Investigation of Key Properties of EPS Geofoams for Highway Embankments on Soft Ground

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ABSTRACT: Differential settlement of bridge abutments has taken place at most bridge abutments on untreated soft ground in Vietnam. The conventional technologies to improve soft ground have often been costly and time-consuming. EPS geofoam, a synthetic and lightweight material, can be used as a fill material to raise the elevation of highway embankments directly on untreat soft ground. However, EPS geofoam has little known as construction materials for transportation structures in Vietnam. This paper attempts to investigate key properties of geofoams made in Vietnam. Several laboratory tests such as compression, water absorption, inflammability, and dissolvent were conducted. The results show that (1**)** Geofoams made in Vietnam have densities of 12.1 to 34.8 kg/m^3 for the EPS-12 to the EPS-34, respectively; (2) q_u increases in increasing in densities; (3) Elastic strain is less than 1.5%; (4) Initial modulus varying from 2-10 MPa with density; (5) Poisson ratio around 0.06-0.14; (6) Water absorption by volume from 0.4-3.2%; (7) Geofoam can be quickly burnt. These key properties will indicate suitable geofoam types that can be utilized as highway embankment fills placed on unimproved soft ground directly.

KEYWORDS: Geofoam; EPS; Bridge abutment; Embankment; Soft ground improvement

1. INTRODUCTION

Geofoam or Expanded Polystyrene (EPS) is a plastic composite foam with mass density of 10 to 46 kg/m^3 which is lighter 30-150 times than that of soil (Elragi 2006). Geofoam has been used for highway embankments instead of soil, especially in the United States of America and European countries since 1960s (Stark et al. 2012). Geofoam, a lightweight fill material for highway embankments, has several advantages such as quick, easy construction and direct fills on soft ground (Stark et al. 2012; Riad et al. 2004). However, Geofoam has not been applied as a fill material for highway embankments in Vietnam. This paper attempts to investigate the key characteristics of EPS Geofoams made in Vietnam to determine potential practical applications for highway embankments on soft ground.

Geofoam under compression was examined at various strains and Geofoam types (Chen et al. 2015, Ossa & Romo 2009; Elragi 2006; Duskov 1997; Horvath 1997). Unconfined compressive strength of Geofoams (UCS) increases sharply with increasing in strain of 5% or less and increases slightly with strain of 5-10% (Chen et al. 2015; Stark et al. 2012; Osso & Romo 2009; Elragi 2006; Duskov 1997). At strains of 1% and 10%, UCS of from EPS-12 to EPS-46 was 15-128 kPa and 40-345 kPa, respectively (Stark et al. 2012). Duskov (1997) proposed that UCS at a strain of 10% is considered the maximum strength or the strength at failure of Geofoams. Geofoam hasn't reached a conventional failure state such as cracks or failure surfaces instead of shrinkage up to a strain of 94% (Chen at el. 2015).

The higher the strain rate, the higher the UCS is (Chen et al. 2015; Ossa & Romo 2009; Duskov 1997). Chen et al. (2015) investigated compressive strength of EPS-13 and EPS-28 at various loading rates of 0.1 to 20 m/s. The UCS of EPS-13 and EPS-28 at loading rates of 0.1 and 20 m/s were 171; 328 kPa and 252; 468 kPa, respectively. Various EPS of EPS-17, EPS-18, EPS-20, EPS-26, EPS-30 examined compression at strain rates of 0.5, 1, 10 mm/min were exhibited the increase of the UCS with increasing in strain rates (Ossa & Romo 2009). Ossa & Romo (2009) reported that the EPS-30 compressive strengths were 145.1, 150.9, and 169.3 kPa under displacement rates of 0.5, 1, 10 mm/minute, respectively. The two EPS-15 and EPS-20 tested under strain rates of 4, 20, 200, and 2000%/minute produced the compressive strengths of 68, 77, 83, 84 kPa and 105, 114, 128, 130 kPa, respectively (Duskov 1997).

EPS Geofoams were slightly impacted under frequent loads of 80% their strengths at a strain of 1% (Ossa & Romo 2011; Trandafir et al. 2010; Elragi 2006). Ossa & Romo (2011) found that the maximum strain and dynamic modulus of elasticity of the tested geofoams were insignificantly influenced under the repeated load of 70% their yield stress for 4000 cycles. An EPS-32 under a repeated load of 70% its strength at a strain of 1% exhibited elastic behaviors and induced an elastic strain of 0.67% (Trandafir et al. 2010). Geofoams can tolerate a repetitive load of 80% their compressive strength for enormous load cycles (Elragi 2006 from Flaate 1987).

Long term deformation or strain of Geofoam depends on vertical loads (Elragi 2006; Srirajan et al. 2001; Duskov 1997). A vertical load of 50% of UCS or less causes negligible deformation in 500 days and a load of 70% of UCS or more applied causes remarkedly vertical deformation in minutes or hours (Elragi 2006). Several geofoam types tested under compressive loads of 50% their compressive strength for 100 hours showed that the vertical strains were minimally developed (Srirajan et al. 2001). Duskov (1997) presented that the vertical strain of EPS-18 was quickly developed in minutes under a vertical load of 70% and 80% of its UCS. A vertical strain of 2% or less was measured for the EPS-18 at a load of 30% and 50% of its UCS.

