Modelling Initial Elastic Modulus of Sand-EPS Mixtures Using Evolutionary Polynomial Regression

Sina Lahijani Afkham
Civil Engineer, Faculty of Civil Engineering,
University of Tabriz,
Tabriz, Iran
sinaafkham@gmail.com

Masoud Hajialilue Bonab
Professor, Faculty of Civil Engineering,
University of Tabriz,
Tabriz, Iran

Abolfazl Najafi
Graduate Student, School of Civil Engineering,
Iran University of Science and Technology,
Tehran, Iran

Abstract— **Due to its low density as well as high strength/density ratio, expanded polystyrene (EPS) has gained significant popularity as a viable approach to soil stabilization. Considering the increasing use of EPS as a lightweight fill material, the development of reliable correlations for predicting its compressibility behavior would be beneficial due to the reduction of the costs connected with conventional laboratory testing. In the current study, undrained-unconsolidated (UU) triaxial compression tests were carried out on sand-EPS specimens prepared with various EPS contents and subjected to different confining pressures. Having observed and analyzed the compressibility responses of the composites, an EPR-based model was proposed and verified for the purpose of predicting the initial elastic modulus. Subsequently, in order to investigate the relative impact of each input variable on the estimated output, sensitivity analysis, as well as parametric study were carried out. The results demonstrate that although both the confining pressure and the EPS volume content have a consequential influence on the predicted initial elastic modulus, the former is a more sensitive component of the model.**

EPS beads, sand-EPS mixture, compressibility behavior, Evolutionary Polynomial Regression, EPR model

1. Introduction

Deemed to have a broad range of civil engineering applications, lightweight geomaterials can be deployed as a fill material for slopes to augment the factor of safety, as backfill for retaining walls to abate the lateral earth pressure, and as seismic buffers to diminish earthquake-induced loads.

Among multifarious lightweight fill materials, EPS geofoam block has recently generated considerable interest as a viable means to protect pipelines [1], decrease swelling pressure in expansive soils [2, 3], and construct lightweight embankment and pavements [4, 5]. Nevertheless, Liu et al. [6] explained that EPS geofoams, in spite of their upsides, are associated with a number of downsides, which include: (1) since EPS blocks are prefabricated off-site, they need to be transported to the project location; (2) EPS geofoams cannot be used to fill irregularly shaped excavations, and (3) characteristics of EPS geofoam blocks cannot be easily altered to match the properties of the soil on site. In order to mitigate the aforementioned problems, Liu et al. advocated using a mixture of soil, cement, and EPS beads as an alternative since not only can this mixture be prepared on-site, but it is rather capable of filling cavities of irregular shapes. Besides, when it comes to cases where a higher compressive strength than what EPS blocks can provide is requisite, this composite would conceivably be useful.

However, the addition of cement to lightweight fill materials would ostensibly culminate in an increase in costs because either an extra workforce or more machines would be necessary for mixing [6]. To address this hurdle, the utilization of the mixtures of soil and EPS beads has been taken into consideration and numerous researches have been conducted to study their behavior, involving the compressibility of these composites. In this regard, having studied the impact of EPS beads on the stress-strain behavior of EPS-sand mixtures, Deng and Xiao [7] illustrated that an increase in the EPS content results in a decline in the drained shear strength of these composites. The compressibility behavior of sand-EPS beads mixtures has also been investigated by Karimpour Fard et al. [8] who proposed an EPR model to predict their one-dimensional stress-strain behavior. Likewise, Edinçliler and Özer [9] carried out a number of triaxial tests under various confining pressures to unravel the influence of EPS beads gradation on the stress-strain behavior of sand-EPS mixtures.

Although the compressibility behavior of EPS-soil composites has formerly been studied, there is still a scarcity of research on the development of a reliable model for predicting the initial elastic modulus (E_{ES}) of these mixtures. Taking the burgeoning deployment of lightweight geomaterials for improving soil characteristics into account, the development of such correlations would be beneficial due to the reduction of the expenses associated with conventional laboratory testing [9].

