



## Evolutionary Polynomial Regression-Based Models for the One-Dimensional Compression of Chamkhaleh Sand Mixed with EPS and Tire Derived Aggregate

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**ABSTRACT:** The use of expanded polystyrene (EPS) and tire derived aggregate (TDA) as soil stabilization materials has received considerable attention in the last few decades. With the increased use of these products for stabilization purposes, investigating their stress-strain behavior emerges as a crucial endeavor. One of the most widely-used methods employed for evaluating the stress-strain behavior of such mixtures under varying overburden pressures is oedometer testing. In this study, the results of oedometer tests on mixtures of sand and EPS beads, as well as sand and TDA, are used to develop Evolutionary Polynomial Regression-based models for both sand-EPS and sand-TDA mixtures. The models presented are developed based on the results of laboratory oedometer tests on the aforesaid mixtures, under different overburden pressures, different relative densities and varying contents of EPS or TDA. Subsequently, by performing multivariate parametric studies on the presented models, the effect of the simultaneous variations of the influencing parameters on the resulting settlement has been investigated. In addition, by carrying out sensitivity analyses, it was found that among the studied parameters, the relative density had the least effect on the resulting settlement for both sand-EPS and sand-TDA mixtures, while the EPS content is the most effective parameter in the settlement of sand-EPS mixtures and for the sand-TDA mixtures, both the TDA content and the overburden pressure had the most effect.

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## 1. INTRODUCTION

The idea of improving soil properties in order to elevate them to the point of being suitable as the main material for different structures, dates back to ancient times. Over time, humans have recognized the weak shear strength and the lack of tensile strength in soil and thus, have always searched for methods to improve soil's mechanical properties including its strength. Recently, researchers have been looking for ways to use tire waste in civil engineering projects to solve both the problem of its disposal and to take advantage of potential benefits it could offer for construction purposes. With the application of recycled tires in various areas of civil engineering, namely as aggregate replacement in the construction of nonstructural sound-barrier fills, lightweight embankment fills crossing soft or unstable ground, regular fills, retaining-wall backfills, edge drains as well as drainage layers, daily cover materials and sorption barriers in landfills [1], several researchers have investigated the mechanical properties of tire inclusions and their performance in improving soil behavior [2-5]. Foose et al. (1996) presented direct shear test results on mixtures of dry sand and shredded waste tire, and showed that the addition of tire chips increases the shear strength of the sand, and normal stress, tire chip content and unit weight have the greatest effect on shear

strength [6]. In addition, due to the low specific gravity of the sand-tire chip mixture in comparison to pure sand, soil properties can be improved by the addition of this material. Slopes reinforced with tire chips present a higher factor of safety and the factor of safety increases as the weight content of the tire chips is increased from 2.5 to 10% [7]. Moreover, tire chips improve soil's hydraulic properties and increase the soil's internal friction angle [8]. Research has also shown that soil-tire chip mixtures experience more deformation in comparison to pure soil and therefore, the elastic behavior of the mixture during unloading is diminished [9]. Shariatmadari et al. (2018a, 2018b, 2019) used the results of monotonic and cyclic hollow cylinder torsional tests to investigate the stress-strain characteristics of sand and ground rubber mixtures and their resistance to liquefaction with results showing a reduction in liquefaction resistance [10-12].

Geofoam also known as expanded polystyrene (EPS), is another material that has received attention in geotechnical engineering particularly for being lightweight, easy to use and cheaper in comparison to other materials. The use of EPS has several advantages, including reducing the weight of filler materials, improvement of soil parameters, reduction of the lateral pressures on retaining structures, reduction of construction costs and a more pleasant appearance of the final structure. Multiple studies have been carried out on the

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mechanical behavior of sand with EPS blocks [13]. In addition, mixtures of soil, EPS and cement have been widely studied and used as lightweight filler material [14-16]. According to previous studies, the addition of EPS to sandy soil and the increase in its content, results in an increase in the cohesion of the mixture and the volumetric strains sustained, while the shear strength and internal friction angle are reduced [17-19]. Moreover, some of the other geotechnical parameters of sand-EPS mixtures such as permeability, coefficient of at-rest lateral pressure, volume compressibility coefficient, and drained and undrained elasticity modulus were evaluated using a large-scale oedometer apparatus, and it was concluded that the EPS beads have a reinforcing effect on the mixtures and they reduce the permeability and drained elastic modulus while increasing the volume compressibility coefficient and the coefficient of at-rest lateral pressure [20]. Recently, the dynamic properties of sand-EPS mixtures have also been investigated where the effect of EPS content on damping properties and small-strain shear modulus has been documented [21].

Due to the increasing use of the aforesaid materials in improving the properties of sandy soils and the important role of the settlement of such mixtures in the design of structures, developing a model to study and predict their one-dimensional stress-strain behavior is a beneficial endeavor.