Initial modulus of elasticity of geofoam at a strain of 1%, E_i, increases with increasing in geofoam densities (Stark et al. 2012; Ossa & Romo 2012, 2009; Elragi 2006; Duskov 1997). E_i of EPS-15, EPS-20, EPS-26, EPS-30 at a strain of 1% were 4.9, 7.4, 8.2, 9.7 MPa, respectively (Ossa & Romo 2009; Duskov 1997). Elragi (2006) reported that E_i increases linearly with density and was inconsistent among researchers.

Geofoam Poisson ratio (υ) was inconsistent and varies from 0.05 to 0.2 (Mohajerani et al. 2017; Elragi 2006; Srirajan et al. 2001; Duskov 1997). Mohajerani et al. (2017), Elragi (2006), and Srirajan et al. (2001) reported that Poisson ratio was relatively low around 0.05 to 0.2 and increases with increasing in density. υ of EPS-20 was from 0.05 to 0.11 and v of EPS-21 was 0.12 (Duskov 1997).

Water absorption is relatively low for all geofoams varying from 1% to 5% in volume (Ossa & Romo 2009; Elragi 2006; Frydenlund et al. 2001; Duskov 1997; Sarlin et al. 1986). Water absorption of EPS-15 and EPS-20 submerged for 2 months was 1.87% and 1.54% in volume and raised up to 2% for 12 months (Duskov 1997). Elragi (2006) reported that EPS-20 increased water absorption up to 4% for 12 months. EPS-20 and EPS-29 absorbed water quickly at 4.7% and 3.9% for the first 30 days, respectively, and almost constant until 234 days (Ossa & Romo 2009). Sarlin et al. (1986) found that EPS-15, EPS-20, EPS-35 increased their water volumes by 4.7%, 2.8%, 1.9% for first 35 days submerged and reached the constant water volumes of 5.1%, 3.4%, 2.6% for longer, respectively.

Geofoam is a flammable material and burning geofoam releases gas of CO and CO_2, water, and ash (Mohajerani et al. 2017; Horvath 1999; Duskov 1997). Geofoam can be made to become less flammable by adding an inflammable chemical substance but to increase the sell price up to 10% (Duskov 1997; Horvath 1999). The melting temperature of the polystyrene is 150^0C, but the polystyrene starts melting at a temperature of 80^0C. Therefore, geofoam should be used at an environmental temperature of 60^0C or less (Mohajerani et al. 2017; Duskov 1997).

Geofoam has no resistance to strong acids, organic solvents, petrol, paraffin/Vaseline/diesel oils. Sea water, bitumen, silicon oils, and alkaline solutions are safe for geofoam (Mohajerani et al. 2017; Elragi 2006; Horvath 1999, 1994; Duskov 1997). For highway embankments, gasoline, diesel, lubricant oils, and bitumen may contact with geofoam accidentally. Therefore, damages of geofoam due to the above substances should be examined.

Geofoam is widely used as heat isolating materials and shock absorption in Vietnam. Geofoam has high potential applications for highway embankments on soft ground but has limit research and has no successful practical applications. This paper attempts to investigate the key properties of geofoams made in Vietnam and appropriate geofoam types for highway embankments. Several types of geofoams were collected and tested for the key properties such as density, UCS, water absorption, chemical resistance, and flammability. The relevant geofoam types with their suitable characteristics is recommended for highway embankment applications in Vietnam based on this study.

2. METHODOLOGY

All geofoam specimens were made and tested in laboratory. Data were obtained to investigate the mechanical and physical behaviors of geofoams made in Vietnam.

2.1 Standards

The ASTM C303, D6817, D2842, D1621, and D2863 standards were utilized for laboratory testing.

2.2 Materials

The 9 blocks of nine different geofoam types were obtained from domestic manufacturers. The Geofoam blocks had dimensions of 0.2 x 0.3 x 0.5 to 0.6 x 1 x 1 m (Figure 1). The all samples were tested for their mass density following the ASTM C303 before conducting other tests for the key properties.

Figure 1 EPS Geofoam blocks collected from domestic manufacturers

2.3 Density test

The 5 specimens with dimensions of 100 x 100 x 200 mm ± 1 mm were formed from the 5 geofoam types (ASTM C303). Each specimen was observed and trimmed for smooth and uniform. Measurements were taken place at the 3 locations (e.g., the center and 25 mm from edges) of each direction. The mass of each specimen was weighted with a bias of ±0.1 g. The density of each specimen is determined by Eq. (1).

$$\rho = \frac{m}{V} \tag{1}$$

where: ρ (kg/m^3) – specimen density; m (kg) – mass of specimen; V (m^3) – volume of specimen.

2.4 Unconfined compressive strength (UCS)

The unconfined compressive strength test (UCS) was conducted following the ASTM D1621. Each cubic specimen was prepared with the dimensions of 150 ± 1.5 mm. Vertical loads were applied at a vertical displacement rate of 1 and 2.5 mm/minute at room temperature. For single cycle tests, vertical loads increase until a vertical strain of 13-15% is achieved. During a test, vertical displacements were captured by two LVTDs, and horizontal displacements were obtained by four LVTDs placed horizontally.

Figure 2 An instrument utilized for UCS tests in laboratory

2.5 Water absorption

Water absorption was performed following the ASTM D2842. Specimen dimensions of 150 x 150 x 75 ± 1 mm was prepared. The three water levels of 50 mm higher the top surface of a specimen, the same as the top surface of a specimen, and 37.5 mm lower the top surface of a specimen were applied for the three sets of the specimens. The all specimens were submerged and weighted every day for 203 days to obtain daily weight gain due to water absorption.

