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An Overview of Expanded Polystyrene as a Contemporary Construction Material

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ABSTRACT

Expanded Polystyrene (EPS) is used as a modern construction material. The light weight of EPS makes it conducive for use in various applications like building construction, soil and pavement. Apart from its light-weight EPS also has low thermal conductivity. All these aspects of EPS had compelled researchers to investigate the use of EPS in different domains of Civil Engineering. Therefore, the present review is conducted to study the effect of different forms of EPS utilized in the domain of Civil Engineering. Generally, EPS beads and foams are used in building construction, backfill soil of retaining wall and embankment construction for weight reduction. Reduction in weight is one of the aspects but inclusion of EPS might affect the other properties of material and structure in which it is included. All these material and structural properties which get changed with the inclusion of EPS are described in the present manuscript. The inclusion of EPS reduces the static loads on the structure but at the same time it reduces the mechanical performance of the material in which it is included. Therefore, while utilizing EPS, the volume fraction to be utilized should be based on the targeted properties of composite materials.

Keywords: *Expanded polystyrene, wall panels, retaining wall, roads, embankments*

1. INTRODUCTION

Contemporary construction demands light weight, durable and stress resisting material not only for building construction but also for other applications in geotechnical and transportation engineering [1]. In construction of building structure, in particular the non-structural elements and finishing material induce greater loads on to the structural elements. The non-structural elements like walls provide partition and thermal insulation but do not contribute to structural performance [2]. Moreover, it increases the dead weight thereby increasing the load and size of the structural components [3]. This leads to an increase in construction costs. Similar is the case with earth retaining structures like retaining walls. The retaining wall retains earthen material towards the back face of the wall. The density of compacted soil is around 1850 kg/m^3 [4], due to such a greater extent of density the force exerted by soil on to the wall is of greater intensity [5]. The resistance to such greater intensity of forces is provided by the conjunctive action of stem and base. The size of these two components depends upon the magnitude of force induced by the backfill soil. So, there is a requirement for such material which is light in nature, non-reactive in nature and fulfills the application criteria without compromising the essential characteristics.

Towards reducing the density of partition walls in building structure or backfill soil for reducing the loads on the primary structural elements, some of the constituents of partition wall and backfill material in retaining walls must be proportionately substituted by light-weight materials [6]. Generally, walls are structured with the help of bricks, autoclaved aerated concrete (AAC) block or thin partition walls (at least 50 mm thick). Out of these elements, bricks and concrete walls have greater unit weight but AAC blocks are lighter in weight which reduces structural loads on the building frames [7]. The major drawback of AAC block is its water absorption capacity, uneven strength [8] and its masonry pose difficulty in joining with plain cement. On the other hand, when it comes to earth retaining structures like retaining walls, the backfill soil could be substituted with industrial wastes like fly ash. The compacted bulk density of fly ash is around 1010 - 1780 kg/m^3 which is equal to or somewhat lesser than compacted soil [9]. But in the modern era of construction, fly ash is no longer considered as a waste material. It is beneficially used in manufacturing of cement, bricks, and other allied construction products.

As a judicious substitute expanded polystyrene (EPS) could be used. EPS is light weight, hydrophobic, chemical resistant, non-reactive, thermally low conductive and is 100 % recyclable [10]. EPS exists in two forms i.e., beads and foams [6]. Both these forms can be used to cater to the needs of today's modern construction. But, before the utilization of EPS in various domains of Civil Engineering, it is very important to review the important application characteristics of EPS. Mostly EPS is utilized in building construction, soil stabilization, providing seismic buffer, and unit weight reduction of back fill soil in earth retaining structures. Therefore, the present review is conducted to assess the effect on various properties of EPS modified material when compared to the original material. The manuscript details and presents a comparative representation of the EPS modified components.

2. MANUFACTURING PROCESS AND PROPERTIES OF EPS

Styrene is a thermoplastic resin and a petroleum byproduct used for manufacturing expanded polystyrene. During the preparation of EPS beads/granules pentane gas is introduced into the beads which acts as a blowing agent [11]. The size of these beads ranges between 0.2 – 3 mm in diameter [12]. This gas is responsible for the expansion of beads. The production of EPS takes place in three stages i.e., a) pre-expansion, b) aging/maturation and c) final moulding. A schematic representation in Figure 1shows the production of EPS foam. In the first stage, EPS granules are fed into the pre-expander. Steam is introduced into the pre-expander and the temperature in the expander varies between 80°C – 100°C [13]. The elevated temperature causes pentane to expand thereby causing the expansion of styrene beads thus creating an air packed cellular structure. These expanded beads are approximately fifty times larger than the bead volume [12]. In the second stage, the expanded beads are transferred into silos for maturation. During this process the expanded beads stabilize (attain stable shape and density). In the third stage the stabilized and expanded beads are inserted into the moulds for desired shape. For creating a final block with desired properties, steam is again applied inside the moulds, which further causes the expansion and compaction of expanded beads [14]. After demoulding the block/foam is allowed to rest for several days. This enables degassing of pentane from the inside of expanded beads which might cause dimensional changes in the finally cooled block [12].

