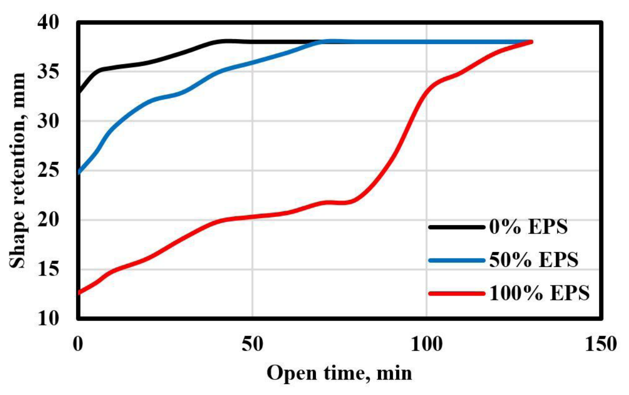

Fig. 7 Effect of expanded polystyrene beads on the buildability

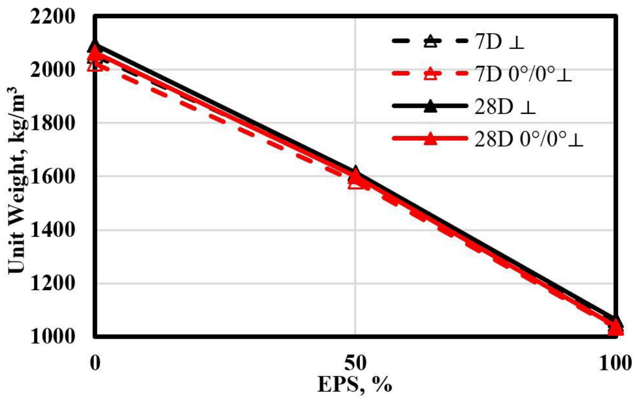

Fig. 8 Unit weights of casted (⊥) and printed (0°/0°⊥) specimens containing EPS

50% when the EPS content is 100%. The fact that the EPS density is quite low compared to the sand density has been effective in this decrease. In addition, since partial gaps can remain between the layers when the samples are printed in 2 layers, a decrease of 2.1% was determined in the unit weight values compared to the casted reference samples. When the unit weight values are evaluated in terms of curing time, an increase of 1.3% was observed in the unit weights of the 28-day samples compared to the unit weights of the 7-day samples. It was evaluated that the continuation of hydration reactions and shrinkage caused this increase.

The ultrasonic pulse velocity of the samples prepared from the mixtures are given in Fig. 9. When Fig. 9 is examined, it is seen that the ultrasonic pulse velocity varies between 2.5–4 km/s. As the EPS content increases, the velocities decrease by up to 33%. The voids in the expanded structure of EPS were effective in this decrease. In 2-layer printing, the inability to fully bond between the two layers and the presence of voids in between caused the ultrasonic pulse velocity to decrease by up to 12%.

The bending strength values of the samples prepared from the mixtures are given in Fig. 10. When Fig. 10 is examined, it is seen that the bending strength values change in the range