2.6 Water discharge

Water discharge was determined by monitoring the change of specimen weight after submerged for 203 days. The all specimens were placed in open air in the laboratory. The weight of the specimens was measured every day for 45 consecutive days.

2.7 Dissolving in Gasoline, diesel, and lubricant oils

All geofoam specimens for dissolving tests were created with dimensions of 60 x 30 x 30 ± 0.5 mm. Gasoline, diesel, and lubricant oil were used to melt the geofoam specimens. Melting time was recorded for each specimen contacting to each solvent.

Figure 3 EPS Geofoam specimens contacting to gasoline

Figure 4 EPS Geofoam specimens submerging in diesel

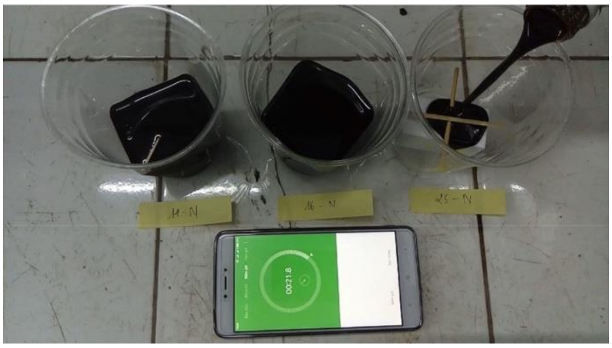


Figure 5 EPS Geofoam specimens immersing in a lubricant oil

2.7 Inflammability

Inflammability was carried out following the ASTM D2863. Three specimens were made from each geofoam type with dimensions of 100 x 10 x 10 ± 0.5 mm. Combusted duration was recorded from the first contact to fire to complete burn.

Figure 6 EPS Geofoam specimens contacting to fire

3. RESULTS AND DISCUSSIONS

3.1 Geofoam density

Table 1 presents the densities (ρ) of the 45 specimens made from the 9 types of the geofoams made in Vietnam. ρ obtained from the tests following the ASTM C303 was slightly higher than the nominated densities of domestic manufacturers. Domestic manufacturers can make geofoams with density of 35 kg/m^3 or lower which is a typical density for highway embankment fills (Mohajerani et al. 2017; Ossa & Romo 2009; Duskov 1997). The unit cost per unit volume of a geofoam type increases with increasing in densities. EPS geofoam types made domestically are approaching worldwide products (Stark et al. 2012).

Conventional materials for highway embankments like sand and clay are typically heavier than geofoams about 100 times (e.g., EPS-19 and EPS-22). At the same height of a highway embankment, geofoam induces significantly low self weight on the surface of untreat soft ground. The self weight of the geofoam fill can be less than the strength of the untreat soft gournd in most of the cases. Therefore, relevant geofoam types can be directly placed on the surface of the untreat soft ground as highway embankment fills.

Table 1 Nominal and tested mass density of Geofoams ρ (kg/m^3) made in Vietnam

Geofoam types	**EPS-12**	**EPS-13**	**EPS-14**	**EPS-19**	**EPS-22**
Nominal mass density	12	13	14	19	22
Tested mass density	12.1	12.8	14.1	19.3	22.5
Geofoam types	**EPS-23**	**EPS-26**	**EPS-28**	**EPS-34**	
Nominal mass density	23	26	28	34	
Tested mass density	23.3	26.4	28.6	34.8	

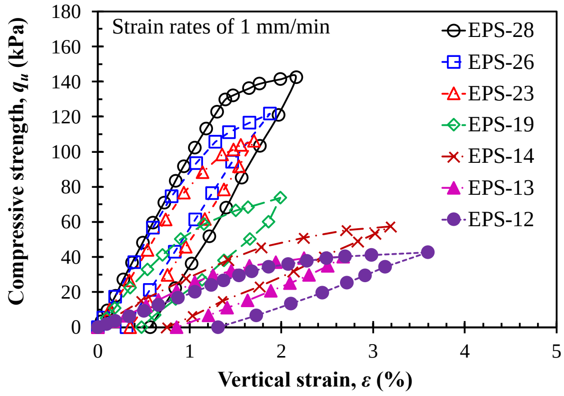
3.2 Unconfined compressive strength

The 35 geofoam specimens shaped from the 7 geofoam types from the EPS-12 to EPS-28 (Table 1) were tested following the ASTM D1621. Each specimen was compressed under various vertical displacement rates of 1 to 5 mm/min. Several loading and unloading cycles were also applied to examine the mechanical behaviors of the geofoams under frequent loads. Vertical displacement was measured using the two LVDTs and horizontal displacement was obtained from the 4 LVDTs installed horizontally in the 4 sides of a specimen. Unconfined compressive strength (q_u), strain at failure (ε_f), initial modulus (E_i), unloading modules (E_u), and Poisson ratio (v) were determined from each UCS test.