EPS is a lightweight material because it consists of 98% air and 2% material by volume. Generally, the EPS granules are colourless but the expanded beads are observed in white colour. According to the application EPS is produced in varying densities. The varying density may affect the mechanical characteristics of EPS. The air inside the expanded beads allows it to be used as an excellent insulating material. However, when exposed to ultraviolet radiation the colour turns pale yellow and the material becomes brittle. EPS is a non-biodegradable material and does not take part in reaction with soil or water. Polystyrene by nature is a hydrophobic material and therefore the EPS foam is also hydrophobic. But during the fusion/moulding of EPS foam, small interstices are observed inside which tend to hold water inside it. The water absorption capacity depends on the density of the produced foam. The water absorption ability decreases with the increase in density of foam. EPS though it is chemically inert but has a tendency to dissolve in certain liquids like diesel, gasoline and acetone [12]. Some of the properties of EPS are stated in Table 1.

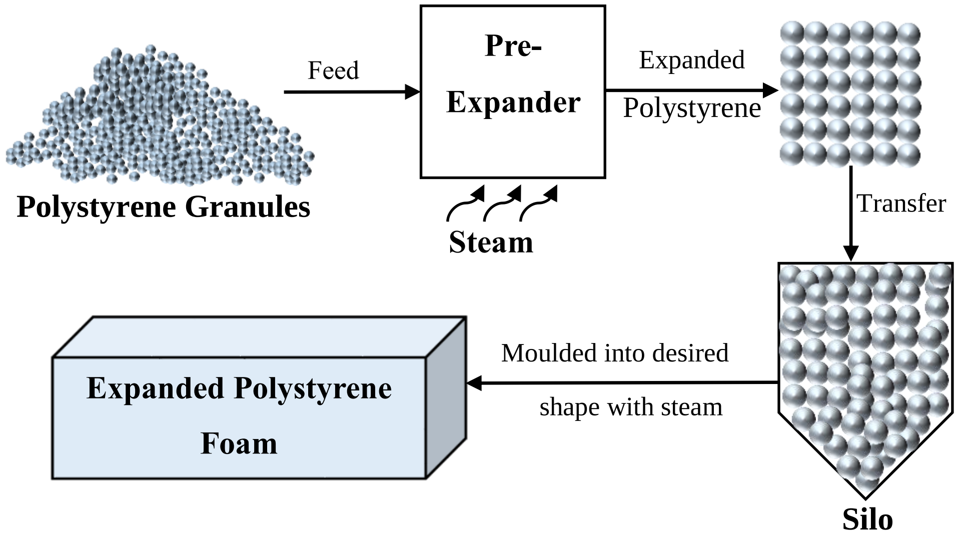

FIGURE 1: Manufacturing process of expanded polystyrene foam.

TABLE 1: Properties of EPS

Sr. No.	Properties	Units	Description	Source
1	Colour	-	White	[12]
2	Density	Kg/m^3	4-40	
3	Compressive Strength	MPa	0.10-0.12	[15]
4	Tensile Strength	MPa	0.21-0.23	
5	Flexural Strength	MPa	0.17-0.22	
6	Shear Strength	MPa	0.21-0.23	
7	Thermal Conductivity	W/(m-k)	0.035	[16]
8	Water Absorption	%	2.88	[17]

3. APPLICATION IN BUILDING CONSTRUCTION

In the building construction sector both the forms of expanded polystyrene are used, i.e., beads and foam. The light weight and rounded nature of expanded polystyrene beads allows its usage as a construction material. These beads generally replace a portion of fine aggregates for concrete making. There are many investigations that have utilized EPS beads, crushed EPS waste foam and crushed-treated EPS waste foam as partial replacement of fine aggregate. Incorporation of EPS reduces the density and increases the insulating properties of concrete. The loss in mechanical performance of concrete is a major drawback observed with utilization of EPS in its original state

[18]. Madandoust et.al. prepared self-compacting light weight concrete using EPS beads. EPS replaced fine aggregates by 10, 15, 22.5 and 30%. The results of EPS mixed concrete were compared with control concrete. The introduction of EPS into the mixes had increased the slump flow of concrete, reduced the density and significantly decreased the compressive strength [19]. Some investigators have reported an increase in slump value while others have reported decreasing slump values with increasing EPS volume. Most of the research has reported that increasing the EPS volume inside the concrete results in lower mechanical performance, and decreased density [18], [20]. All these variations in properties of concrete could be observed from Table 2. Since EPS is a lightweight material containing air therefore the mechanical properties and density of developed product reduces.

TABLE 2: Investigation results of EPS based concrete/mortar by various authors.

Sr. No	Author (Product Name)	EPS	CS	TS	Slump	Density	Thermal conductivity	Source
		%	MPa	MPa	mm	Kg/m^3	W/m.K	
1	Sayadi et.al. (Foamed Concrete)	0	9.18	-	-	1200	-	[21]
		45	0.85	-	-	400	0.1566	
		67	0.29	-	-	250	0.0927	
		73	0.24	-	-	200	0.0864	
		82	0.067	-	-	150	0.0848	
2	Saradhi et.al. (Concrete)	0	43	3.63	43.5	2578	-	[22]
		16.3	12.5	2.04	54	1723	-	
		28.5	7.8	1.04	55	1484	-	
		38	6	1.15	61	1304	-	
		49	3.83	0.89	53	984	-	
		58	2.3	0.64	45	779	-	
		66.5	1.1	-	-	582	-	
3	Chen and Liu (Concrete)	0	68.3	9.7	-	2440	-	[10]
		25	25.7	2.4	-	1850	-	
		40	2.1	2.22	-	1370	-	
		55	11.3	1.73	-	882	-	
4	Ali et.al (Hollow mortar blocks)	0	9.5	-	-	2119	-	[23]
		10	6.9	-	-	1758	-	
		15	4.1	-	-	1487	-	
		20	4.3	-	-	1256	-	
		26	2.4	-	-	956	-	
5	Ubi et.al. (Concrete)	0	21.68	1.73	25	2536	-	[24]
		4	17.25	1.72	20	2443	-	
		8	15.87	1.64	16	2363	-	
		12	14.53	1.33	12	2339	-	
		16	13.92	1.49	10	2316	-	
6	Dixit et.al. (Concrete)	0	149.8	-	249	2301	2.14	[25]
		16	94.0	-	228	2045	1.69	
		25	56.9	-	222	1828	1.39	
		36	44.7	-	212	1677	0.58	
		45	27.2	-	165	1463	0.49	