The primary purpose of this paper is to present and validate a model for estimating the initial elastic modulus of sand-EPS beads mixtures based on the parameters confining pressure (σ_3) and EPS volume content (δ). For this to happen, Evolutionary Polynomial Regression (EPR) [10], which is a data-driven mechanism founded on evolutionary computing, is utilized. In the current study, first, the properties of the used materials will be explained. Second, the test procedure pursued and the results obtained will be described. Third, an EPR-based model for the prediction of E_{ES} will be proposed and verified. Finally, the results of both sensitivity analysis and parametric study, which were conducted to measure the impacts of fluctuations in input parameters on the estimated output, will be elucidated.

2. Materials

The experiments were conducted on "Chamkhaleh Sand", acquired from Chamkhaleh Beach, a coastal zone located in the SW of the Caspian Sea [11, 12]. The specific gravity and minimum dry unit weight were ascertained according to ASTM D 854 [13], whilst the maximum dry unit weight was determined based on ASTM D 4253 [14]. With regard to Table 1, the deployed sand had a specific gravity of 2.62, a maximum dry unit weight of 16.4 kN/m^3, and a minimum dry unit weight of 14.3 kN/m^3. Besides, the coefficient of uniformity and the coefficient of curvature of the soil were 1.4 and 0.92 respectively, and thus, the soil was classified as poorly graded sand (SP) under the Unified Soil Classification System. The particle size distribution of the sand is illustrated in Figure 1.

Provided by a local EPS geofoam block molding company, the beads employed in this study were super light polymer foam, pre-puffed from polystyrene resin. Moreover, the EPS beads were even, white, spherical, and as depicted in Figure 1, sized between 2 and 5 mm. The specific gravity and dry unit weight of beads were ascertained

Table 1. Properties of the tested materials

Material	Specific gravity G_s	Dry unit weight (kN/m^3)	Effective size D_{10} (mm)	Mean grain size D_{50} (mm)	Uniformity coefficient C_u	Coefficient of curvature C_c
Sand	2.62	14.3 (min) 16.4 (max)	0.15	0.20	1.40	0.92
EPS beads	0.02	0.12	2.22	3.40	1.69	0.90

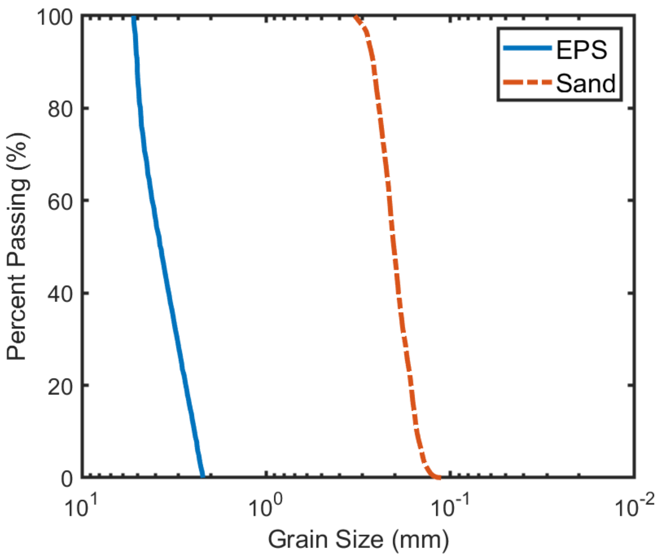

Figure 1. Grain size distribution curves of both sand and EPS beads used for the mixtures

Figure 2. A photo of EPS beads

as 0.02 and 0.12 kN/m^3 respectively according to ASTM C 128 [15]. The index properties pertinent to EPS beads are presented in Table 1.

3. Apparatus and test procedure

Sand-EPS samples were formed by mixing sand with various volume contents of EPS beads, which are shown in Table 2. A water content of 5% was also added to the specimens to provide bonding between sand particles and beads since EPS beads are liable to float in the composite when the mixing process is performed under the dry condition. In order to prepare each sample, first, the weight-based proportions of sand and EPS were determined. Then, all these materials were mixed in a thoroughgoing way until the composite was homogenous. The subsequent task was to ascertain the weight of each triaxial specimen to reach the target relative density of 70%. To do so, upon the determination of the maximum and minimum dry unit weights based on ASTM D 4253 [14] and ASTM D 854 [13] respectively, a dry unit weight corresponding to the desired relative density was calculated (Table 2). After the determination of the total amount of material required for filling the 70 mm × 140 mm test sample, the mixture was placed in a split mold and compacted in three equal hight lifts to attain the specified relative density.