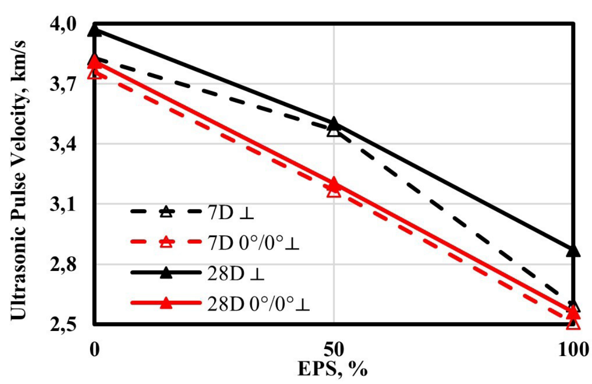

Fig. 9 Ultrasonic pulse velocities of casted (⊥) and printed (0°/0°⊥) specimens

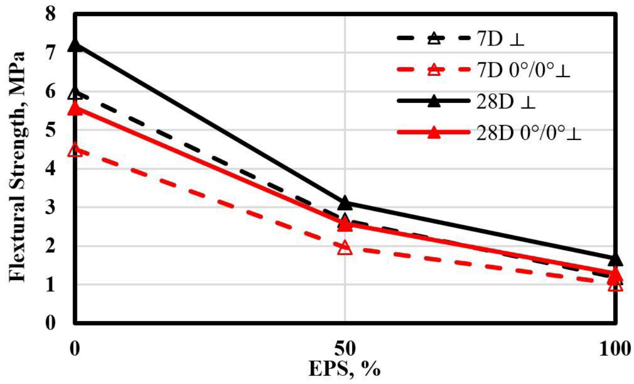

Fig. 10 Flexural strengths of casted (⊥) and printed (0°/0°⊥) specimens

of 1–7.3 MPa. As the EPS content increases, the bending strength values decrease by up to 76%. The weak structure of EPS with pores causes the section under the bending effect to weaken and the bending strength to decrease. Compared to the casted reference samples, the bending strength of the concrete printed in two layers decreased by 22.7%. The fact that the contact section between the layers is not completely filled during printing is effective in this decrease. It was observed that 83% of the 28-day bending strength value was reached in 7 days. The high early strength of the cement is effective in obtaining high strength on the 7th day.

The compressive strength values of the samples are given in Fig. 11. When Fig. 11 is examined, it is determined that the compressive strength of the samples containing 50% EPS decreases by 46% compared to the samples without EPS, and the compressive strength of the samples containing 100% EPS decreases by 82%. The fact that EPS has almost no strength compared to sand causes it to act like a void under the effect of pressure in the concrete and therefore the strength decreases. In the case of printing in 2 layers, the compressive strength losses reached 12%. Since both placement and compression were more effective in the reference samples, the compressive strength values increased.

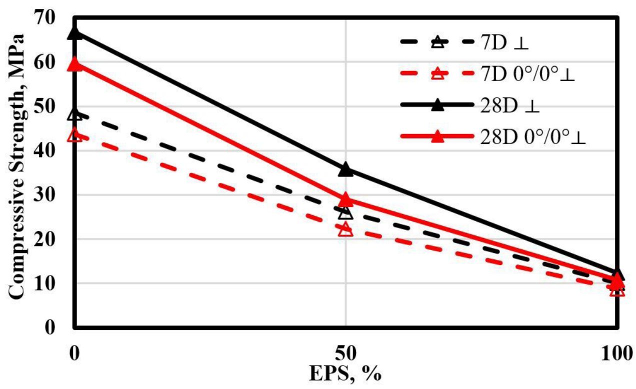

Fig. 11 Compressive strength of casted (⊥) and printed (0°/0°⊥) specimens

When the 7-day and 28-day compressive strengths were compared, as expected, there was an increase of nearly 30% in the 28-day strength of the concrete.

The splitting tensile strength values of the samples are given in Fig. 12. When Fig. 12 is examined, it is seen that the splitting tensile strengths vary between 0.91–4.23 MPa. In the reference samples, as the EPS ratio increases, the splitting tensile strengths decrease by 74%. The splitting tensile strengths determined depending on the linear force applied from the full bonding part of the two-layer printed concrete decrease by 69% as the EPS content increases.

When these results are taken into consideration, it is understood that the EPS content actually makes a positive contribution to the bonding between the layers. When the splitting tensile strengths of the reference samples and the two-layer printed concrete are compared, it is determined that the bonding strength between the two layers is provided in the range of 81%–95% compared to the reference samples. Thus, it is evaluated that sufficient performance is achieved although there is a decrease in the interlayer bond strength in samples containing EPS.