Sayadi et.al. developed EPS based foamed concrete. The volume of EPS used was 45, 67, 73 and 82%. The foamed concrete with 45% EPS beads had the highest density (400 kg/m^3) and compressive strength (0.85 MPa) which decreased with increasing percentage of EPS. The lowest thermal conductivity (0.0848 W/m.K) was observed for foamed concrete with 82% EPS volume [21]. From Table 1 it is observed that, with increasing percentage of EPS beads the thermal conductivity reduces. The air packets inside the beads obstruct the direct flow of heat thus serving as a thermal insulator, therefore the thermal conductivity of concrete/mortar with increasing volume of EPS beads reduces.

There have been some efforts by researchers to enhance the mechanical characteristics of EPS based concrete. Towards this, they incorporated fibers, pozzolanic material, changed the type of curing or have tried treating EPS. Azimi et.al. have used modified EPS (MEPS) and higher curing temperature for modifying the properties of concrete. A heat treatment procedure was adopted for changing the properties of EPS. The density of MEPS was increased to 330 kg/m^3 and the average particle size was reduced to 1.6 mm. The results show that the mechanical performance of concrete with MEPS beads increased with increasing temperature and was maximum at a temperature of 200°C [18]. The utilization of pozzolanic material like silica fumes and fly ash have been known to increase the strength of concrete. Similarly, incorporating these supplementary cementing materials into the EPS based mixes also increases the strength of EPS based concrete/mortar [10], [22], [26]. The increase in mechanical performance of concrete may be due to the pozzolanic reaction which supplement additional C-S-H gel. Research also progressed in the direction of incorporating different kinds of fibers into the EPS based concrete/mortar. The experimentations have manifested either a decrease in mechanical performance or it was at par with conventional EPS based concrete/mortar [10], [23]. The incorporation of fibers may cause a problem of packing within the mix and hence the mechanical performance of EPS based concrete/mortar with fibers is either stagnant or reduced.

Apart from utilizing EPS beads in making light weight concrete, EPS foams are used in sandwich panel technology. These panels are lighter than the traditional brick partition walls and also possess adequate strength. The system consists of wythes, EPS core and shear connectors. The cross section of the system is shown in Figure 2. The EPS core provides insulation, external cladding provides strength to the panels and shear connectors provides integrity to the system [27]. Serpili et.al experimentally validated the axial and shear strength of these EPS core sandwich panel system. Panels with aspect ratio (height to width ratio) of 1 and 2.7 were used for the tests. The external claddings were made of concrete and were 50 mm thick whereas the EPS core was 140 mm. The axial load sustained by panel with aspect ratio 1 (1555 kN) was 1.47% greater than panel with aspect ratio of 2.7 (1532 kN). Diagonal compression test on panels with aspect ratio 1 was conducted to find the shear strength of panels. The average load resisted by against shear loading was 446.4 kN and the average equivalent shear strength was 3.10 MPa [28]. O'Hegarty et.al assessed the flexural performance of EPS core sandwich panels. The EPS core was 90 mm thick and the internal wythes were used in two thickness i.e., 25 mm and 40 mm whereas the external wythe was 40 mm thick. The flexural resistance provided by 25 mm (8.3 kN) thick internal wythe panel was lesser than 40 mm (17.7 kN) thick internal wythe panel. It was very obvious that due to increase in moment of inertia the resistance to flexure also increased [29].

