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Technical Paper

Sandwich panels of ultra-high performance concrete composite with expanded polystyrene

Ji-Hyung Lee; Sung-Gul Hong*; and Yu-Jin Ha

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Abstract: The performance of sandwich panels is upgraded by increasing thermal resistance using UHPC (ultra-high performance concrete) with EPS (expanded polystyrene) beads composite. The core of the sandwich panels is made of lightweight UHPC composite with EPS and the face sheet by thin UHPC plates. The core provides the thermal resistance and the outer face sheets provide the flexural strength of the sandwich panels. Fresh UHPC is prepared to mix with EPS beads to produce new composite material with improved thermal resistance. The weak bond at interfaces between UHPC and EPS beads can be improved by pre-wetting the beads for one day. The ratio of UHPC to EPS beads should be proportioned to balance between strength and thermal resistance. Various thermal and mechanical properties of UHPC composite core material and the flexural strength of sandwich panels for architectural components are investigated in this paper. The performance of sandwich panels of UHPC composite core with UHPC face sheets shows one of potential applications of UHPC.

Keywords: sandwich panel; lightweight aggregate concrete; ultra-high performance concrete (UHPC); expanded polystyrene.

1. Introduction

The higher-rise and larger and longer spanning structures are being constructed rapidly in various ways with more diversity of buildings and civil engineering structures. Better structural and durability performance of construction materials with higher strength, lower density, higher energy efficiency and others is required. Especially, the demand for lightweight concrete in many applications of modern construction is increasing. Owing to the advantage of lower density and load-bearing elements of smaller cross sections, a corresponding reduction in the size and a significant reduction in the self-weight have a positive impact on the economics of construction projects. Lightweight concrete can be applied in a variety of ways. One of them is the application as a core material of the composite sandwich structure. The composite sandwich panels have been widely used for weight-sensitive structures that require high flexural strength for several decades.

The composite sandwich panels have emulated a typical structure comprising a relatively thin, stiff, and strong face sheet with a relatively thicker and lighter core. Sandwich structures can be combined in a variety of face sheets and core materials to create an optimal design. The main advantages of composite sandwich panels are high strength and stiffness, lightness, high insulation, and the possibility of creating versatile functions.

The main purpose of this paper is to investigate the thermal and mechanical properties of ultra-high-performance concrete composite sandwich panels by combining various core materials and face sheets. The possible panel configurations of sandwich panels were selected and ultra-high-performance concrete with expanded polystyrene composite (UHPEPC) was used as the core material. In addition to UHPEPC, the mechanical properties of the sandwich panels were also investigated. The actual panel behavior was observed by bending load tests on seven types of composite sandwich panels.

2. Background

The material for sandwich panel selection is based on its mechanical properties, low cost, low density, resistance to fluctuations in temperature,

Ji-Hyung Lee is a post-doctor, Dept. of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea.
Corresponding author Sung-Gul Hong *is a professor* at Dept. of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea.
Yu-Jin Ha *is a formerly graduate student* at Dept. of Architecture and Architectural Engineering, Seoul National University, Seoul, Korea.

moistures and chemicals, and good formability. Expanded polystyrene is used because its strength properties are well matched to the needs of particular structures and a wide range of concrete densities and strength can be achieved by incorporating the EPS beads in the concrete or mortar at different volume ratio [1]. Furthermore, EPS possesses low moisture absorption characteristics. It should be noted that the moisture absorption rates decrease as density increases, but not significantly. It has quite uniform and reliable density of 32 kg/m^3.

The core usually is the weakest portion of sandwich panels and therefore in many ways control the capacity and lifetime of the whole composite sandwich structure. Earlier researchers reported that EPS beads have extremely low density and are hydrophobic. It can result in a poor mix distribution and segregation, necessitating admixtures or treatment on EPS beads' surface. In that context, bonding additives such as water-emulsified epoxies and aqueous dispersions of polyvinyl propionate were added [2] or chemically treated EPS beads which are capable of preventing the segregation in the concrete mixture were used [3].