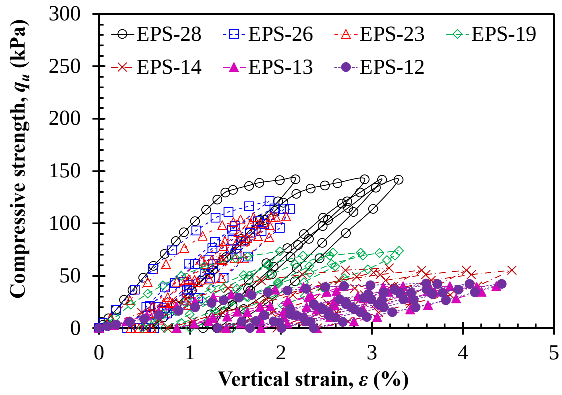
3.2.1 Unconfined compressive strength (q_u) versus strain (ε)

All geofoam types have the true elastic behavior at a strain of 1% under vertical loads at a displacement rate of 1 and 2.5 mm/min (Figure 7). At a strain of 1.5%, the unrecoverable strains of the all specimens were slightly developed (Figure 7a, b, c, d). For highway embankments, a geofoam strength at a train of 1.5% or less can be considered an elastic strength. Several researchers suggested that EPS geofoam behaves linearly at a strain of 1% (Chen et al. 2015; Stark et al. 2012; Ossa & Romo 2009; Duskov 1997).

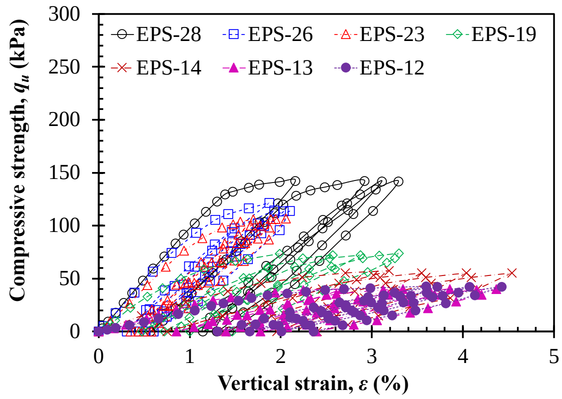
q_u of the all geofoam specimens at a strain of 15% was slightly greater about 10% than those at a train of 1% (Figure 7b, d) and there was no the failure state of the all specimens taken place up to a strain of 15% (Chen et al. 2015; Ossa & Romo 2011; Trandafir et al. 2010; Negussey 2007). This geofoam behavior is thought of as its structure compounding 2% polystyrene and 98% air (Mohajerani et al. 2017; Horvath 1994).



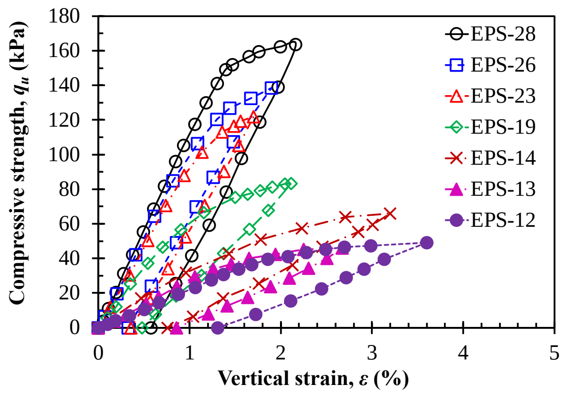
(a) For the first loading-unloading cycle rate of 1 mm/minute



(b) For five loading-unloading cycles rate of 1 mm/minute



(c) For the first loading-unloading cycle rate of 2.5 mm/minute



(d) For five loading-unloading cycles rate of 2.5 mm/minute

Figure 7 q_u versus ε under a displacement rate of 1 and 2.5 mm/minute

Several specimens were conducted by the UCS at a displacement rate of 2.5 mm/min to compare with geofoam compression behavior at the displacement rate of 1 mm/min. Figure 8 exhibits q_u of all geofoam specimens at strains from 1.7% to 2% under the two displacement rates varying with their densities. The higher displacement rate is applied, the greater the strength. Chen et al. (2017), Ossa & Romo (2011), and Tandafir et al. (2010) reported the similar trend.

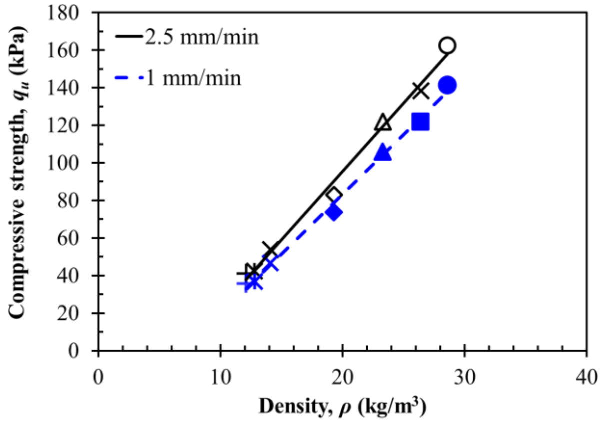
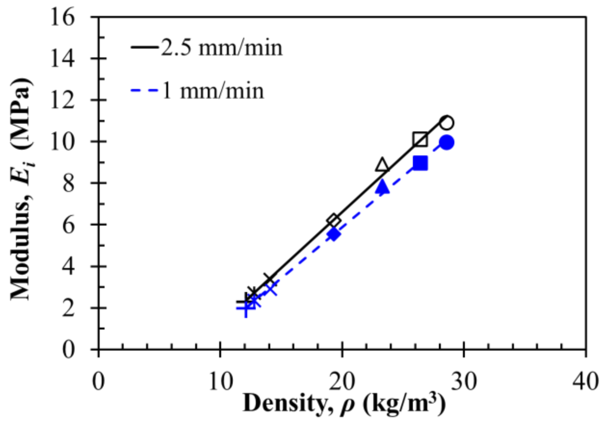


Figure 8 q_u at strains of 1.7% to 2% under the displacement rates of 1 and 2.5 mm/minute