Evolutionary polynomial regression (EPR) is a data-driven regression method that is based on evolutionary computing. In this study, results of laboratory oedometer

experiments on sand-TDA and sand-EPS beads mixtures are used to develop and present EPR models that can predict their one-dimensional stress-strain behavior. Based on the experimental results, the measured vertical strain data is fed to the EPR process as the sole output parameter, while three parameters are selected as input parameters. The first input parameter is the overburden pressure which is the vertical pressure imposed on the samples under which one-dimensional compression takes place. The second input parameter is the unconventional material content which is the weight/volumetric content of EPS or TDA in the mixture. The third and final input parameter is relative density which is the skeletal relative density of the sand matrix. In addition, the effect of different input parameters on the predicted output value is investigated using parametric and sensitivity analyses.

**2. MATERIALS**

**2-1- Sand**

In this study, experiments were carried out on the Chamkhaleh sand collected from the Chamkhaleh beach in the southwest of the Caspian Sea. Table 1 presents the geotechnical parameters of this soil. Fig. 1 presents the grain size distribution of the Chamkhaleh sand.

**2-2- EPS beads**

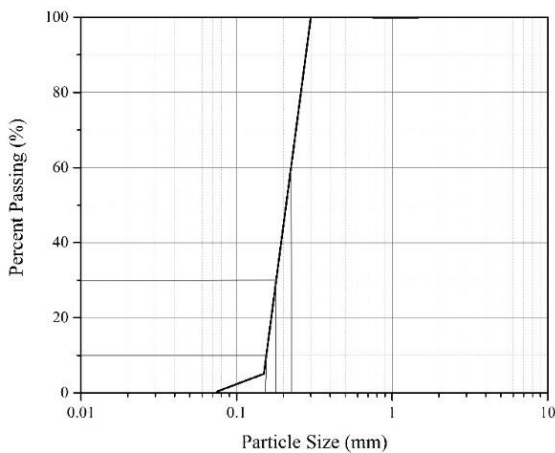
In this study, EPS beads with a specific gravity of 0.013 and physical properties as presented in Table 2 were used. Fig. 2

**Table 1. Geotechnical properties of Chamkhaleh sand**

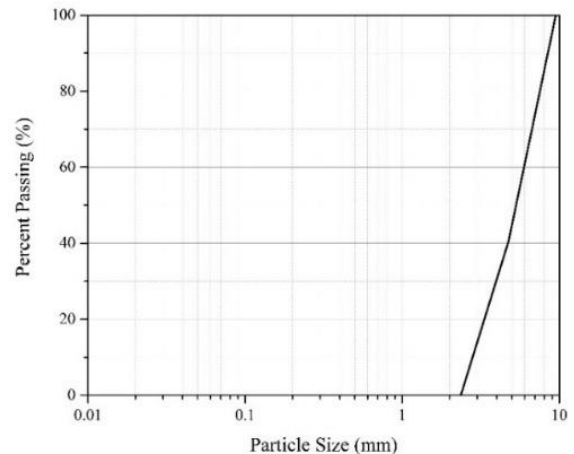
Sand	Unified Classification	Specific Gravity	$e_{min}$	$e_{max}$	$D_{10}$ (mm)	$D_{30}$ (mm)	$D_{60}$ (mm)	$C_c$	$C_u$
Chamkhaleh Sand	SP	2.63	0.6	0.81	0.15	0.18	0.22	0.98	1.47

**Table 2. Physical properties of the EPS**

Material	Specific Gravity	$D_{10}$ (mm)	$D_{50}$ (mm)	$C_c$	$C_u$
EPS beads	0.013	2.6	4	0.9	1.7



**Fig. 1. Grain size distribution of the Chamkhaleh sand**



**Fig. 2. Grain size distribution of the EPS beads**



Fig. 3. EPS beads

Table 3. Physical properties of the TDA

Material	Specific Gravity	$e_{min}$	$e_{max}$	$D_{50}$ (mm)	$C_c$	$C_u$
TDA	1.1	1.06	1.97	1.58	1.92	1.11



Fig. 4. TDA

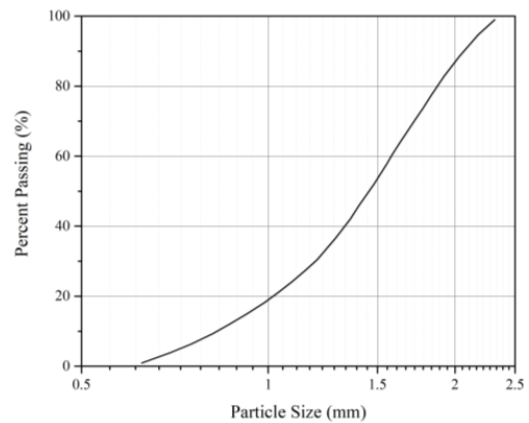


Fig. 5. Grain size distribution of the TDA

presents the grain size distribution of the EPS beads.