Previous research reported that the compressive strength of EPS concrete increases with a reduction in EPS bead size for the same concrete density [4, 5]. This scaling phenomenon was first observed by Parant and Le Roy based on an experimental study aiming to formulate and optimize an EPS concrete with a density ranging from 600 to 1,400 kg/m^3 and having structural strength more than 20 MPa [6].

Sandwich panels, comprising of a core covered by face sheets, are frequently used as an alternative of solid plates because of their high bending stiffness-to-weight ratio. The high bending stiffness is the result of the distance between the face sheets, which carry the load, and the light weight is owing to the light weight of the core [7]. The separation of the face sheets by the core increases the moment of inertia of the panel with little increase in weight, producing an efficient structure for resisting bending and buckling loads. The face sheet materials are typically aluminum or fiber-reinforced composites such as glass fiber reinforced polymer (GFRP); the cores are rigid polyurethane, expanded polystyrene (EPS) or paper-resin honeycombs, or balsa wood, aluminum [8]. Despite their very competitive costs, the structural capacity of these conventional sandwich panels is hardly compatible with their use for floors, walls in buildings or bridge decks. The main weaknesses of these panels originate from the low stiffness and strength of the core, and the top face sheet vulnerability to delamination and buckling, due to the local incongruity stiffness and the absence of reinforcements connecting the core and the face sheets [9].

The contribution of core material that has high strength and shear stiffness is significant. It should be used to determine the overall behavior of the composite sandwich beams. Correia et al. [9] fulfilled the experimental investigations that included material characterization and flexural tests on composite sandwich panels. The panels are constituted by a rigid plastic polyurethane (PU) foam and polypropylene (PP) honeycomb – combined with glass fiber reinforced polymer (GFRP) face sheets. Characteristics of the core material – a PU rigid foam and PP honeycomb core were compared. The panels made of PP honeycomb core were stiffer than those made of PU foam core, fundamentally due to the higher shear modulus of the PP honeycomb core. The panels collapsed attributable to core shear failure.

Considering their possible structural use in real applications, the structural capacity of panels should be studied with experiments. Manalo et al. [10] studied the flexural behavior and failure mechanisms of composite sandwich beams in flatwise and edgewise positions. In the flatwise position, the composite sandwich beams failed with sudden brittle failure under flexural loading. In the edgewise position, the introduction of fiber composite face sheets increased the ultimate strength of the composite sandwich beams. When tensile cracks occurred in the core, the non-horizontal face sheets prohibited it from widening and prevented the sudden failure of the beam.

Typical concrete composite sandwich panels comprise of concrete and insulation. Various types of composite sandwich panels have been developed to increase the thermal efficiency. These panels have been applied to various building structures, such as residential and office buildings, cold storages, and industrial buildings. They have been more commonly used for the exterior wall, but they have also been used for the interior wall. There are various insulation materials, including fiberglass, mineral wool, and polystyrene. The extruded polystyrene (XPS) and expanded polystyrene (EPS) are most commonly used for the insulation due to high thermal performance and workability. Their construction cost is lower than that of other materials when the same thermal performance is secured.

3. Mechanical properties of UHPEPC

To facilitate the evaluation of the varying thermal and mechanical characteristics per the quantity of EPS lightweight aggregate, the method of volumetric substitution for UHPC was investigated in this paper. The basic approach of material design is to replace the UHPC contained in the unit volume with EPS. As the volume of EPS beads increases, the UHPC of the same volume decreases, the strength decreases, and the lightness and heat insulation characteristics are improved.

3.1 Preparation of materials

The mixing proportion of UHPC is presented in Table 1. The specimens were cast and wet cured for 24 hours. After demolding, they were steam cured for 48 hours. Type I Portland cement meeting the requirements of ASTM C150, and silica fume made in Norway were used in this research. A commercial silica powder with particle-size distribution of 45~800 μm was used as aggregate. This silica powder contained 97% of SiO_2 and the hardness and density were 7 and 2.65 g/cm^3, respectively. The silica powder filler which was of medium size between cement and silica fume and improves the compressive strength of concrete. It also activates hydration reaction by supplying additional SiO_2 component. Super plasticizer which has 1.01 g/cm^3 density and the steel fiber with 0.2 mm of diameter and 13 mm of length were used as shown in Table 1.