Formerly used by numerous researchers to establish the compressibility behavior of soils combined with additives, encompassing geotextile [16], cement [17], cement and EPS beads [18], cement and fiber [19], fly ash and lime [20], undrained-unconsolidated (UU) triaxial test was similarly conducted in this study, according to ASTM D 2850-03 [21], to investigate the stress-strain characteristics of sand-EPS composites. In order to carry out the tests, after the completion of the compaction process in the split mold, the specimens were placed in the triaxial cell and subjected to the confining pressure. Afterward, by the forthwith application of the deviatoric stress at a strain rate of 0.35%/min, the shear phase commenced. While the cell pressure was remained constant during this phase, by raising the axial load, the samples were sheared until failure. The failure criteria, furthermore, was considered as the deviatoric stress at 15% axial strain or the maximum deviatoric stress obtained, whichever was achieved first. Table 2 demonstrates the triaxial test schedule, which comprised 12 specimens prepared with EPS volume contents ranging from 5 to 30 percent and subjected to confining pressures 50 and 150 kPa.

Table 2. Triaxial compression test program

Sample number	EPS content by volume, δ (%)	Dry unit weight min, max (kN/m^3)	Dry unit weight of sand-EPS (kN/m^3)	Relative density, D_r (%)	Cell pressure, σ_3 (kN/m^3)
1	5	8.7, 14.2	11.9	70	50 and 150
2	10	7.9, 13.1	11.0		
3	15	7.1, 12.6	10.3		
4	20	6.3, 11.5	9.2		
5	25	5.8, 9.9	8.1		
6	30	5.2, 8.6	7.2		

4. Results and discussion

In order for the results of sand-EPS composites to be juxtaposed with that of sand only sample, a control test using merely sand was carried out. However, the results of the aforementioned experiment were not utilized to develop the EPR model for predicting the initial elastic modulus of sand-EPS beads mixtures. Figure 3 illustrates the stress-strain curves of both sand only and EPS-sand specimens. Based on these results, it is evident that under the lower cell pressure, the compressibility behavior of the composites is predominantly influenced by the sand as the stress-strain curves reach a clear peak. Conversely, the curves do not flatten under the higher confining pressure and thus, the deviatoric stress at 15% axial strain is chosen as the peak deviatoric stress for these samples. In addition, the strain hardening of the sand-EPS mixtures subjected to high cell pressure is the offspring of the remarkable volumetric compression of the beads, which results in their densification. Accordingly, under high confining pressures, the compressibility behavior of the composites is mainly affected by EPS beads. Figure 3 also indicates that although the peak deviatoric stress correlates positively with the cell pressure, it is inversely proportional to the EPS content.