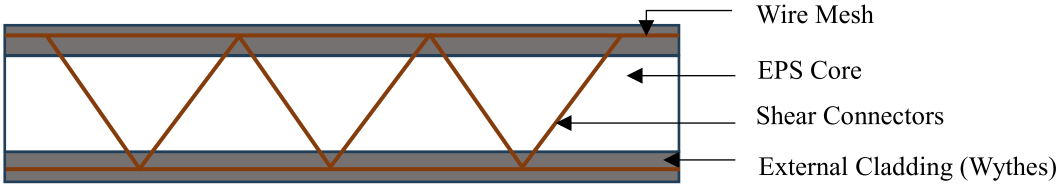

FIGURE 2: Cross section of EPS sandwich panel system

4. APPLICATION IN GEOTECHNICAL ENGINEERING

Many researchers across the globe have explored EPS in soil engineering applications. Both the forms of EPS, beads as well as foams are utilized for the benefits by EPS. The applications include construction of soft grounds, embankment widening, slope stabilization [30], light weight filler behind retaining walls, bridge abutments, over pipelines, and below foundations [13]. Various studies have been conducted on utilization of EPS foams/blocks as a backfill material for reducing the lateral pressure on retaining walls [31]. Salam et.al states two different methods for lowering the lateral pressure on retaining walls by utilizing EPS foams. The two methods are named as Zero Earth Pressure (ZEP) and Reduced Earth Pressure (REP). In the ZEP method, the EPS foams completely substitute the earthen backfill in the retaining walls. The mass of EPS foams falls around 1 – 2 % that of soil, depending of the density of foam used and hence the lateral pressure exerted by EPS foams is nearly zero. In the REP method a comparatively lower thickness EPS foam is placed exactly between the retaining wall and backfill soil. The EPS foam has the ability to deform under loads. Now the stress on the retaining wall is a function of foam thickness and compressibility. The EPS foam allows the lateral movement of backfill soil by getting self-compressed and lowers the lateral pressure on the retaining wall when the soil moves from at rest condition to active state [32]. Figure 3 shows a typical cross section of a retaining wall installed with EPS foam. The insertion of EPS foam not only relieves the static loading, but it also provides a seismic buffer [30]. It also mitigates thermal distress in permafrost region [33]. Ertugrul et.al. conducted laboratory experiments on rigid nonyielding retaining walls with EPS geofoam inclusion. The model consisted of a stiff sand box augmented with steel retaining wall rigidly welded to a steel base plate. River sand was used as a backfill material and EPS block with a density of 15 kg/m^3 was used as a geofoam inclusion. The geofoams were used in three thickness for which the thickness to height (t/H) ratio was 0.07, 0.14 and 0.28. The results showed that imparting geofoam inclusion significantly reduced the static lateral load on the wall. This could be noticed from the lateral load reduction efficiency graphs. The maximum load reduction efficiency was observed with geofoam having t/H ratio of 0.28 [31]. Another study was conducted by Ertugrul et.al. on flexible cantilever retaining wall with deformable geofoam inclusion. The lateral thrust on retaining wall without geofoam inclusion was 0.866 kN and with geofoam inclusion was 0.658 and 0.519 kN for a t/H ratio of 0.14 and 0.28 respectively. The thrust on retaining wall with geofoam inclusion were 24% (t/H =0.14) and 40% (t/H =0.28) lesser than retaining wall without geofoam inclusion [34].

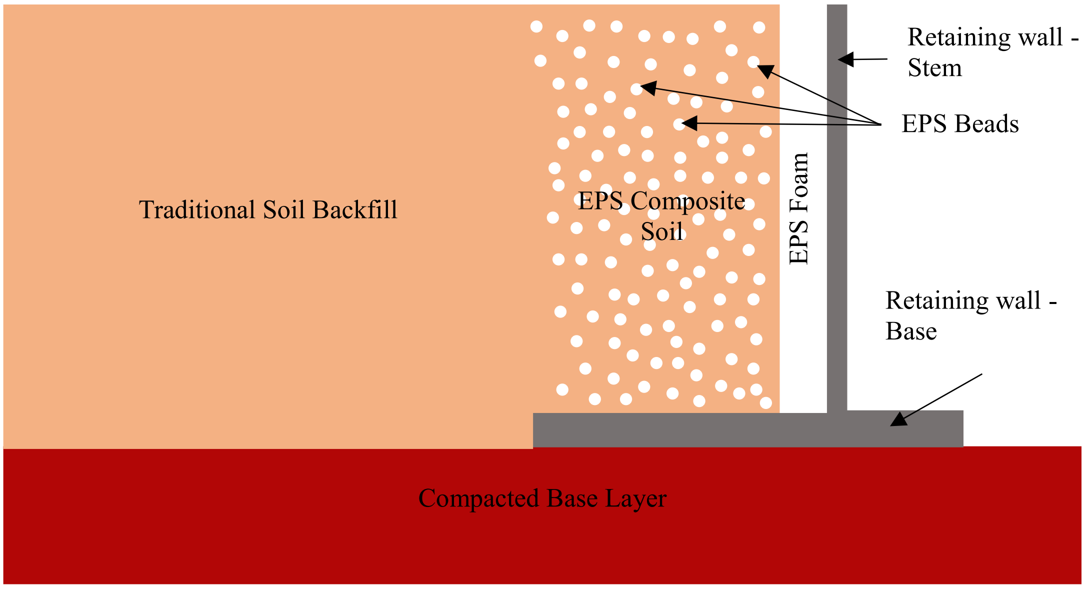

FIGURE 3: Typical cross section of retaining wall fitted with EPS foam.

One of the major drawbacks of using EPS foam as backfill material is its inability to occupy irregular volume. As a solution to this problem, it is recommended to use light filler compared to the traditional backfill material. The light filler material is composed of a mixture of EPS beads, soil, cement, and water [35]. This fusion is known as EPS composite soil (EPSCS). The research of EPSCS is very limited. Those researchers who have worked on EPSCS claim 30 – 50 % reduction in unit weight of backfill material which is beneficial in resisting settlements [1]. Deng and Xiao studied the shear characteristics of sand EPS bead mix as a backfill material. The experimentation utilized three different EPS beads ratio of 0.5%, 1.5% and 2.5%. The effects of these EPS ratios were studied through direct shear test and triaxial compression tests. The results show that increasing EPS bead volume lowers the shear strength of sand EPS mix. The application of normal stress increases the shear strength of mix. Also, the mix allows considerable shear contraction which is due to the ability of EPS bead compressibility [36]. In another study by Deng and Xiao the stress strain characteristics of varying EPS beads proportion in sand as backfill was investigated. An increment in volumetric strain and reduction in shear strength was observed with increasing EPS beads content in the mix. Increasing the confining pressures from 100 kPa to 400 kPa at an interval of 100 kPa, raised the shear strength of soil. The optimum EPS bead content was found as 0.5%, which yielded workable shear strength and density [33].