Expanded polystyrene (EPS) beads were utilized as artificial lightweight aggregates for decreasing the weight and producing different grades of EPS concrete. The size of 85% of EPS particles was about 3.5 mm and their true density was evaluated to be 50.58 kg/m^3.

The strength of high performance expanded polystyrene concrete was varied by changing the steel fiber addition rate from 0% to 2% by volume to improve the flexural strength. Curing temperatures were set to 20, 60, and 90 °C, respectively, to investigate the effects of different curing temperatures on high performance expanded polystyrene concrete. The total 17 high performance expanded polystyrene concrete specimens were tested under compression and, in addition, flexural strength was also examined for 7 specimens among them. Table 2 presents the parameter of test specimens. The mixtures include substituting 0%, 30%, 40%, 50%, 55%, 60%, and 70% of aggregate volume by EPS beads as partial replacement of UHPC. The mixing was done in a specific sequence. EPS beads were prepared initially and mixing with UHPC was continued until a uniform and well flowing mixture was obtained. To prevent segregation of fresh UHPEPC, EPS beads were soaked in a super plasticizer for one day before mixing with the other material. The weak bond at interfaces between UHPC and EPS beads was improved by prewetting the beads.

Cubes (50 x 50 x 50 mm) were used to measure the compressive strengths at 7 and 28 days. Beam specimens of 160 x 40 x 40 mm size were used to conduct flexural strength test. To evaluate modulus of elasticity and Poisson’s ratio, cylindrical concrete specimens with 100-mm diameter and 200-mm height were used. The replacement ratio of UHPC with EPS beads was 30%, 40%, 50%, 60%, and 70% by volume as shown in Fig. 1.

Table 1 – Mixing proportion of UHPC

Materials	Cement	Silica Fume	Sand	Filler	Super plasticizer	Water	Steel fiber
Wt. % of cement	1.0	0.25	1.1	0.35	0.025 ~ 0.04	0.185 ~ 0.225	2.0 (vol. %)

(a) EPS 30% (b) EPS 50% (c) EPS 70%

Fig. 1 – Section of UHPEPC specimens depending on the EPS by volume ratio

3.2 Test results

The average values of density measured by three specimens are presented in Table 2. The density is in the range of 801.5 ~ 1,695.6 kg/m^3 and decreases as the EPS replacement ratio increases. The test specimens cured at 90 °C showed that the density of UHPEPC for every 10% increase in EPS content by volume decreases by an average of about 223.5 kg/m^3. For the specimens with EPS aggregates, it shows a wide compressive strength range of 4.81 ~ 65.1 MPa when the density is 801.5~ 1,695.6 kg/m^3. The compressive strength of UHPEPC varies depending on the content of EPS beads. Compressive strength decreases by 15.09 MPa on average as EPS content increases from 30% to 70% by 10% in Fig. 2. Test results show that the strength of the concrete is greatly influenced by the curing method. The most important factors affecting the strength of concrete are curing temperature and curing time. Particularly, in the case of UHPC, it is effective to perform high-temperature curing in early ages to promote the hydration reaction resulting in the strength gain. Therefore, the strength of high performance expanded polystyrene concrete highly depends on temperature in early stage of curing._Lightweight aggregate concrete has a low density because it uses porous aggregates to lighten the concrete. However, the lightweight aggregate weakens the compressive strength of the concrete due to the weak strength of the aggregates.