Fig. 3 presents the EPS beads used in the study.

### 2-3- Tire derived aggregate (TDA)

In this study, TDA obtained from crushing and milling of worn-out tires has been used. Table 3 presents the physical properties of the TDA used. Fig. 4 and 5 present the TDA used in the study and its grain size distribution respectively.

## 3. METHOD

### 3-1- Sand-EPS beads sample preparation

Sand-EPS beads samples were prepared with EPS to sand weight ratios of 0, 0.25, 0.5 and 1%. A water content equal to 5 % of the sand weight was also added to the mixtures to induce bonding between the sand and EPS particles and prevent segregation. Mixtures were prepared at two different relative densities of 40 and 80%. The samples were all prepared at the fixed volume of 1554.03 m<sup>3</sup>. For each mixing ratio, the dry weight of the sand and EPS beads is determined and the materials are mixed together with the required water thoroughly, in order to achieve a homogenous mixture. Fig. 6

presents the sand-EPS mixture. Mixtures were poured into the cell in five layers and compacted using a manual tamper. Table 4 presents the weight of the materials used for each sample. A total of eight samples were prepared and each sample was subjected to increasing levels of overburden pressure, namely 75, 150, 300, 600, and 1200 kPa in the oedometer tests.

### 3-2- Sand-TDA sample preparation

Sample preparation for the sand-TDA mixtures was similar to the method described in section 3.1. However, for the sand-TDA mixtures, TDA was added to sand in volumetric ratios of 10, 20, 30 and 40%. As described before, overburden pressures of 75, 150, 300, 600 and 1200 kPa were inflicted on the samples in stepwise stages. Table 5 presents the laboratory testing program for the sand-TDA mixtures.

### 3-3- Tall oedometer apparatus

The standard oedometer test, also known as one-dimensional consolidation or compression test, is one of the oldest tests to measure the compressibility parameters of geomaterials. In this study, a tall pneumatic oedometer



Fig. 6. Sand-EPS beads mixture

Table 4. Oedometer testing program for the sand-EPS beads mixtures

Sample Number	Relative Density (%)	EPS Weight Content (%)	Sample Weight (gr)	Sand Weight (gr)	EPS Weight (gr)	Water Weight (gr)
1	40	0.00	2360.90	2360.9	0.00	0.00
2		0.25	1921.94	1826.07	4.57	91.30
3		0.50	1569.23	1487.42	7.44	74.37
4		1.00	1147.74	1082.77	10.83	54.14
5	80	0.00	2483.97	2483.97	0.00	0.00
6		0.25	1998.52	1898.83	4.75	94.94
7		0.50	1619.79	1535.34	7.68	76.77
8		1.00	1174.42	1107.94	11.08	55.40

Table 5. Oedometer testing program for the sand-TDA mixtures

Sample Number	Relative Density (%)	TDA Volume Content (%)	Sample Weight (gr)	Sand Weight (gr)	TDA Weight (gr)	Water Weight (gr)
1	40	10	2376.5	2177.0	90.7	108.8
2		20	2311.9	2031.4	179.0	101.5
3		30	2237.6	1863.6	280.9	93.1
4		40	2156.0	1679.5	392.6	83.9
5	80	10	2492.0	2282.8	95.1	114.1
6		20	2416.5	2123.3	187.1	106.1
7		30	2330.1	1940.6	292.5	97.0
8		40	2236.0	1741.8	407.2	87.0

device, designed and fabricated in Guilan University was employed. Composite geomaterials such as sand-TDA and sand-EPS beads are both highly compressible and experience considerable deformations during loading. As a result, a tall oedometer apparatus would be ideal to evaluate the compressibility properties in mixtures of soil and these materials. The tall oedometer is used in this study, to measure and evaluate the settlement and deformation of the composite mixtures. Fig. 7 and 8 present a schematic view and a photograph of the employed tall oedometer apparatus respectively. The oedometer steel cell has an internal nominal diameter of 85 mm, wall thickness of 7.5 mm and height of 300 mm. It is equipped with a lateral pressure cell as well as a bottom pressure cell installed

at the bottom of the oedometer cell.

In this study, samples are subjected to loading while dry, and no extra water is added to the samples. Loading is started by imposing a 75-kPa stress on the samples. After the load is applied, enough time is allowed to pass for the displacement readings to fully stabilize. Once no more changes are witnessed in the LVDT readings, the load is increased to the next level (doubled). This is continued until the load is increased to 1200 kPa.

### 3-4- Evolutionary polynomial regression modeling

Evolutionary polynomial regression (EPR) is a data-driven regression method that is based on evolutionary computing.