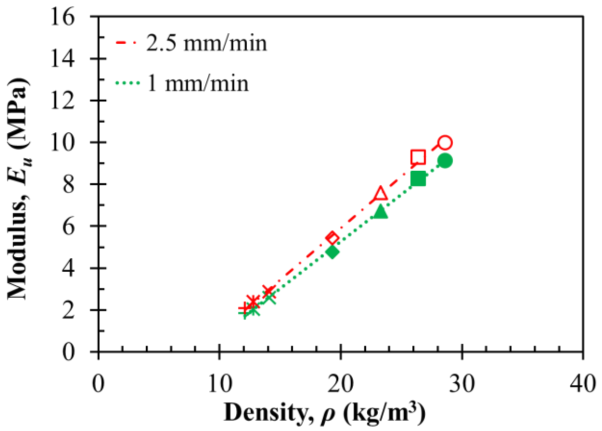
The typical deadload on geofoam in a highway embankment is a pavement layer which is around 15-20 kPa. The half strength of an EPS-19 or heavier (e.g., 40 kPa) is strong enough to tolerate the pavement load. Therefore, the EPS-19 or heavier are suitable for highway embankments.

3.2.2 Initial modulus (E_i) and unloading modulus (E_u)

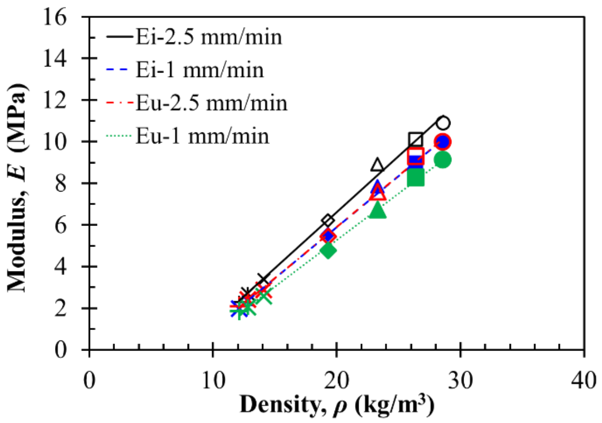
E_i was determined at a strain of 1% or less and E_u was calculated at a strain of 2% or more due to unloading cycles. The E_i and E_u of the EPS-12 to EPS-28 specimens are displayed in Figure 9, 10. The both E_i and E_u increased linearly with increasing in densities. The E_i of the EPS-12 to EPS-28 specimens increases from 1.98-9.95 MPa at the displacement rate of 1 mm/min to 2.29-10.88 MPa at the displacement rate of 2.5 mm/min. The E_u of the all specimens at the displacement rates of 1 and 2.5 mm/min was 1.85-8.51 MPa and 2.1-9.41 MPa, respectively. E_u was slightly lower than E_i. Figure 10 shows that E_i of this study agrees well with Ossa & Romo (2009), Negussey (2007), Duskov (1997), and Horvath (1994) in terms of trend, but is slightly different from value. Geofoam modulus of elasticity was relatively low and about 2 to 11 MPa for the all tested specimens.



(a) E_i versus ρ at the displacement rates of 1 and 2.5 mm/min



(b) E_u versus ρ at the displacement rates of 1 and 2.5 mm/min



(c) E_i and E_u versus ρ at the displacement rates of 1 and 2.5 mm/min

Figure 9 E_i and E_u versus ρ at the displacement rates of 1 and 2.5 mm/min

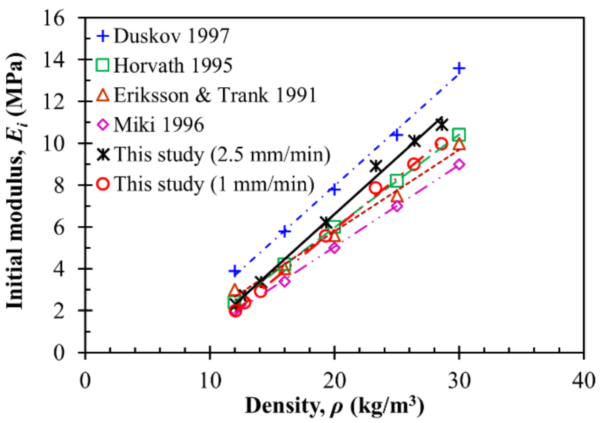


Figure 10 Comparison of E_i to other research results (modified from Elragi 2006)

3.2.3 Poisson ratio (v)

Poisson ratios (v) of the EPS-12 to EPS-28 specimens at the displacement rates of 1 and 2.5 mm/min varied from 0.06 to 0.14, respectively (Figure 11). v was quite small and increased linearly with increasing in densities. The result is consistent with Mohajerani et al. (2017), Srirajan et al. (2001), and Duskov (1997). The small Poisson ratio is believed due to high porosity of geofoam material.