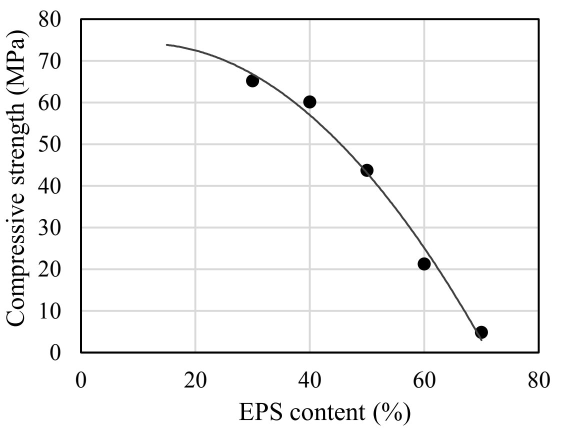


Fig. 2 – Relationship between compressive strength and EPS content by volume ratio

When the flexural strength of UHPEPC was determined on specimens with the EPS content of 50%, 55%, and 60% respectively, it was found to be distributed in the range of 5.0 ~ 12.5 MPa. In Table 2, as the EPS content increases for specimens without steel fibers, the flexural strength is decreased and the higher strength is exhibited at 90 °C curing than at 60 °C curing. The flexural strength of UHPC is strongly influenced by the amount of steel fibers. In case of high performance expanded polystyrene concrete, because the strength is governed by UHPC, the incorporation of steel fibers is a very important parameter in measuring the flexural strength. When comparing the specimens that contain 50%, 55%, and 60% EPS with steel fibers of 2% volume ratio and the specimens without steel fibers, the flexural strength of specimens with steel fibers are 1.74, 1.5 and 1.24 times larger than those without fibers, respectively.

As shown in Table 2, the modulus of elasticity decreases by an average of about 0.05 GPa for every 10% increase of EPS content volume. It is increased by an average of about 0.05 GPa for an average 223.5 kg/m^3 increase of the density and every 15.09 MPa increase of the compressive strength.

The Poisson's ratio increases from 0.55 to 0.63 with increasing compressive strength as shown in Table 2. The shear modulus of elasticity also increased from 36.9 MPa to 202.6 MPa. The Poisson's ratio of UHPEPC exceed the theoretical maximum value of 0.5 probably because of the volume changes due to the presence of voids inside and because the material is not homogeneous.

4. Thermal insulation performance of new materials

Thermal properties of four types of new materials including UHPEPC were investigated. EPS mortar was compared as an alternative core material, and two types of UHPC panels with different reinforcement - steel fiber of 2% volume fraction and glass fiber reinforced polymer (GFRP) mesh - were tested to be used for face sheets. It is common to incorporate steel fiber as a method to improve the flexural performance of UHPC. However, steel is a heavy material and has high thermal conductivity, making it an inefficient material for structures requiring heat performance or light weight. GFRP mesh belongs to textile reinforcement, and is expected to play a role of increasing the tensile strength of UHPC instead of steel fiber as a representative material with high thermal capacity and light weight. In this study, orthogonally netting mesh type of reinforcement was used to maximize the tensile strength of GFRP by securing the smoothness of the shell and the convenience of installation [11].

Three thermal properties were measured in this study. Firstly, *k* value (thermal conductivity) was measured. The ASTM Standard C168 [12] defines the term as follows: Thermal conductivity is the time rate of steady state heat flow through a unit area of a material induced by a unit temperature gradient in a direction perpendicular to that unit area. Secondly, *R* value, thermal resistance is the quantity determined by the temperature difference, at steady state, between two defined surfaces of a material that induces a unit heat flow through a unit area. Finally, there is *U* value, known officially as thermal transmittance. This is more of an engineering term used to designate the thermal performance of a system. Thermal transmittance is the heat transmission in unit time through unit area of a material and the boundary air films, induced by unit temperature difference between the environments on each side.