Edincliler and Ozer experimented the effect of different EPS bead size and densities while investigating the stress strain behavior of EPS bead and sand mix. The specific gravity and effective size (D_{10} in mm) are EPS 1 – 0.02, 2.2 mm; EPS 2 – 0.03, 2.0 mm; EPS 3 – 0.05, 1.2 mm. Samples were tested under triaxial compression tests with three confining pressures i.e., 40 kPa, 100kPa and 200kPa. The outcomes suggest smaller sized beads provide greater stiffness than larger sized beads [35]. It is clear from these studies that modification of backfill soil properties by inclusion of EPS beads allows deformation by self-contraction and full mobilization of soil shear strength relieving the extent of stress on the earth retaining structures. Gao et.al. performed shake table test on retaining wall backfilled with EPS composite soil and compared the results with sand backfill. The setup was tested under two different time histories i.e., El-centro and Taft. It is observed that with increase in the peak acceleration the peak displacement of retaining wall increased for both the time histories and loading conditions. When the results of sand and composite soil as backfill material in the retaining wall were compared the performance of retaining wall with composite backfill material was observed better. This is because the seismic load induced due to the ground motions was less in case of composite than pure river sand [37].

5. APPLICATIONS IN PAVEMENT ENGINEERING

EPS in pavement construction find its application as a sub-base material, in particular when the roads are to be laid on soft soil (subgrade with low bearing capacity e.g., clays, peat etc.), over the underground utilities and in the extreme cold regions [38]. The parameters of EPS which are important while designing the pavement are compressive strength, density, shear strength, water absorption, and poisons ratio [39]. The specifications relating to the specified parameters are given in Table 3. While utilizing EPS in construction of road embankments, proper care should be taken to protect EPS from certain chemicals like diesel, petrol etc. because EPS dissolves in these liquids. Therefore, a protective geo-membrane should be placed wrapping the EPS arrangements. The placing of geo-membrane and other constituent parts of embankments are shown in Figure 4. Also, burrowing animals can cause harm to EPS foams. Many researchers have worked on the aspect of inclusion of EPS geofoam for road embankments utilizing different components inside it.

TABLE 3: Important properties and specifications of EPS for use in embankment.

Sr. No.	Properties	Specifications	Citations
1	Compressive Strength	• Compressive strength values are calculated are calculated at 10% strain. • No standard failure pattern exists for EPS foam, rather, it crushes and turns in polystyrene. • Designers should not cross the elastic range of EPS while designing embankments based on EPS.	[38]
2	Density	• A higher density of EPS is always preferred. • The minimum density of EPS irrespective of the loading condition should 20 kg/m^3.	[40]
3	Shear Strength	• Adequate shear should exist between EPS and other material and between two EPS adjoining layers.	[39]
4	Poisson’s ratio	• At smaller loads Poisson’s ratio is small, while this is relatively high for larger loads. • At large volumetric strains of around 1% the Poisson’s ratio became negative.	[41]
5	Creep	• The behavior of creep is well understood at an age of 50 years, especially in case of road embankments. • According to the European Committee for Standardization, it is possible to extrapolate the creep of 50 years with standardized experimentation within the age of 1.5 – 2 years. • Creep deformations will occur once the load is over 2% of the compressive strain limit.	[38], [40]
6	Water Absorption	• The value of water absorption should be within 6% of total EPS volume after 96 hours.	[42]

Duskov et.al., conducted research on the construction of embankment for flexible pavement. The thickness of the EPS in the subbase was 1.0 m and the research was conducted to assess the deflection due to heavy traffic loads with Falling Weight Deflectometer (FWD). Two densities of EPS foams were used i.e., 25 kg/m^3 which was used in bottom layer and 30 kg/m^3 which was placed over the 25 kg/m^3 foam. It was concluded that the strain in overlaying asphalt layer was more or less constant [43]. Puppala et.al. investigated the rehabilitated embankment bridge site situated on a US highway in Texas. In a span of 16 years the bridge approach has undergone settlement greater than 0.4 m. Different treatment methods have been implemented but resulted in unsuccessful mitigation. EPS foams were applied in the redevelopment of embankment. The redeveloped road embankment was monitored for a span of three years. Based on the investigating result of redeveloped road, the method of developing road embankment with EPS has proven to mitigate the problem of differential settlement and bump settlements [44].