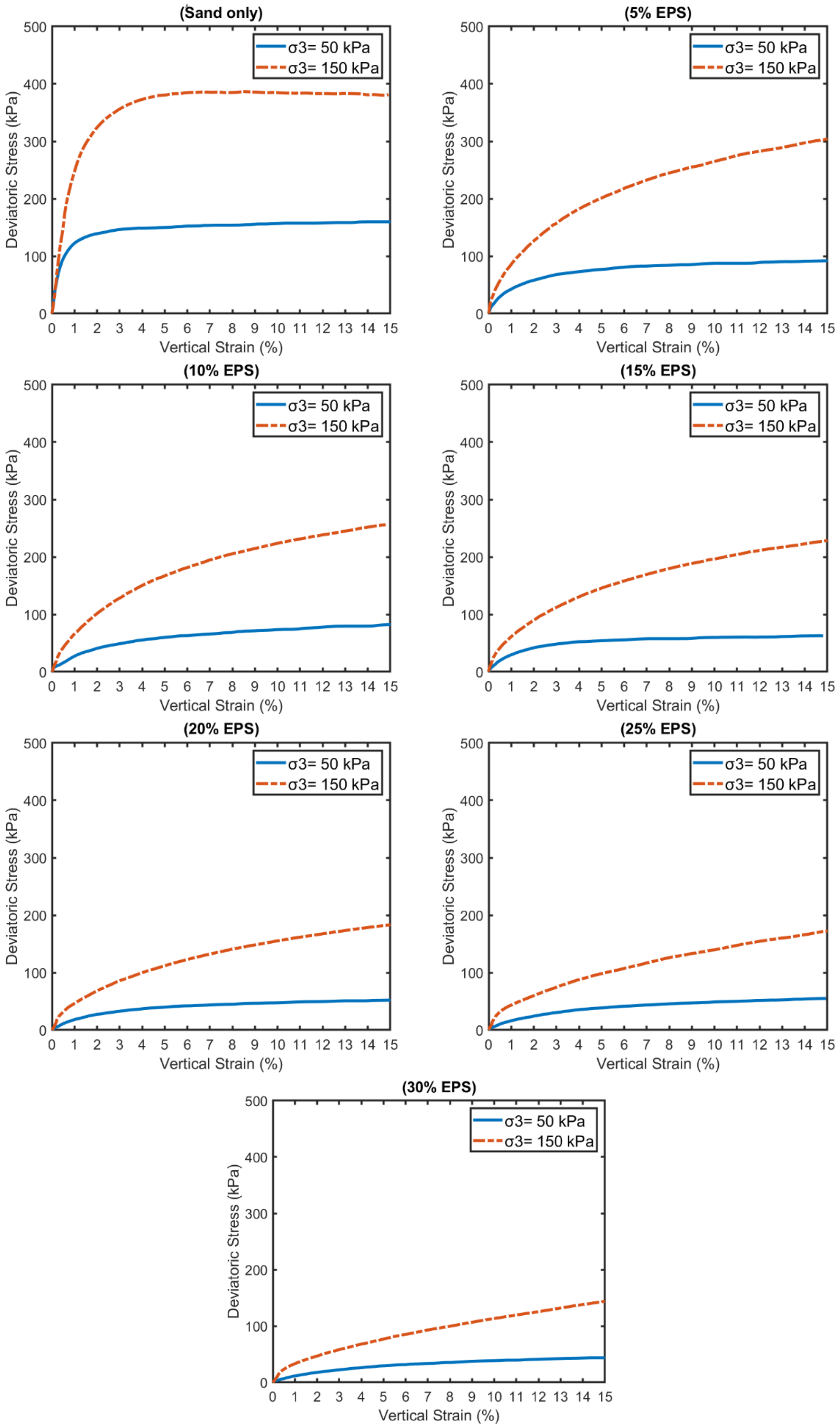

Figure 3. Deviatoric stress-strain behavior of sand only as well as sand-EPS specimens

With regard to Figure 4, which presents the initial elastic modulus associated with each specimen, E_{ES} is a function of both confining pressure and EPS beads content. Moreover, assuming other variables remain constant, a rise in the amount of cell pressure culminates in an increase in E_{ES}. Conversely, when the EPS volume content increases, E_{ES} linearly declines, provided that other parameters remain the same.

While numerous additives, involving plastic waste, tire shreds, and cement, augment the shear strength of sand, EPS bead inclusions, as previously elucidated, diminish the peak deviatoric stress as well the initial elastic modulus. Although this fact can be considered as a downside connected with sand-EPS composites, it should also be taken into account that EPS beads provide a lighter fill material when compared to conventional lightweight geomaterials. Deemed to be consequential, the relatively lower density of EPS-sand mixtures is ostensibly an advantage in field applications, especially on soft-soil sites [9]. To secure a satisfactory combination of shear strength and unit weight of EPS beads, Deng and Xiao [7] proposed an optimum EPS content of 0.5% based on consolidated-drained (CD) triaxial test results.

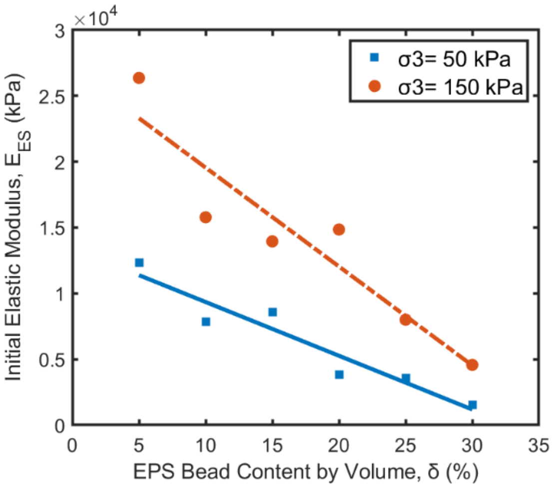

Figure 4. Variation of initial elastic modulus with EPS content and confining pressure