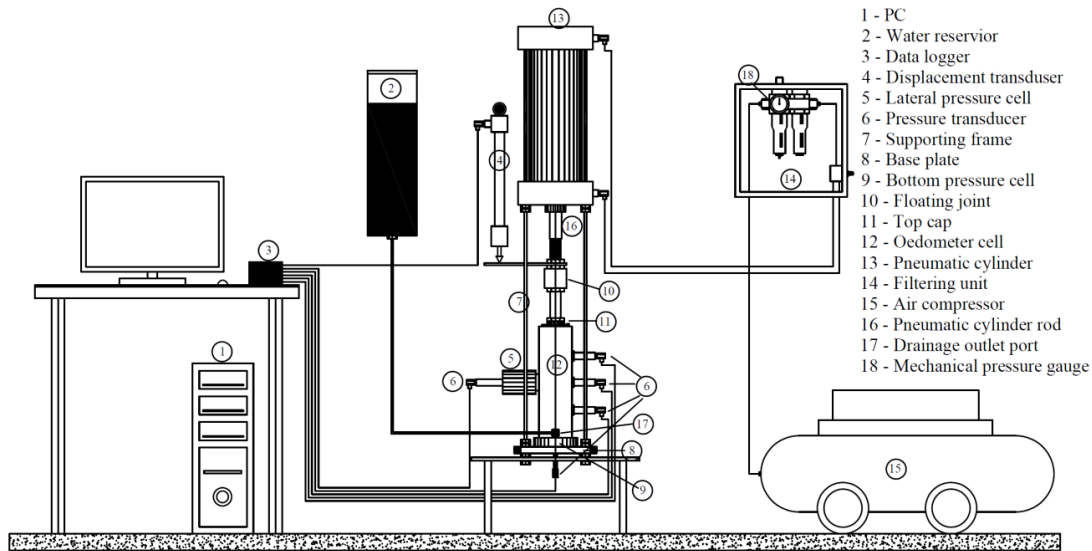


Fig. 7. Schematic view of the tall oedometer apparatus



Fig. 8. Tall pneumatic oedometer apparatus

The evolutionary procedure first looks for exponents of polynomial expression using a genetic algorithm with a fixed maximum number of terms [22]. Next numerical regression is used to solve least-squares problems that determine the constant values for the polynomial expressions. The process starts from a constant mean of output values. As the evolutions continue, the model picks up different participating parameters and forms expressions that describe the relationship between them. The procedure is terminated once a criterion set by the user, such as the maximum number of terms in the mathematical expression, the maximum number of generations, or a particular allowable error is satisfied [23, 24].

## 4. ANALYSIS

### 4-1- Experimental results

As previously mentioned, increasing levels of overburden pressure are applied to the samples placed in the tall oedometer apparatus. It has been well established that the friction that develops between the soil sample and the inner walls of a tall oedometer apparatus (height to diameter ratio greater than 0.4) is not negligible [25, 26]. Therefore, its effects on the stresses in such an oedometer have to be accounted for. Hence, when an overburden pressure is applied to the sample, the distribution of the vertical stresses along the sample height is not uniform. As mentioned in section 3-3, the oedometer is equipped with a bottom pressure cell through which the vertical stress at the bottom of the oedometer cell can be measured. The friction generated along the cell wall is the difference between the applied overburden pressure and the bottom vertical stress. The distribution of the vertical stress between the top and bottom can also be determined according to the analytical solution provided by Lovias and Sivakugan (2015):

$$\sigma_z = qe^{-4K_0 \tan \delta (z/D)} = qe^{-4\beta (z/D)} \quad (1)$$

where  $D$  is the cell diameter,  $\sigma_z$  is the effective vertical stress at depth  $z$ ,  $q$  is the applied overburden pressure,  $K_0$  is the at-rest lateral pressure coefficient and  $\delta$  is the friction angle of the interface between the soil and the cell wall [26]. By measuring the vertical stress at the bottom of the oedometer cell at a depth of  $z=h$ , the value of  $\beta$  can be calculated.

In comparison to the overburden pressure, an average vertical stress for a tall oedometer, is a more accurate representation of the stress imposed on the sample. The average vertical stress imposed on a sample of height  $h$ , can then be calculated according to the following:

$$\bar{\sigma}_v = \frac{1}{h} \int_0^h qe^{-4\beta (z/D)} dz = \frac{q \times (e^{-4\beta h/D} - 1)}{-4\beta h / D} \quad (2)$$