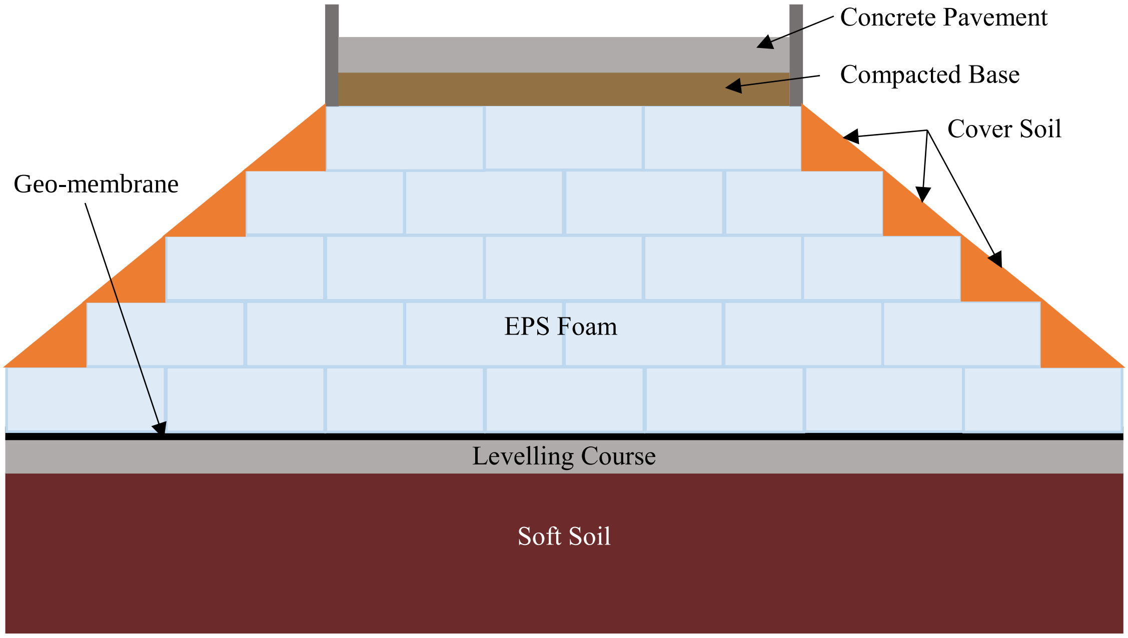

FIGURE 4: Cross sectional view of EPS foam-based embankment.

6. CONCLUSIONS

The review conducted on EPS foam and beads in various domains of Civil Engineering, brings out the following conclusions.

a. Inducing air inside the granules expands the beads and makes it light weight. The air inside the beads makes it suitable for light weight and thermal insulation application.
b. The utilization of EPS beads to modify the properties of concrete or earthen backfill reduces the compressive, flexural and tensile strength of concrete and shear strength of compacted backfill in retaining walls.
c. The treated EPS beads are more beneficial in concrete development. These beads drastically reduce the density and mechanical performance of concrete. Therefore, the volume of beads used in concrete making should be based on the targeted properties.
d. EPS foams in conjunction concrete cladding and shear connectors can be accordingly designed for providing thermal comfort and mechanical performance.
e. Addition of EPS beads into the backfill soil reduces the density and thus reduces the static load on the earth retaining structure.

f. Augmentation of retaining wall with EPS foam inclusion also reduces the static lateral load on the retaining wall.
g. Adding EPS as beads in earthen backfill or as foam inclusion behind retaining wall or both not only reduces the static load but also brings economy in construction and also reduces the seismic loads.
h. Utilization of EPS foams in construction of embankments on soft soil helps to mitigate the drawbacks of soft soil like differential settlements.

REFERENCES

[1] L. Miao, F. Wang, J. Han, W. Lv, and J. Li, “Properties and Applications of Cement-Treated Sand-Expanded Polystyrene Bead Lightweight Fill,” *Journal of Materials in Civil Engineering*, vol. 25, no. 1, pp. 86–93, Jan. 2013, doi: 10.1061/(asce)mt.1943-5533.0000556.

[2] F. Karadogan *et al.*, “Improved infill walls and rehabilitation of existing low-rise buildings,” *Geotechnical, Geological and Earthquake Engineering*, vol. 10, pp. 387–426, 2009, doi: 10.1007/978-90-481-2681-1_19.

[3] M. Barros, E. Cavaco, L. Neves, and E. Júlio, “Effect of non-structural masonry brick infill walls on the robustness of a RC framed building severely damaged due to a landslide,” *Eng Struct*, vol. 180, pp. 274–283, Feb. 2019, doi: 10.1016/j.engstruct.2018.11.027.

[4] T. Islam, Z. Chik, M. M. Mustafa, and H. Sanusi, “Modeling of electrical resistivity and maximum dry density in soil compaction measurement,” *Environ Earth Sci*, vol. 67, no. 5, pp. 1299–1305, Nov. 2012, doi: 10.1007/s12665-012-1573-7.

[5] S. S. AbdelSalam and S. A. Azzam, “Reduction of lateral pressures on retaining walls using geofoam inclusion,” *Geosynth Int*, vol. 23, no. 6, pp. 395–407, Dec. 2016, doi: 10.1680/jgein.16.00005.

[6] R. M. El-Sherbiny, S. H. Ramadan, and M. A. El-Khouly, “Dynamic properties of sand-EPS bead mixtures,” *Geosynth Int*, vol. 25, no. 4, pp. 456–470, Aug. 2018, doi: 10.1680/jgein.18.00021.

[7] K. Sherin and J. K. Saurabh, “Review of Autoclaved Aerated Concrete:-Advantages and Disadvantages,” 2018.

[8] N. P. Zade, P. Sarkar, and R. Davis, “Current Status and Future Challenges of Autoclave Aerated Concrete Masonry,” *Practice Periodical on Structural Design and Construction*, vol. 28, no. 3, Aug. 2023, doi: 10.1061/ppscfx.sceng-1302.