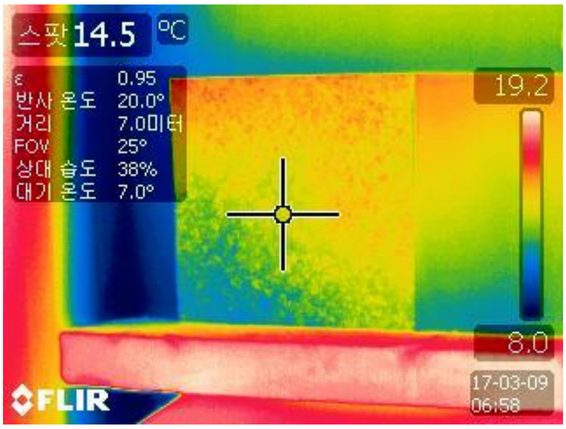
The thermal conductivity *k*, thermal transmittance *U*, and thermal resistance *R* values are presented in Table 3. For the core material, the *U* value and *k* value of UHPEPC is about 3.34 times lower than that of EPS mortar. It means UHPEPC is a better material for insulation. For the material of face sheets, UHPC with GFRP face sheet has 1.43 times higher *U* value and lower *R* value than that of UHPC with steel fibers. The greater the performance of a piece of insulation, the greater its *R* value. Figure 3 shows the surface temperature of specimens. It can be seen that the temperature difference between the top and bottom of UHPC with GFRP mesh specimen. It appears to be a phenomenon caused by peeling between UHPC and GFRP. On the other hand, the steel fibers are perfectly integrated with UHPC and maintains a tight structure resulting in better heat shielding effect.

Table 2 – Density and compressive strength of UHPEC

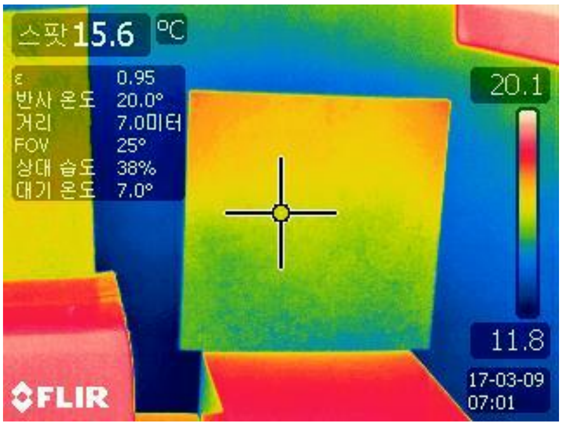
ID	Bulk of EPS (%)	Volume fraction of Steel fibers (%)	Curing temp. (°C)	Density (kg/m^3)	Compressive strength (MPa)		Young's modulus (GPa)	Flexural strength (MPa)
					7 days	28 days		
1	0	0	90	2311.07	196.83	-		-
2	30	0		1695.65	65.15	-	0.25	-
3	40	0		1551.71	60.07	-	0.19	-
4	50	0		1382.33	43.65	-	0.16	9.09
5	60	0		1198.14	21.23	-	0.12	-
6	70	0		801.55	4.81	-	0.05	-
7	0	0	60	2301.63	167.78	175.7		-
8	50	0		1513.57	29.12	32.33		7.20
9		1		1558.21	33.25	34.59		-
10		2		1576.16	35.86	37.25		12.50
11	55	0		1194.8	16.40	-		5.80
12		2		1253.1	15.20	-		8.70
13	60	0		1084.3	11.90	-		5.0
14		2		1067.4	7.90	-		6.20
15	50	0	20	1447.63	-	21.58		-
16		1		1513.07	-	21.40		-
17		2		1545.95	-	30.89		-

Table 3 – Thermal properties of new materials

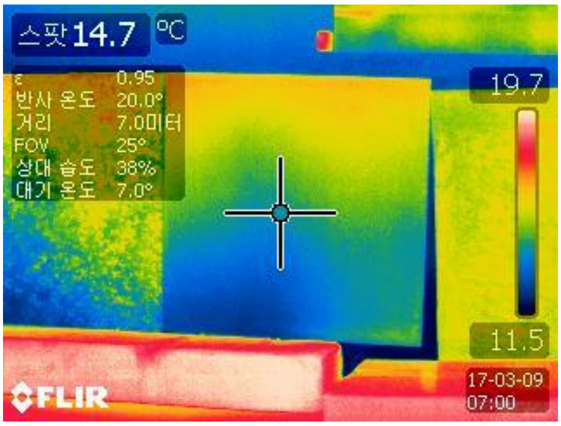
T-specimen ID	Target area	Material type	Density (kg/m^3)	*k* (W/mK)	*U* (W/m^2K)	*R* (m^2K/W)
1	Core	EPS mortar	1384.07	1.649	32.987	0.030
2		UHPEPC	1382.33	0.493	9.864	0.101
3	Face sheet	UHPC with GFRP mesh	2244.96	1.203	24.053	0.042
4		UHPC with steel fiber	2311.07	0.837	16.743	0.060