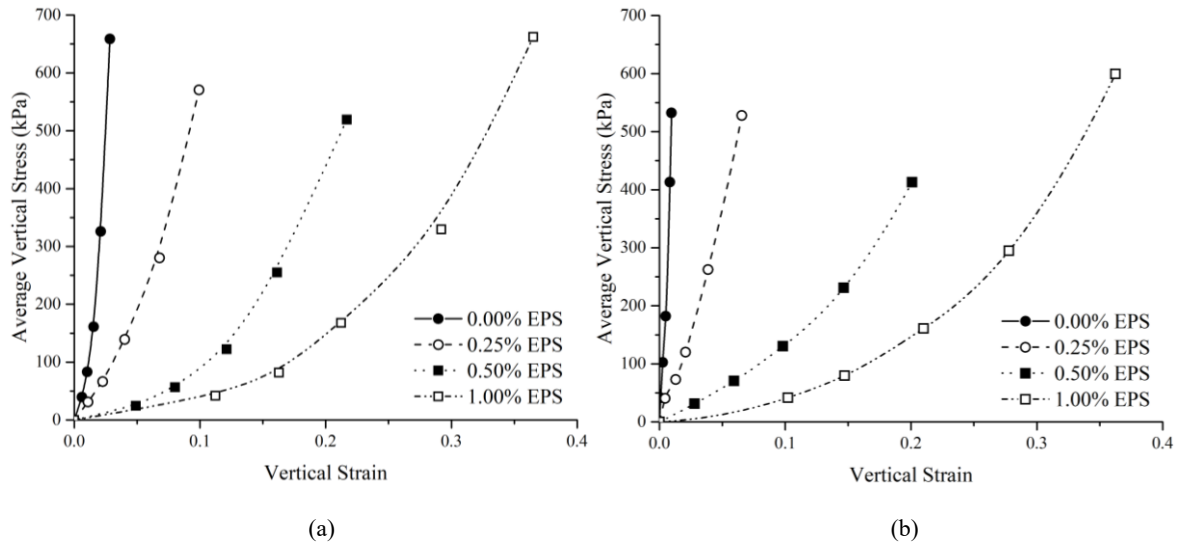


Fig. 9. One-dimensional stress-strain curves for the sand-EPS mixtures at: a)  $D_r=40\%$ ; b)  $D_r=80\%$

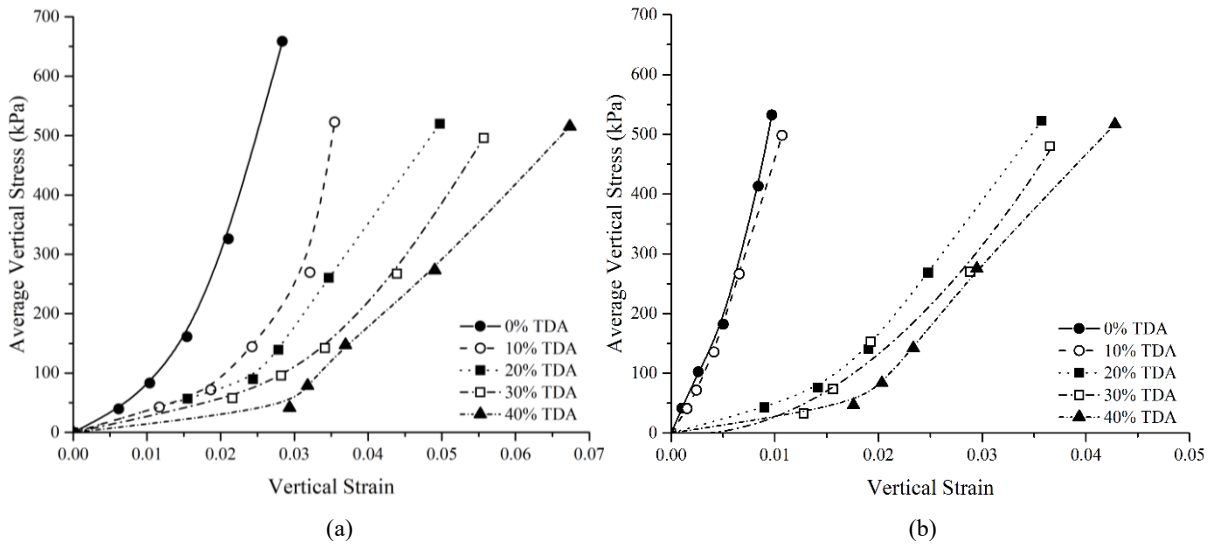


Fig. 10. One-dimensional stress-strain curves for the sand-TDA mixtures at: a)  $D_r=40\%$ ; b)  $D_r=80\%$

Fig. 9 presents the stress-strain curves for the sand-EPS beads mixtures at the relative densities of 40 and 80% respectively at varying levels of average vertical pressure while Fig. 10 presents similar data for the sand-TDA mixtures. As seen from the figures, for a given EPS or TDA content, with the increase in vertical pressure, the one-dimensional vertical strain increases. Moreover, for a given overburden pressure, with the increase in EPS and TDA content, vertical strain increases. This increase is more prominent for the mixtures containing EPS in comparison to the mixtures containing TDA. Moreover, the vertical strains measured for the samples prepared at the higher relative density experience lower strains for both mixtures.