5. Predictive Model

As initial elastic modulus is conventionally determined through time-consuming laboratory testing, the development of predictive models capable of estimating this parameter based on easily measured properties would be a beneficial endeavor. For this to happen, Evolutionary Polynomial Regression (EPR) [10] is employed in the current study. Aimed to seek polynomial structures representing the behavior of the system, EPR is a data-driven mechanism founded on evolutionary computing. In this mode, in order to ascertain feasible structures and associated parameters, an amalgam of least squares method and genetic algorithm is deployed.

Figure 5 depicts the procedure of Evolutionary Polynomial Regression. With regard to this flow chart, EPR comprises two major stages. First, the main structure of the model is identified through the genetic algorithm strategy. Second, the parameters are estimated based on the least square regression. The process initiates with a constant mean of output values and as the evolution continues, the model gradually picks up various participating parameters to form expressions describing the relation between them. Finally, the process stops when a termination criterion, which can be a particular allowable error, or the maximum number of generations, or the maximum number of terms, is satisfied.

In this study, using a dataset collected from triaxial tests on sand-EPS mixtures, an EPR-based model was developed for predicting the initial elastic modulus. The data were divided randomly into two sets of training and testing. The former constituted 75% of the data points and was utilized to calibrate the model, whereas the latter constituted 25% of the data and was used for the purpose of verification. The development of the model was performed by employing the software, EPR MOGA-XL Version 1, in which the internal parameters were selected based on the trial and error approach. The options associated with the optimum model are presented in Table 3.

Deemed to be the most salient factors affecting the output, cell pressure (σ3) and EPS volume content (δ) are deployed as input variables for the development of the model, which is as follows:

$$E_{ES} = 0.23873\left(\frac{\sigma_3^3}{\delta}\right) - 0.20039\left(\frac{\sigma_3^3}{\delta^{0.5}}\right) + 36110.6208\sigma_3^{0.5} \\ -0.82702\delta^{0.5}\sigma_3^2 - 250.6793\delta - 231729.071 \quad (1)$$

Where σ_3 and E_{ES} are both in units of kPa and δ is in percent. Figure 6 demonstrates a comparison between the measured E_{ES} and the predicted outputs based on both training and testing datasets. The R^2 value of the model is 0.9923.