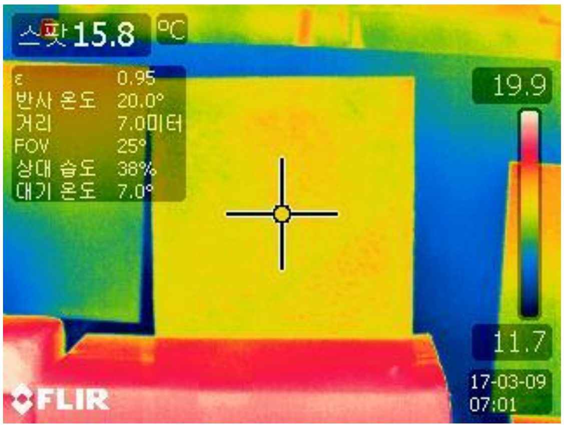
(a) EPS mortar



(b) UHPEPC



(c) UHPC with GFRP mesh



(d) UHPC with steel fibers

Fig. 3 – Surface temperature of different new materials

Table 4 – Specimen details and flexural test results

S-specimen ID	Core	Adhesive	Face sheet	Failure mode	Delamination	P_{max} (kN)
M-U1	EPS mortar	Mortar	UHPC with steel fiber	Face sheet failure	n/a	9.26
M-G			GFRP	Core, bond failure	Observed	3.4
U-U1	UHPEPC	Mortar	UHPC with steel fiber	Core failure	n/a	21.1
U-U2			UHPC with GFRP mesh	Face sheet failure	Partially observed	18.02
U-G			GFRP	Core, bond failure	Observed	15.29
U-U1-E		Epoxy bond	UHPC with steel fiber	Core failure	n/a	6.18
U-G-E			GFRP	Core failure	n/a	8.99

(a) U-U1 specimen (b) U-G specimen

Fig. 4 – Typical failure mode of flexural test results

5. Flexural structural behavior of composite sandwich panels

To investigate the mechanical behavior of composite sandwich panels, the panels studied are constituted by core and face sheets and the influence of the three components – the mechanical properties of the core material, the strength of the face sheet material, and the bond strength adhesive material – was evaluated. The combination of the tested sandwich panel is shown in Table 4. The first character of S-specimen ID indicates core material and the second one indicates the face sheet material. The GFRP face sheet was manufactured using three different types of mats, embedded in a polyester resin matrix. The core thickness is 55 mm and the thickness of each face sheet is 5 mm. Flexural tests were conducted on each type of panels (one specimen for each type) according to ASTM C393 [13] standard in a four-point bending configuration. The sandwich panels which were 650-mm long, 320-mm wide and 65-mm thick, were tested in a 600-mm span and the loaded sections were distanced 200 mm apart. The supports were materialized by steel rollers. Composite sandwich panels were monotonically loaded up to failure. Test results are indicated in Table 4. Figure 4 shows the core failure of specimens with and without delamination.

All panels exhibited an approximately linear behavior up to failure of the core material. The EPS mortar core of specimen M-U1 cracked at the load of 6.41 kN, and then the sheet yielded subsequently at the load of 9.26 kN. M-G specimen collapsed because of the bond failure of core-to-facing interface, followed by core failure instantly. The flexural strength of specimens with EPS mortar core strongly depends on the face sheet capacity because the core capacity is relatively weaker than the flexural capacity of face sheets. The flexural capacity of the specimens with UHPEPC core showed high strength in a stable linear behavior before core crack. The maximum strength also depends on types of face sheet material. The core cracking load of U-U2 and U-G specimen recorded at 14.48 kN and 15.29 kN respectively. However, the maximum strength of U-U2 was 18.02 kN with a considerable deformation but U-G specimen failure right after core crack occurred. The U-U1 failed due to core cracking, but the stiffness and the maximum strength was greater than other specimens. The specimens bonded by epoxy failed by core cracking with low capacity although the core material was used as UHPEPC.