#### 4-1- Sand-EPS beads one-dimensional stress-strain EPR models

Based on the results presented in Fig. 9, EPR models

were developed in order to predict the one-dimensional stress-strain behavior of the sand-EPS mixtures. Equation (3) presents the EPR model obtained for the sand-EPS mixtures. The model predicts the one-dimensional vertical strain based on the three input parameters of average vertical pressure, relative density and the EPS content of the samples.

$$\begin{aligned} \varepsilon_a = & -3.0991 \times 10^{-14} \times \delta^{-0.5} \times \sigma_v^{0.5} \times Dr^{0.5} + 1 \\ & -5.7781 \times 10^{-9} \times \delta^{0.5} \times \sigma_v^2 \times Dr + 0.029009 \\ & -0.00010376 \times \delta^2 \times \sigma_v \times Dr^{0.5} - 0.0011651 \\ & 0.0032003 \times \sigma_v^{0.5} - 0.00224 \times \delta^{0.5} \times \sigma_v^{0.5} \times Dr^{0.5} \\ & \times \delta \times \sigma_v^{0.5} + 1.6436 \times 10^{-5} \times \delta \times \sigma_v \times Dr \end{aligned} \quad (3)$$

where  $\varepsilon_a$  is the vertical strain,  $D_r$  is the relative density

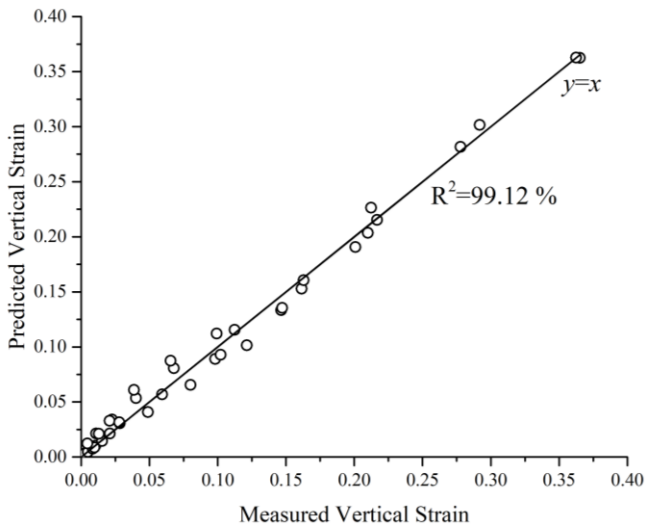


Fig. 11. Predicted versus measured vertical strain for the proposed sand-EPS model

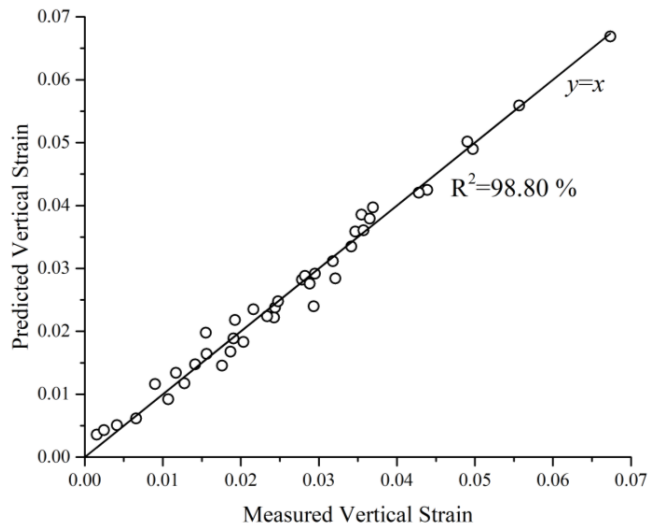


Fig. 12. Predicted versus measured vertical strain for the proposed sand-TDA model