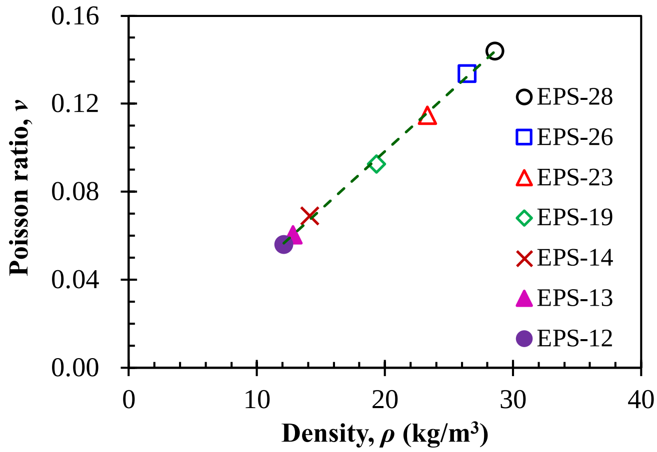
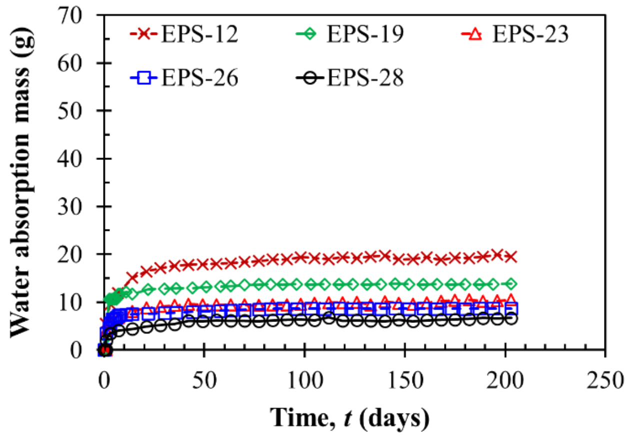


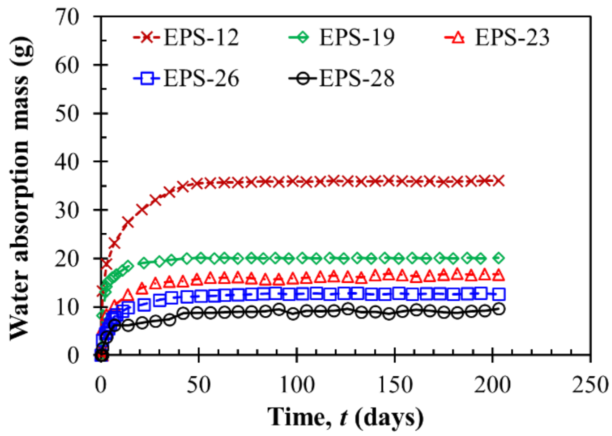
Figure 11 Poisson ratio v versus ρ at the displacement rate of 1 and 2.5 mm/min

3.3 Water absorption

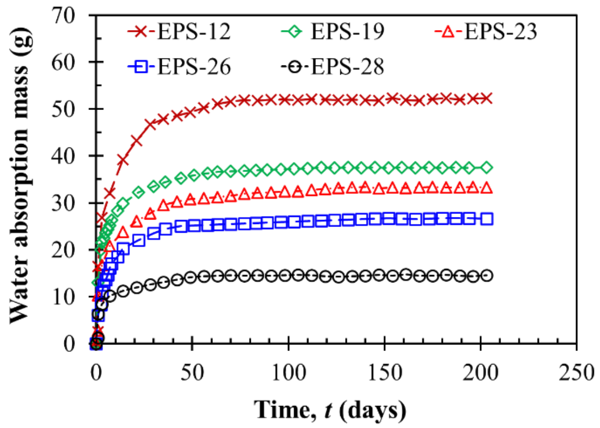
The 15 specimens made from the 5 geofoam types of the EPS-12, EPS-19, EPS-23, EPS-26, and EPS-28 were tested following the ASTM D2842 to determine water absorption. The all specimens were submerged in water at the 3 water levels of 50-mm above, the same of the top surface, and a half of specimen height for 203 days. Figure 12 displays variation of specimen mass due to water absorption.



(a) Water level at the middle of the specimen height (H_1)



(b) Water level at the specimen height (H_2)

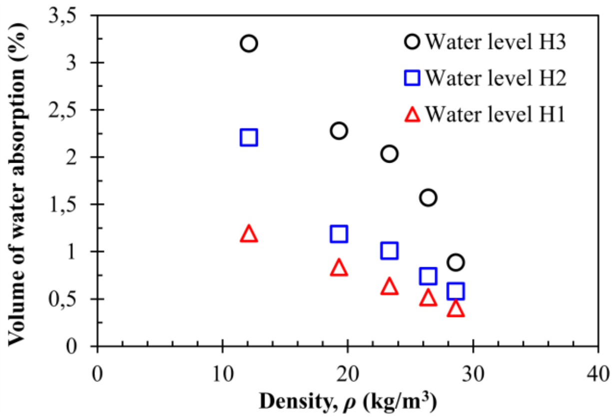


(c) Water level of 50 mm above the specimen height (H_3)

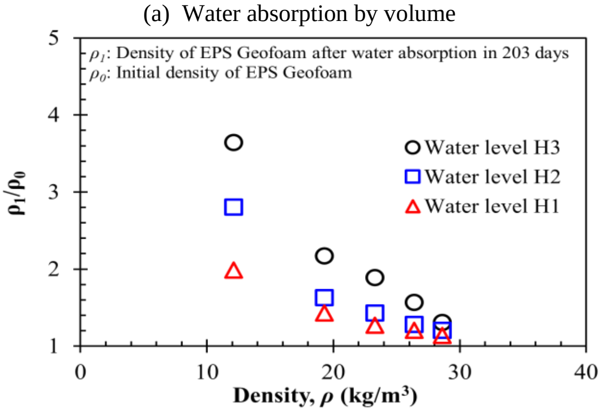
Figure 12 Variations of specimens' mass due to water absorption varying with time

Water absorption by volume decrease with increasing in densities (Figure 13) (Ossa & Romo 2012, Frydenlund et al. 2001, Duskov 1997, Sarlin et al. 1986). Geofoam specimens absorbed 60% of their water absorption capacity for the first week, up to 90% for next 4 weeks, and almost 100% after 8 weeks submerged. The similar trend was found by Ossa & Romo (2012), Duskov (1997), and Sarlin et al. (1986).