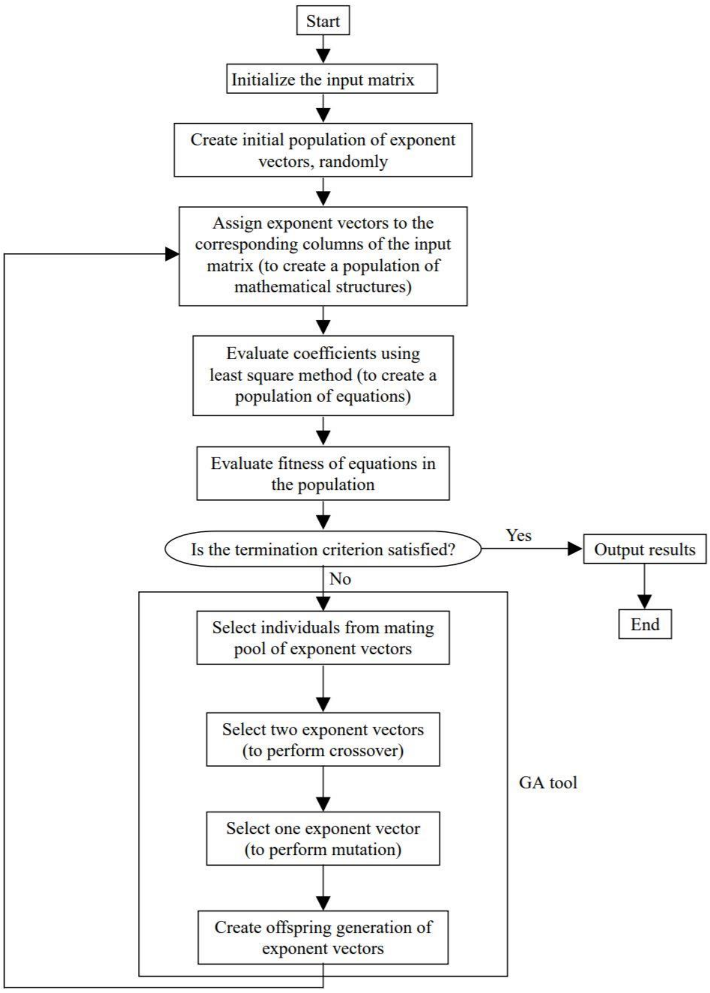

Figure 5. Typical flow chart for EPR procedure [22]

Table 3. Options used in EPR modelling

Parameter	EPR setting
Modelling type	Statistical
Expression structure	$y=sum(a_i*X_1*X_2*f(X_1)*f(X_2))+a_0$
Inner function type	No function
Range of exponents	[-1:0.5:3]
Range of terms	[1:10]
Number of generations	200
Bias (a_0)	Yes
Optimization strategy	Least squares

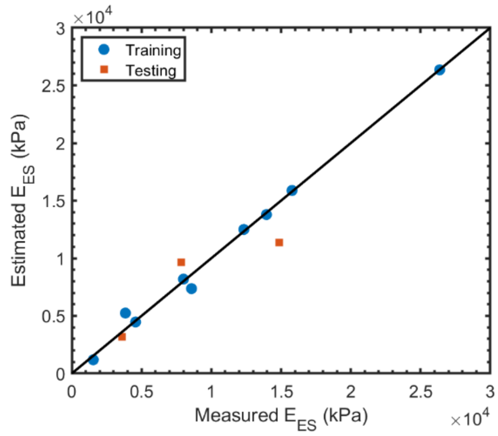

Figure 6. Comparison between measured and predicted initial elastic modulus

5.1. Parametric study

In order to investigate the influence of each input variable on the predicted initial elastic modulus, a parametric study [22] was conducted. The mechanism of parametric analysis is based on changing one input parameter while other input variables are kept constant at the mean values of their entire datasets. Based on the results of the parametric study showed in Figure 7, it is evident that an increase in EPS content induces a virtually linear decline in E_{ES}, whilst as confining pressure rises, E_{ES} increases as well.

5.2. Sensitivity analysis

When it comes to the appraisement of an EPR model, along with predictive accuracy, the interpretive ability of the model needs to be taken into account. To make this happen, a sensitivity analysis, which quantifies the relative importance as well as the contribution of each input variable to the corresponding output, can be performed. In this study, a sensitivity analysis was carried out using the cosine amplitude method [23, 24]. In this mode, first, each input parameter is expressed as an element in the array X, as illustrated in Eq. 2.

$$X = \{x_1,\ x_2,\ x_3, \dots, x_n\} \quad (2)$$

Where each element is a vector of the length m, as presented in Eq. 3.

$$x_i = \{x_{i1},\ x_{i2},\ x_{i3}, \dots, x_{im}\} \quad (3)$$

Finally, the strength of relationship between x_i and x_j can be determined utilizing the formula below:

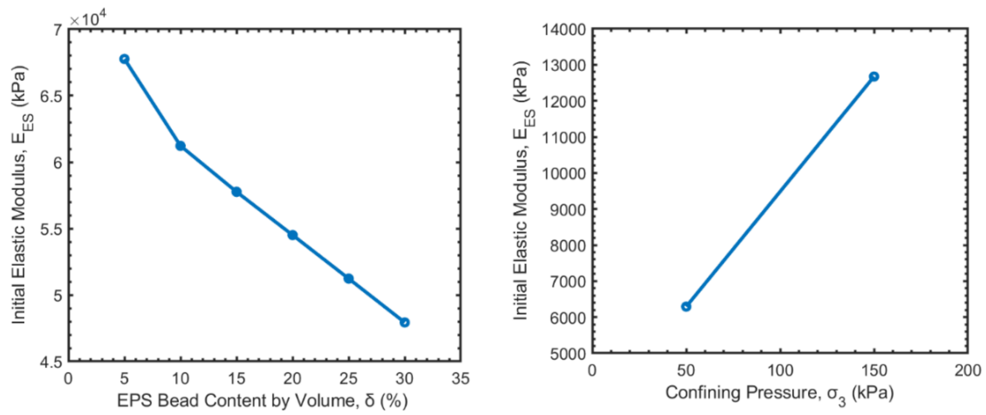

Figure 7. Results of parametric study

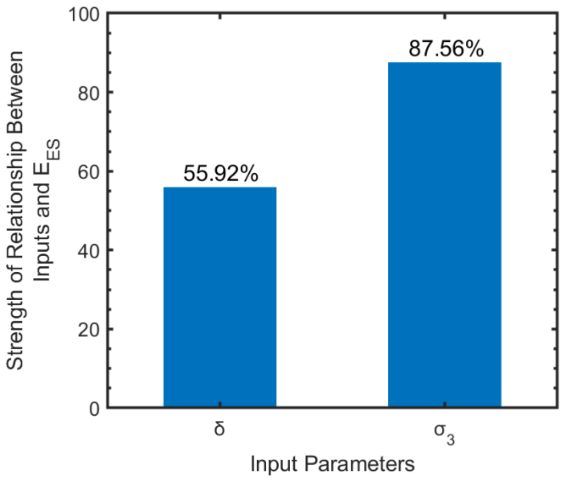

Figure 8. Sensitivity analysis conducted between E_{ES} and input variables

$$r_{ij} = \frac{\sum_{k=1}^{m} x_{ik}x_{jk}}{\sqrt{\sum_{k=1}^{m} x_{ik}^2 \sum_{k=1}^{m} x_{jk}^2}} \tag{4}$$

Figure 8 depicts the dependency of initial elastic modulus on input variables. Based on these results, cell pressure is the most influential parameter with 87.56%, followed by EPS volume content with 55.92%.

6. Conclusion

A total of 12 undrained-unconsolidated (UU) triaxial compression tests were conducted on EPS-sand samples prepared with different EPS volume contents and subjected to various cell pressures. The following lists a number of conclusions drawn from the experimental program as well as the model analysis:

- The compressibility behavior of sand-EPS composites is a function of both EPS content and confining pressure.
- The stress-strain behavior of EPS-sand mixtures under low confining pressure resembles that of sand, whilst under high cell pressure, the stress-strain behavior of sand-EPS composites is predominantly influenced by EPS beads.
- By raising the EPS content, the unit weight of sand-EPS fill can be dramatically reduced for applications where primary settlement is a concern. However, to procure a reasonable amalgam of both unit weight and shear strength of these mixtures, the optimum bead content needs to be ascertained.
- An EPR model is proposed based on confining pressure and EPS volume content for predicting the initial elastic modulus in order to diminish the expenses connected with laboratory testing. The R^2 value of the model is 0.9923, which indicates that the model has a reasonable accuracy.
- Based on the results of parametric study, a rise in EPS content engenders a linear decrease in initial elastic modulus, as long as confining pressure remains constant. Conversely, E_{ES} is proportional to cell pressure.
- The results of sensitivity analysis demonstrate that confining pressure and EPS content have the highest and next highest effect on E_{ES} respectively.

Acknowledgment

The corresponding author would like to express his earnest gratitude to Dr. Luigi Berardi, one of the developers of the EPR MOGA-XL software, for the grant of the license of the program, which was used for the development of the model presented in this study.