3.3 Characteristics of printable epscrete structural beam elements

The unit weight and ultrasound ultrasonic pulse velocity of the printable structural beam elements are given in Fig. 13. When Fig. 13 is examined, it is seen that the unit weight values vary between 1073–2109 kg/m^3 and the velocity values vary between 2.75–3.9 km/s. While the unit weight values of the samples decrease by 49% with the increase in EPS content, the ultrasonic pulse velocities decrease by 27%. Due to the low density of EPS, printable concrete beam elements with a lightness close to the density of water could be produced. In this way, the decrease in the load caused by the structure's own weight is important in terms of

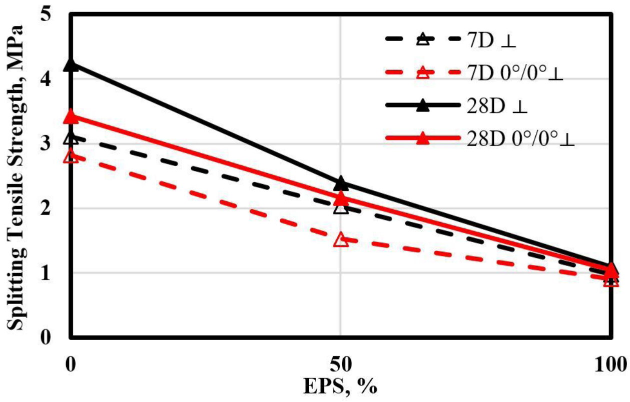

Fig. 12 Splitting tensile strength of casted (⊥) and printed (0°/0°⊥) specimens

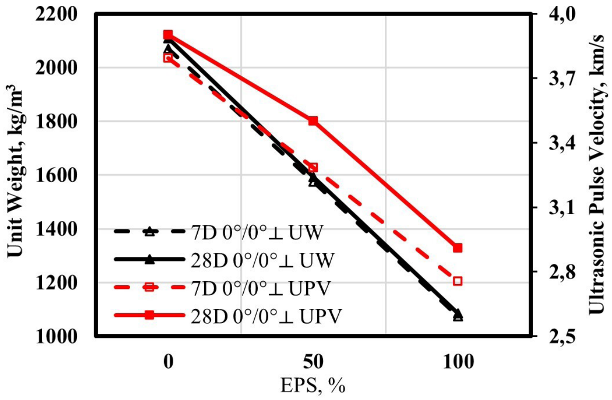

Fig. 13 Physical properties of printed structural beam elements

reducing the vertical loads as well as decreasing the earthquake loads. When the 7-day and 28-day unit weight and ultrasonic pulse velocity results are compared, no significant change is observed in the unit weights, while the ultrasonic pulse velocities of the 28-day samples are higher due to the increased hydration products.

The bending strength of the printable structural beam elements was determined. In addition, compressive strength and splitting tensile strength tests were also performed on samples prepared by cutting from beam elements. The results of all these tests are given in Fig. 14. When Fig. 14 is examined, the bending strength of the samples with 100% EPS ratio decreased by 68%, their compressive strength by 83%, and their splitting tensile strength by 70% compared to the samples without EPS. The porous and weak structure of EPS was effective in this decrease. However, the compressive strength of the load-bearing wall elements in masonry structures is below 10 MPa. A strength of over 10 MPa was obtained in the printable lightweight structural element obtained here. Bending strengths are also important in structural beam elements. A bending strength of 1.6 MPa was obtained in samples containing 100% EPS. However, due to the 49% decrease in unit weight, the bending loads that may occur on such elements will also decrease. When the 7-day strengths

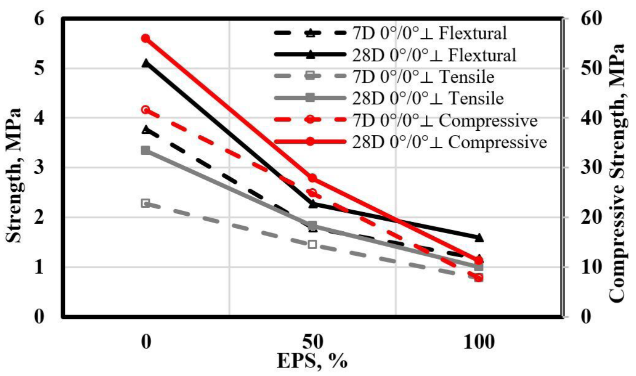

Fig. 14 Mechanical properties of printable structural beam elements

were examined, around 70% of the 28-day strengths were obtained, while in the samples containing 100% EPS, these strengths were 85% in bending, 70% in compressive strength and 77% in splitting tensile strength. Thus, it is understood that the time-dependent strength development of concretes containing EPS is better.