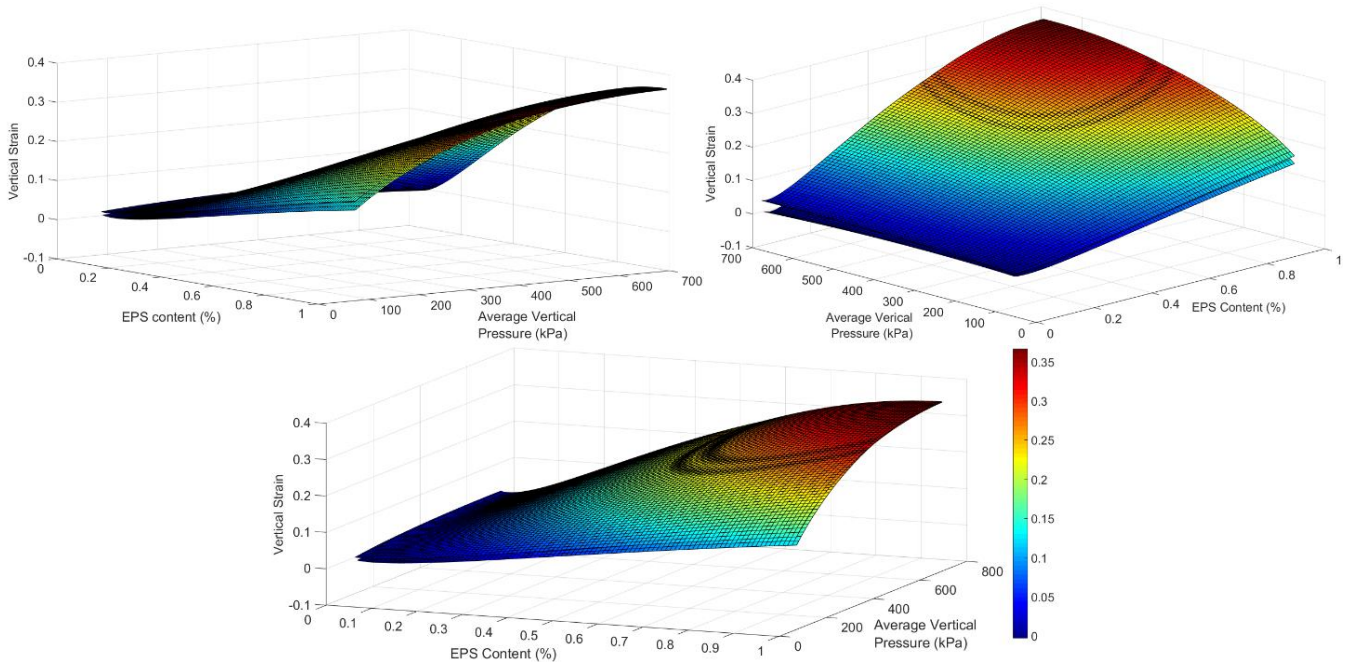


Fig. 13. Graphical multivariate parametric study of the sand-EPS model from three different angles

(by percent),  $\sigma_v$  is the average vertical stress and  $\delta$  is the EPS weight content (by percent).

Fig. 11 shows the predicted versus measured vertical strain values for the sand-EPS models. It can be seen that the predicted=measured line can be regressed to the data with a value of  $R^2$  equal to 99.12 %. Therefore, it can be inferred that the proposed EPR relationship has a high accuracy in predicting the one-dimensional stress-strain behavior of such mixtures.

#### 4-2- Sand-TDA stress-strain one-dimensional EPR models

In order to predict and evaluate the one-dimensional stress-strain behavior of sand-TDA mixtures, EPR models

were developed based on the data presented in Fig. 10. Equation (4) presents the EPR model developed for the sand-TDA mixtures which predicts the vertical strain based on the input parameters of average vertical pressure, TDA content and relative density of the mixture.

$$\begin{aligned} \epsilon_a = & -0.0028188 \times \eta^{-2} \times \sigma_v^{0.5} \times Dr + 0.099687 \times \eta^{-1} \times \sigma_v^{0.5} \times Dr^{-0.5} \\ & + 0.00019749 \times \sigma_v^{0.5} \times Dr^{0.5} - 9.9327 \times 10^{-5} \times \eta^{0.5} \times \sigma_v \times Dr^{-0.5} \\ & + 1.1454 \times 10^{-8} \times \eta^{0.5} \times \sigma_v^2 + 0.11148 \times \eta \times \sigma_v^{0.5} \times Dr^{-2} - 0.00014369 \end{aligned} \quad (4)$$

where  $\eta$  is the TDA volume content (by percent).