[9] A. Bhatt, S. Priyadarshini, A. Acharath Mohanakrishnan, A. Abri, M. Sattler, and S. Techapaphawit, “Physical, chemical, and geotechnical properties of coal fly ash: A global review,” *Case Studies in Construction Materials*, vol. 11, Dec. 2019, doi: 10.1016/j.cscm.2019.e00263.

[10] B. Chen and J. Liu, “Properties of lightweight expanded polystyrene concrete reinforced with steel fiber,” *Cem Concr Res*, vol. 34, no. 7, pp. 1259–1263, Jul. 2004, doi: 10.1016/j.cemconres.2003.12.014.

[11] A. Petrella, R. Di Mundo, and M. Notarnicola, “Recycled expanded polystyrene as lightweight aggregate for environmentally sustainable cement conglomerates,” *Materials*, vol. 13, no. 4, 2020, doi: 10.3390/ma13040988.

[12] J. S. Horvath, “Expanded Polystyrene (EPS) geofoam: An introduction to material behavior,” *Geotextiles and Geomembranes*, vol. 13, no. 4, pp. 263–280, 1994, doi: 10.1016/0266-1144(94)90048-5.

[13] N. H. Ramli Sulong, S. A. S. Mustapa, and M. K. Abdul Rashid, “Application of expanded polystyrene (EPS) in buildings and constructions: A review,” *J Appl Polym Sci*, vol. 136, no. 20, pp. 1–11, 2019, doi: 10.1002/app.47529.

[14] H. Nyambara Ngugi, “Use of Expanded Polystyrene Technology and Materials Recycling for Building Construction in Kenya,” *American Journal of Engineering and Technology Management*, vol. 2, no. 5, p. 64, 2017, doi: 10.11648/j.ajetm.20170205.12.

[15] Ł. Smakosz and J. Tejchman, “Evaluation of strength, deformability and failure mode of composite structural insulated panels,” *Mater Des*, vol. 54, pp. 1068–1082, 2014, doi: 10.1016/j.matdes.2013.09.032.

[16] I. Gnip, S. Vejelis, and S. Vaitkus, “Thermal conductivity of expanded polystyrene (EPS) at 10 °c and its conversion to temperatures within interval from 0 to 50 °c,” *Energy Build*, vol. 52, pp. 107–111, 2012, doi: 10.1016/j.enbuild.2012.05.029.

[17] Y. Z. Beju and J. N. Mandal, “Expanded Polystyrene (EPS) Geofoam: Preliminary Characteristic Evaluation,” *Procedia Eng*, vol. 189, no. May, pp. 239–246, 2017, doi: 10.1016/j.proeng.2017.05.038.

[18] S. A. Azimi, A. Allahverdi, and M. Alibabaie, “Properties of Green, Lightweight, and High-Strength Reactive Powder Concrete Incorporating Modified Expanded Polystyrene Beads,” *Journal of Materials in Civil Engineering*, vol. 33, no. 12, Dec. 2021, doi: 10.1061/(asce)mt.1943-5533.0003995.

[19] R. Madandoust, M. M. Ranjbar, and S. Yasin Mousavi, “An investigation on the fresh properties of self-compacted lightweight concrete containing expanded polystyrene,” *Constr Build Mater*, vol. 25, no. 9, pp. 3721–3731, Sep. 2011, doi: 10.1016/j.conbuildmat.2011.04.018.

[20] Eiji Matsuo, “Properties of Lightweight Concrete Using Expanded Polystyrene as Aggregate,” *International Journal of Environmental and Rural Development*, vol. 10, no. 2, pp. 8–13, 2019.

[21] A. A. Sayadi, J. V. Tapia, T. R. Neitzert, and G. C. Clifton, “Effects of expanded polystyrene (EPS) particles on fire resistance, thermal conductivity and compressive strength of foamed concrete,” *Constr Build Mater*, vol. 112, pp. 716–724, Jun. 2016, doi: 10.1016/j.conbuildmat.2016.02.218.

[22] D. S. Babu, K. Ganesh Babu, and T. H. Wee, “Properties of lightweight expanded polystyrene aggregate concretes containing fly ash,” *Cem Concr Res*, vol. 35, no. 6, pp. 1218–1223, Jun. 2005, doi: 10.1016/j.cemconres.2004.11.015.

[23] Y. A. Y. Ali, E. H. A. Fahmy, M. N. AbouZeid, Y. B. I. Shaheen, and M. N. A. Mooty, “Use of expanded polystyrene wastes in developing hollow block masonry units,” *Constr Build Mater*, vol. 241, Apr. 2020, doi: 10.1016/j.conbuildmat.2020.118149.

[24] S. E. Ubi, D. E. Ewa, A. R. Bessong, and E. D. Nyah, “Effects of Incorporating Expanded Polystyrene in Concrete Construction,” *Journal of Building Construction and Planning Research*, vol. 10, no. 03, pp. 79–101, 2022, doi: 10.4236/jbcpr.2022.103004.

[25] A. Dixit, S. D. Pang, S. H. Kang, and J. Moon, “Lightweight structural cement composites with expanded polystyrene (EPS) for enhanced thermal insulation,” *Cem Concr Compos*, vol. 102, pp. 185–197, Sep. 2019, doi: 10.1016/j.cemconcomp.2019.04.023.