3.4 Effect of printing direction on concrete properties

The effect of printing direction and EPS content on concrete unit weight is given in Fig. 15. When Fig. 15 is examined, it is seen that the unit weight values vary in the range of 1038–2137 kg/m³. It is seen that the printed concrete unit weight values decrease by 51% due to the increase in EPS ratio. While the unit weight values of the samples without EPS decreased by 3% with the effect of printing direction, the unit weight values of the samples containing 100% EPS decreased by 2.2%. It is understood that the printing direction does not have a significant effect on the printable concrete unit weight.

Changes in concrete ultrasonic pulse velocity depending on printing direction and EPS content are given in Fig. 16. When Fig. 16 is examined, it is seen that printable

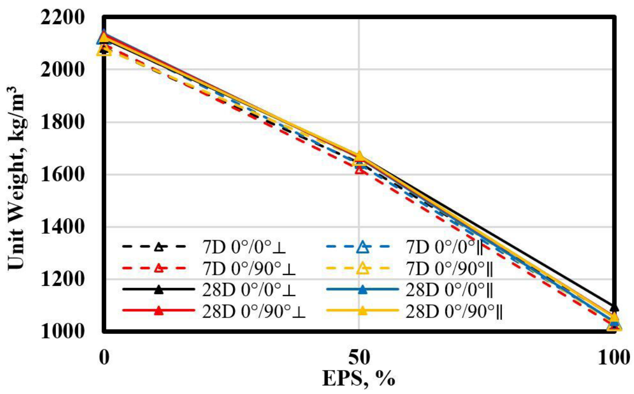

Fig. 15 Effect of EPS content and printing direction on concrete unit weight

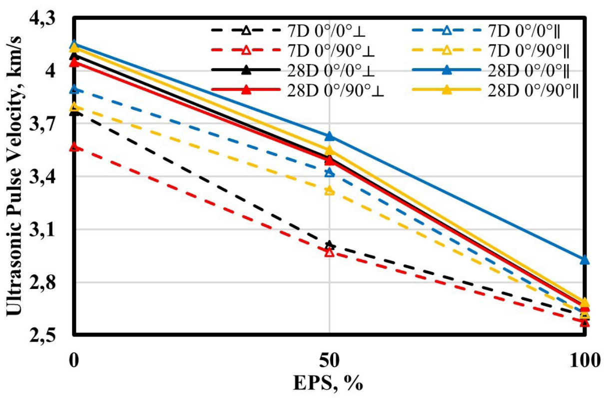

Fig. 16 Effect of EPS content and printing direction on concrete ultrasonic pulse velocity

concrete ultrasonic pulse velocities vary between 2.57–4.15 km/s. As the EPS ratio increases, the velocities decrease to a rate of up to 36%. Both the voids in the EPS and the voids formed during printing have been effective in the decrease in ultrasonic pulse velocity. However, the change in ultrasonic pulse velocities depending on the printing direction gradually decreases over time due to changes caused by the formation of hydration products in the internal structure.

The changes in concrete compressive strength with loading direction, printing direction and EPS content are given in Fig. 17. When Fig. 17 is examined, the compressive strengths decreased as the EPS content increased. When the effect of the loading direction is taken into account, the strengths decreased by up to 8% in parallel loading compared to perpendicular loading. This value reached 23% in samples containing 100% EPS. Since the samples were separated from the contact point in parallel loading, the strengths decreased. When the compressive strengths were compared depending on the printing direction, a decrease of up to 13% was observed in samples consisting of layers with different directions compared to samples consisting of layers with the same direction. This value reached 23% in samples containing 100% EPS. In samples consisting of layers with different printing directions, the decrease in adhesion surfaces between layers compared to samples consisting of layers with the same printing direction causes a decrease in strength.