6. Conclusions

This study investigated the mechanical properties of ultra-high performance concrete with expanded polystyrene composite (UHPEPC) and the structural behavior of composite sandwich panels containing UHPEPC core experimentally.

The conclusion from the research is as follows:

(1) The compressive strength, flexural strength, and modulus of elasticity of UHPEPC increases with increasing density. Material can be designed depending on the EPS content in large range of strengths and densities for various applications. The UHPEPC has superior mechanical properties when the density ranges between 1,200 ~ 1,500 kg/m^3.

(2) The thermal resistance of UHPEPC is about 3.34 times lower than that of EPS mortar, which shows that UHPEPC can perform as a better insulation as a core material.

(3) From the flexural test results of sandwich panels, it can be concluded that elastic behavior of the composite sandwich panels depends on the core capacity and the post-core cracking behavior is governed by the types of face sheet material. The sandwich panel specimens with UHPEPC core shows outstanding flexural capacity except for applying epoxy as an adhesive material. UHPC reinforced by steel fiber and GFRP mesh enhanced flexural capacity with respect to the ultimate load and ductility, respectively.

References

1. Babu, K.G. and Babu, D.S. (2003) "Behaviour of lightweight expanded polystyrene concrete containing silica fume," Cement and Concrete Research, 33(5), pp. 755-762.
2. Cook, D.J. (1972) Expanded polystyrene beads as lightweight aggregate for concrete, School of Civil Engineering, Ph.D. dissertation, University of New South Wales, Australia.
3. Ravindrarajah, R.S.; and Tuck, A.J. (1994) "Properties of Hardened Concrete Containing Treated Expanded Polystyrene Beads," Cement and Concrete Composites, 16(4), pp. 273-277.
4. Miled, K.; Roy, R.L.; Sab, K.; and Boulay, C. (2004) "Compressive behavior of an idealized EPS lightweight concrete: size effects and failure mode," Mechanics of Materials, 36(11), pp. 1031-1046.
5. Miled, K.; Sab, K.; and Roy, R.L. (2007) "Particle size effect on EPS lightweight concrete compressive strength; Experimental investigation and modelling," Mechanics of Materials, 39(3), pp. 222-240.
6. Parant, E.; and Le Roy, R. (1999) Opimisation des bétons de densité inférieure à l. Tech. rep., Laboratoire Central des Ponts et Chaussées, Paris, France.
7. Kollar, l.P. and Springer, G.S. (2003) Mechanics of Composite Structures, Cambridge University Press, USA.
8. Gibson, L.J. and Ashby, M.F. (1999) Cellular solids: Structure and properties, Second edition, Cambridge University Press, UK.
9. Correia, J.R.; Garrido, M.; Gonilha, J.A.; Branco, F.A.; and Reis, L.G. (2012) "GFRP sandwich panels with PU foam and PP honeycomb cores for civil engineering structural applications," International Journal of Structural Integrity, 3(2), pp. 127-147.
10. Manalo, A.C.; Aravinthan, T.; Karunasena, W.; and Islam, M.M. (2010) "Flexural behaviour of structural fibre composite sandwichbeams in flatwise and edgewise positions," Composite Structures, 92(4), pp. 984-995.
11. Shams, A.; Stark, A.; Hoogen, Fl; Hegger, J.; and Schneider H. (2015) "Innovative sandwich structures made of high performance concrete and foamed polyurethane," Composite Structures, 121, pp. 271-279.
12. ASTM C618, Standard Terminology Relating to Thermal Insulation, American Society for Testing and Materials, West Conshohocken, USA.
13. ASTM C393, Standard Method for Core Shear Properties of Sandwich Constructions by Beam Flexure, American Society for Testing and Materials, West Conshohocken, USA.