Water absorption increases with increasing in water levels (Figure 13). Static water pressure drives water farther inside Geofoam specimens. Full water absorption by mass at 203 days increased by ratios of 1.2 to 3.7 to dry geofoam specimens (Figure 13b). Water absorption by volume was from 0.4 to 3.2% and to be relatively low (Figure 13a). For practical applications, the total weight at full water absorption of geofoam is significantly lower than conventional soils such as sand, silt, and clay.



(a) Water absorption by volume



(b) Normalized water absorption by mass

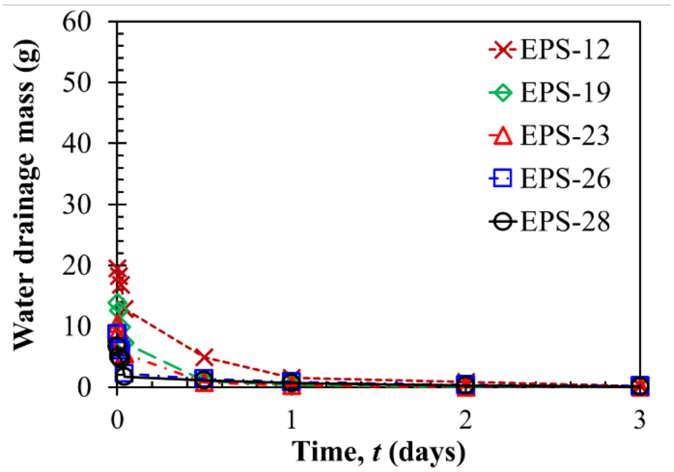
Figure 13 Water absorption by volume and mass for 203 days submerged

3.4 Water discharge

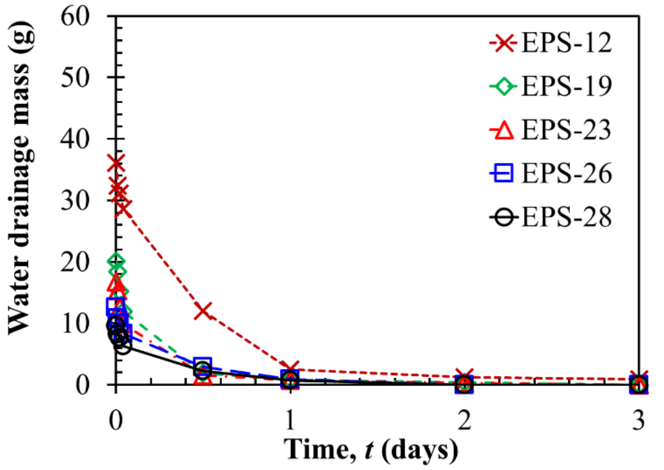
The all geofoam specimens were taken out of water after 203 days submerged. The weight of the specimens was measured with time to investigate the change of specimen weight in open air. Figure 14 plots the mass of the specimens with time. Water drained out of the specimens at least 80% of their water absorption in open air for the first day and almost 100% for next 3 days. This result is crucial for practical applications as highway embankment fills, especially highway embankments affected by annual floods.

3.5 Petroleum solvents

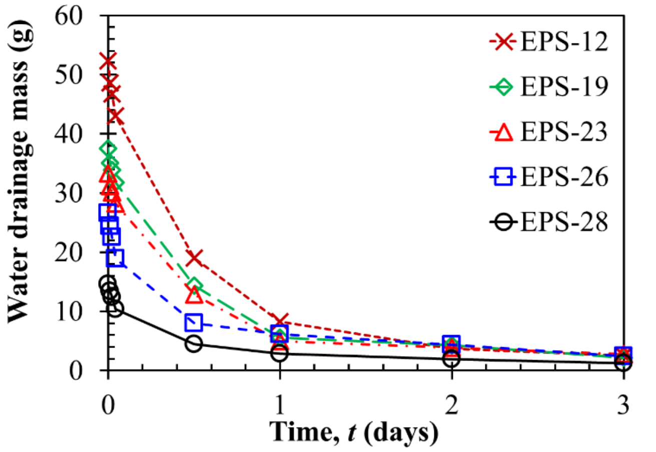
Gasoline, diesel, and lubricant oils were used to examine how geofoam dissolves. Figure 15, 16 display the durations of the geofoam specimens dissolving completely in gasoline and diesel. The all geofoam specimens have no damage to submerge into a lubricant oil for 45 days. The all specimens were totally melted in gasoline in seconds which vary from 6 to 33 seconds for the EPS-12 to EPS-34 specimens, respectively (Figure 15). Diesel can dissolve geofoam but much slower than gasoline. The EPS-12 to EPS-34 specimens were dissolved in diesel for 11 to 27 minutes, respectively (Figure 16).