3.5 Microstructural analyses of printable epscrete

SEM images of samples taken from the printable epscrete layer produced using EPS beads as aggregate are given in Fig. 18. When Fig. 18 is examined, it is seen that in the control concretes printed without EPS, air is entrained with the effect of the new generation super plasticizer used, and a dense structure is formed with the effect of CSH gels. In the epscrete sample, the closed-cell and hydrophobic nature of the EPS particles limited direct physical bonding with the cement matrix, leading to the formation of a distinct interfacial transition zone (ITZ). In this region, micro-voids and weak mechanical interlocking were observed due to restricted hydration near the EPS surface. However, localized ettringite formations and C–S–H gel deposits were detected around the EPS boundaries, indicating partial chemical interaction facilitated by the adsorption of hydration products on the rough outer surfaces of some EPS beads. This heterogeneous ITZ morphology is considered one of the primary reasons for the reduction in mechanical strength observed in EPS-containing mixtures.

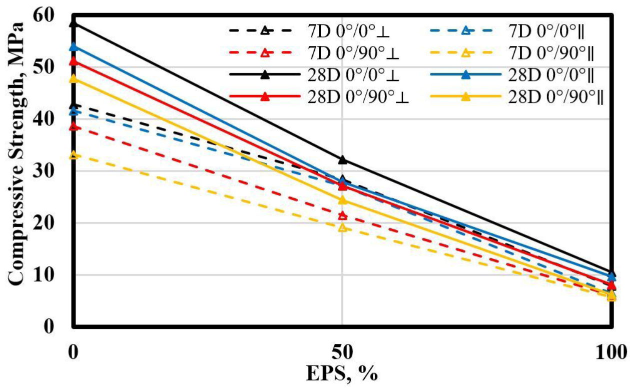

Fig. 17 Effect of loading and printing direction on concrete compressive strength

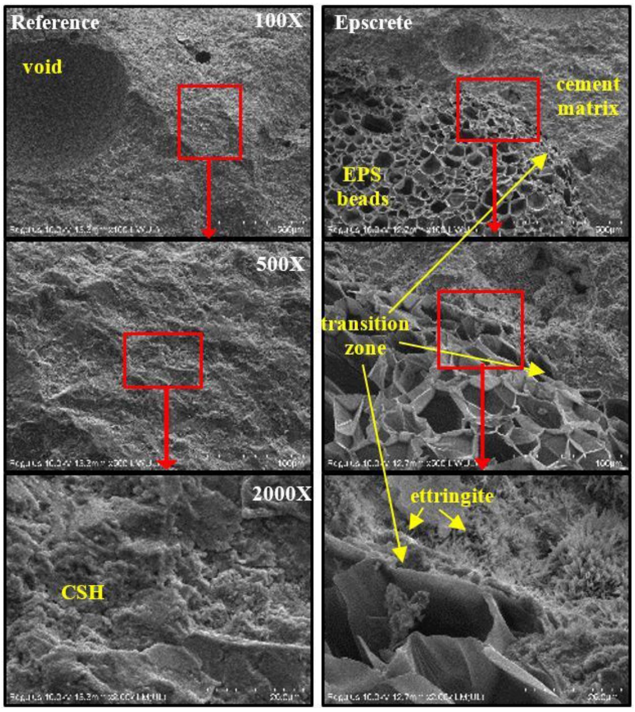

Fig. 18 Micrograph of epscrete and reference samples

The results of the EDS analysis of the samples are shown in Table 7. This analysis was performed to verify that the results obtained from the grain and matrix of the epscrete sample represent the EPS bead and cement matrix.