[26] K. G. Babu and D. S. Babu, “Behaviour of lightweight expanded polystyrene concrete containing silica fume,” *Cem Concr Res*, vol. 33, no. 5, pp. 755–762, May 2003, doi: 10.1016/S0008-8846(02)01055-4.

[27] J. Daniel Ronald Joseph, J. Prabakar, and P. Alagusundaramoorthy, “Experimental studies on through-thickness shear behavior of EPS based precast concrete sandwich panels with truss shear connectors,” *Compos B Eng*, vol. 166, pp. 446–456, Jun. 2019, doi: 10.1016/j.compositesb.2019.02.030.

[28] M. Serpilli, F. Clementi, and S. Lenci, “An experimental and numerical study on the in-plane axial and shear behavior of sprayed in-situ concrete sandwich panels,” *Eng Struct*, vol. 232, Apr. 2021, doi: 10.1016/j.engstruct.2020.111814.

[29] R. O′Hegarty, R. West, A. Reilly, and O. Kinnane, “Composite behaviour of fibre-reinforced concrete sandwich panels with FRP shear connectors,” *Eng Struct*, vol. 198, Nov. 2019, doi: 10.1016/j.engstruct.2019.109475.

[30] S. Selvakumar and B. Soundara, “Swelling behaviour of expansive soils with recycled geofoam granules column inclusion,” *Geotextiles and Geomembranes*, vol. 47, no. 1, pp. 1–11, Feb. 2019, doi: 10.1016/j.geotexmem.2018.08.007.

[31] O. L. Ertugrul and A. C. Trandafir, “Reduction of Lateral Earth Forces Acting on Rigid Nonyielding Retaining Walls by EPS Geofoam Inclusions,” *Journal of Materials in Civil Engineering*, vol. 23, no. 12, pp. 1711–1718, Dec. 2011, doi: 10.1061/(asce)mt.1943-5533.0000348.

[32] S. S. AbdelSalam, S. A. Azzam, and B. M. Fakhry, “Reliability and 3D Modeling of Flexible Walls with EPS Inclusion,” *International Journal of Geomechanics*, vol. 17, no. 7, Jul. 2017, doi: 10.1061/(asce)gm.1943-5622.0000853.

[33] A. Deng and Y. Xiao, “Measuring and Modeling Proportion-Dependent Stress-Strain Behavior of EPS-Sand Mixture 1,” *International Journal of Geomechanics*, vol. 10, no. 6, pp. 214–222, 2010, doi: 10.1061/ASCEGM.1943-5622.0000062.

[34] O. L. Ertugrul and A. C. Trandafir, “Lateral earth pressures on flexible cantilever retaining walls with deformable geofoam inclusions,” *Eng Geol*, vol. 158, pp. 23–33, May 2013, doi: 10.1016/j.enggeo.2013.03.001.

[35] A. Edinçliler and A. T. Özer, “Effects of EPS bead inclusions on stress-strain behaviour of sand,” *Geosynth Int*, vol. 21, no. 2, pp. 89–102, 2014, doi: 10.1680/gein.14.00001.

[36] A. Deng and X. Yang, “Shear behavior of sand-expanded polystyrene beads lightweight fills,” 2008. [Online]. Available: http://link.springer.com/article/10.1007%2Fs11771-008-0454-4http://hdl.handle.net/2440/75358PERMISSIONShttp://www.springer.com/engineering/journal/11771

[37] H. Gao, Y. Hu, Z. Wang, C. Wang, and G. Chen, “Shaking table tests on the seismic performance of a flexible wall retaining EPS composite soil,” *Bulletin of Earthquake Engineering*, vol. 15, no. 12, pp. 5481–5510, Dec. 2017, doi: 10.1007/s10518-017-0189-4.

[38] A. Mohajerani, M. Ashdown, L. Abdihashi, and M. Nazem, “Expanded polystyrene geofoam in pavement construction,” *Construction and Building Materials*, vol. 157. Elsevier Ltd, pp. 438–448, Dec. 30, 2017. doi: 10.1016/j.conbuildmat.2017.09.113.

[39] T. D. Stark, National Cooperative Highway Research Program., and National Research Council (U.S.). Transportation Research Board., *Guideline and recommended standard for Geofoam applications in highway embankments*. Transportation Research Board, National Research Council, 2004.

[40] G. Beinbrech and R. Hillmann, “EPS in Road Construction Current Situation in Germany,” 1997.

[41] G. E. Abdelrahman I) and F. Tatsuoka, “SMALL-STRAIN STRESS-STRAIN PROPERTIES OF EXPANDED POLYSTYRENE GEOFOAM.”

[42] D. J. Thompsett, A. Walker, R. J. Radley, and B. M. Grieveson, “Design and construction of expanded polystyrene embankments Practical .design methods as used in the United Kingdom,” 1995.

[43] M. Duskov, “Measurements on a Flexible Pavement Structure with an EPS Geofoam Sub-Base,” 1997.

[44] A. J. Puppala, P. Ruttanaporamakul, and S. S. C. Congress, “Design and construction of lightweight EPS geofoam embedded geomaterial embankment system for control of settlements,” *Geotextiles and Geomembranes*, vol. 47, no. 3, pp. 295–305, Jun. 2019, doi: 10.1016/j.geotexmem.2019.01.015.