(a) The water level H_1



(b) The water level H_2



(c) The water level H_3

Figure 14 Water discharge freely in open air out of the Geofoam specimens for the first 3 days

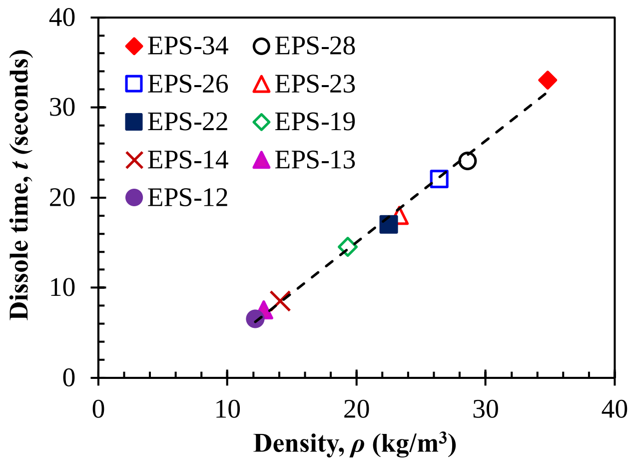


Figure 15 Geofoam specimens contacting to gasoline

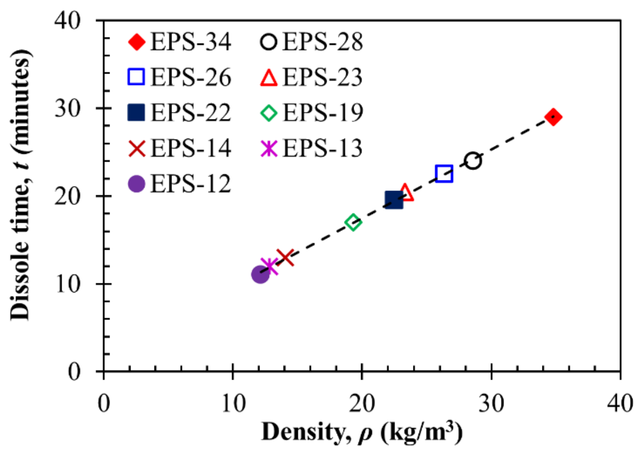


Figure 16 Geofoam submerged in diesel

3.6 Inflammability

Geofoam inflammability is studied following the ASTM D2863. The all geofoam specimens created from the 9 geofoam types were quickly burnt in seconds. Figure 17 shows the combusted duration of the all specimens. Burning duration varied from 22 to 40 seconds for the EPS-12 to EPS-33 specimens and duration increased with increasing in densities. Geofoam is a polystyrene material which is destroyed at a temperature of 80^0C or higher (Mohajerani et al. 2017; Hovarth 1999; Duskov 1997).

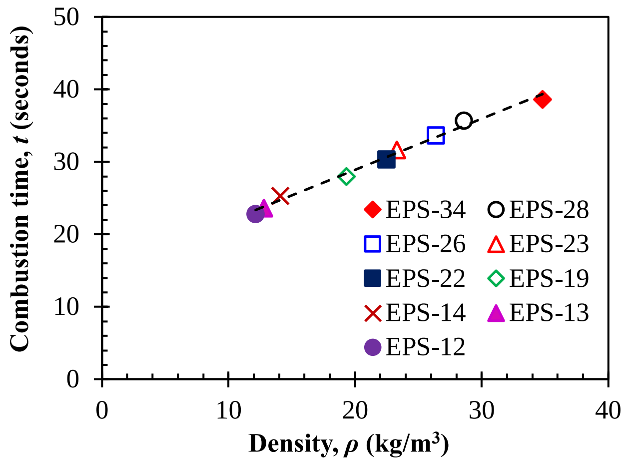


Figure 17 Combusted duration of the Geofoam specimens contacting to fire

4. CONCLUSION

The over 140 geofoam specimens were shaped from the 9 geofoam types with various dimensions to conduct several tests following the ASTM standards to investigate geofoam characteristics in the laboratory. The all geofoam specimens were measured for mass densities. Water absorption, water discharge, inflammability, dissolution in petroleum solvents, and mechanical properties such as strength, modulus of elasticity, and Poisson ratio were obtained. The all tests were conducted in more than 250 days. The results recommend the following findings:

(1) Geofoam densities from 12.1 to 34.8 kg/m^3 for the EPS-12 to EPS-34 geofoams, respectively.

(2) q_u increases linearly with increasing in densities at a strain of 1% or less, and consider the elastic strength of geofoam.

(3) q_u at a strain of 1.5% was from 35 to 140 kPa and at displacement rates of 1 and 2.5 mm/min were from 40 to 160 kPa for the EPS-12 to EPS-28 geofoams, respectively. q_u is recommended as the design strength.

(4) Geofoam modulus of elasticity was from 2 to 10 MPa at the strain of 1% and from 2.3 to 11 MPa at the displacement rates of 1 and 2.5 mm/min for the EPS-12 to EPS-28 geofoams, respectively.

(5) Geofoam Poisson ratio is relatively low, which ranges from 0.06 to 0.14 for the geofoams of the EPS-12 to EPS-28, respectively.

(6) Geofoam absorbs water fully in the first 8 weeks submerged. The saturated geofoam density is higher than the dry density from 1.2 to 3.7 times for the EPS-28 to EPS-12 geofoams, respectively. The volume of water absorption was from 0.4% to 3.2%.

(7) Water is quickly discharged out of geofoam in the first 3 days.

(8) Geofoam is totally and very quicky dissolved in gasoline, gradually in diesel, and no reaction with lubricant oils.

(9) Geofoam has no resistance to fire and is quickly burnt.

(10) The EPS-19 or heavier can be suitable for highway embankemnt fills based on their strength, stiffness, densities, deformation, and water absorption.

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