4 Conclusions

This research aimed to investigate the effects of expanded polystyrene beads and printing direction on the fresh, hardened, and microstructural properties of 3D printable lightweight concrete which was called epscrete. For this purpose,

Table 7 EDS analysis of epscrete composites

Element Wt%	Ca	Si	Al	C	O
Cement matrix	27.69	7.46	1.65	-	63.20
EPS beads	-	-	-	94.72	5.28

mixtures containing different EPS ratios (0%, 50%, and 100%) were prepared, and a comprehensive experimental program including rheological tests, mechanical strength tests, and microstructural analyses was carried out. The main findings obtained from the study are summarized below:

- The use of EPS increased fluidity in printable concrete mixtures but reduced the shape retention. Considering the open time of the concrete, it is important to reduce the printing speed of the concrete containing 100% EPS to improve shape retention. In the samples containing 50% EPS, rheological properties were similar to the control specimens. However, in all shape retention tests, the same load was applied to the reference and EPS-containing samples. In actually, considering that the weight of the concrete that EPS concrete must carry much less due to its lightness, it is evaluated that shape retention of EPS samples is sufficient.
- In samples containing 100% EPS, printable epscrete with a unit weight of 1.04 kg/dm^3, a flexural strength of 1.3 MPa, a compressive strength of 10.8 MPa, and a splitting tensile strength of 1.1 MPa were obtained. In the case of using 50% EPS, printable epscrete with a unit weight of 1.6 kg/dm^3, a flexural strength of 2.6 MPa, a compressive strength of 30 MPa, and a splitting tensile strength of 2.2 MPa were obtained. Considering that the unit weight of aerated concrete used in the structures is 0.4 kg/dm^3, the compressive strength is 2.5 MPa, the unit weight of bricks is 0.6 kg/dm^3, and the compressive strength is in the range of 1–5 MPa, it is understood that the epscrete printable concrete obtained in this study is partially lightweight but has quite high strength.
- It has been observed that printable concretes with 1.6 MPa flexural strength and 11.2 MPa compressive strength can be produced when using only EPS. Buildings produced with printable concrete are generally low-rise and low-story structures. Considering that the weight of these structures will decrease by up to 49% when produced with printable epscrete, it is understood that lightweight concretes with sufficient structural performance can be produced using EPS.
- Printable concrete has the highest strength in loading perpendicular to the printing layers due to its anisotropic behavior. However, in parallel loading, compressive strengths exceeding 50 MPa were still obtained in samples without EPS. The compressive strengths of the samples containing 100% EPS showed similar behaviors depending on the printing direction, and the compressive strengths of the samples varied between 6.2–10.5 MPa. In orthotropic samples obtained by changing the printing direction between layers, strength losses increased due to the decrease in adhesion surfaces.
- In microstructure studies, intense ettringite formations were detected in the EPS bead and cement matrix transition zones, which is evaluated that caused a decrease in strength. It was also observed that the superplasticizer formed irregular voids in the cement matrix due to the air entrainment effect.

In contrast to the study by Thajeel et al. [28], which investigated the effects of metakaolin and silica fume on printability and directional strength in 3D printable concrete, this research explores the anisotropic mechanical behavior of EPS-based 3D printable concrete by systematically analyzing the influence of printing directions on fresh-state rheology and hardened-state strength. Thus, the present work uniquely combines lightweight aggregate optimization (EPS) with directional printing evaluation to extend the literature on 3DPC anisotropy. In addition, the behavior of fresh concrete is investigated with some different rheological tests and the mechanical behavior properties that are important for structural elements are evaluated. It was seen that lightweight structural printable epscrete can be produced using 100% EPS. In cases where structural capacity needs to be increased, it is recommended to use printable epscrete containing 50% EPS. It has been understood that 3D printable structural lightweight concrete elements can be produced with printable epscrete. However, for further studies, it would be useful to examine not only the durability effects and the structural performance on larger printed elements, but also the thermal and fire resistance of epscrete under high-temperature exposure. In addition, the applicability of recycled shredded EPS fractions in 3D printable concrete should be investigated to enhance sustainability and reduce plastic waste in construction materials.

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