References

[1] Bartlett, Steven F, BretN Lingwall, Aurelian C Trandafir, and Evert C Lawton, 2. Protection of Steel Pipelines from Permanent Ground Deformation Using EPS Geofoam. Seismic Resilience of Natural Gas Systems: Improving Performance, 2012. 34: p. 5.
[2] Aytekin, Mustafa, Numerical modeling of EPS geofoam used with swelling soil. Geotextiles and Geomembranes, 1997. 15(1-3): p. 133-146.
[3] Ikizler, S Banu, Mustafa Aytekin, and Evin Nas, Laboratory study of expanded polystyrene (EPS) geofoam used with expansive soils. Geotextiles and Geomembranes, 2008. 26(2): p. 189-195.
[4] Stark, Timothy D, Guideline and recommended standard for geofoam applications in highway embankments. Vol. 529. 2004: Transportation Research Board.
[5] Bartlett, S, D Arellano, J Vaslestad, R Aabøe, and T Ahmed. Bridge foundations supported by EPS geofoam embankments on soft soil. in Proceedings of the 5th International Conference on Geofoam Blocks in Construction Applications, Kyrenia, Cyprus. 2018.
[6] Liu, Han-long, An Deng, and Jian Chu, Effect of different mixing ratios of polystyrene pre-puff beads and cement on the mechanical behaviour of lightweight fill. Geotextiles and Geomembranes, 2006. 24(6): p. 331-338.
[7] Deng, An and Yang Xiao, Measuring and modeling proportion-dependent stress-strain behavior of EPS-sand mixture 1. International Journal of Geomechanics, 2010. 10(6): p. 214-222.
[8] Fard, M Karimpour, R Mashmouli Juybari, and G Rezaie Soufi, Evolutionary Polynomial Regression-Based Models for the One-Dimensional Compression of Chamkhaleh Sand Mixed with EPS and Tire Derived Aggregate.
[9] Edinçliler, A and AT Özer, Effects of EPS bead inclusions on stress–strain behaviour of sand. Geosynthetics International, 2014. 21(2): p. 89-102.
[10] Giustolisi, Orazio and Dragan A Savic, A symbolic data-driven technique based on evolutionary polynomial regression. Journal of Hydroinformatics, 2006. 8(3): p. 207-222.
[11] Karimpour Fard, Mehran, R Jamshid Chenari, and F Soheili, Shear strength characteristics of sand mixed with EPS beads using large direct shear apparatus. Electronic Journal of Geotechnical Engineering, 2015. 20(8): p. 2205-2220.
[12] Chenari, Reza Jamshidi, Mehran Karimpour Fard, Sabina Pourghaffar Maghfarati, Faranak Pishgar, and Sandro Lemos Machado, An investigation on the geotechnical properties of sand–EPS mixture using large oedometer apparatus. Construction and Building Materials, 2016. 113: p. 773-782.
[13] ASTM, D, 854-14. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, 2014.
[14] ASTM, D, 4253-00. Standard test methods for maximum index density and unit weight of soils using a vibratory table, 2006. 1.
[15] Standard, ASTM, C128-12, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. ASTM International, West Conshohocken, PA, 2012.
[16] Noorzad, R and SH Mirmoradi, Laboratory evaluation of the behavior of a geotextile reinforced clay. Geotextiles and Geomembranes, 2010. 28(4): p. 386-392.
[17] Sariosseiri, Farid, Critical state framework for interpretation of geotechnical properties of cement treated soils. 2008: Washington State University.
[18] Yoonz, Gil-Lim, Sang-Soo Jeon, and Byung-Tak Kim, Mechanical characteristics of light-weighted soils using dredged materials. Marine Georesources and Geotechnology, 2004. 22(4): p. 215-229.
[19] Tajdini, Milad, Masoud Hajialilue Bonab, and Sina Golmohamadi, An experimental investigation on effect of adding natural and synthetic fibres on mechanical and behavioural parameters of soil–cement materials. International Journal of Civil Engineering, 2018. 16(4): p. 353-370.
[20] Li, Wenjuan, Performance assessment of stabilized pavement subgrades. 2011.
[21] Standard, ASTM, D2850-03a,". Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils" ASTM International, West Conshohocken, PA, 2007.
[22] Moharrami, Abdolreza, Gholam Moradi, Masoud Hajialilue Bonab, Javad Katebi, and Gholamreza Moharrami, Performance of cutoff walls under hydraulic structures against uplift pressure and piping phenomenon. Geotechnical and Geological Engineering, 2015. 33(1): p. 95-103.
[23] Yang, Y and Q Zhang. Analysis for the results of point load testing with artificial neural network. in Proc Int Conf Compu Methods & Advances in Geomechanics. 1997.
[24] Shariatmadari, Nader, Mehran Karimpour-Fard, Hadi Hasanzadehshooiili, Saman Hoseinzadeh, and Zaniar Karimzadeh, Effects of drainage condition on the stress-strain behavior and pore pressure buildup of sand-PET mixtures. Construction and Building Materials, 2020. 233: p. 117295.