Fig. 12 presents the predicted versus measured vertical

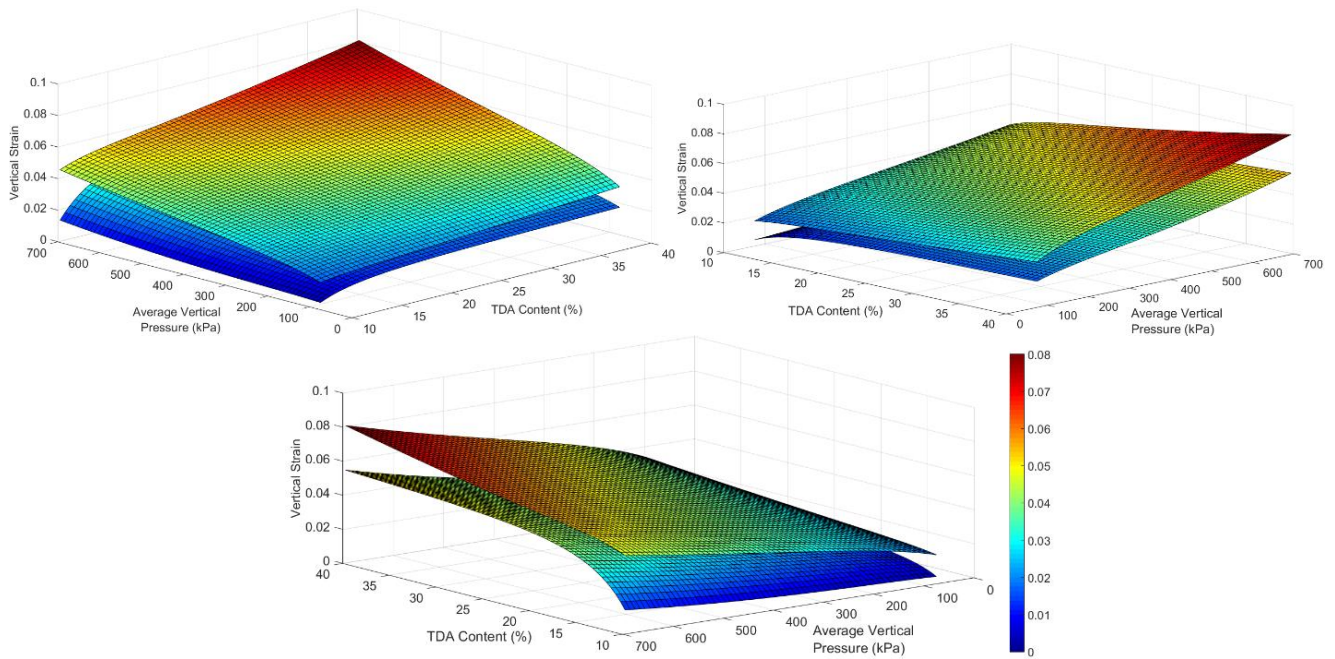


Fig. 14. Graphical multivariate parametric study of the sand-TDA model from three different angles

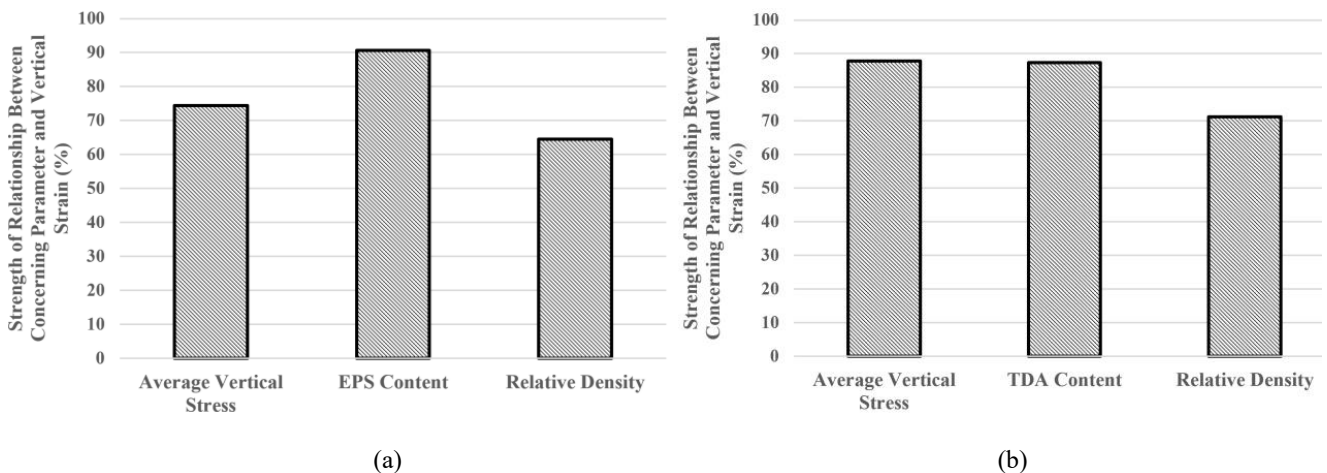


Fig. 15. The dependency of vertical strain on each effective parameter for the: a) sand-EPs model, and b) sand-TDA model

strain values for the sand-TDA models. As inferred from the  $R^2$  value, (98.80%), the proposed model is highly accurate.

#### 4-3- Multivariate parametric analysis of the sand-EPs EPR model

As previously mentioned, the vertical strain for the sand-EPs mixtures is predicted by the EPR model as a function of EPS content, average vertical stress and relative density. In this section, parametric analysis is carried out graphically, in order to investigate the combined effect of the input parameters on the predicted sand-EPs strain. Fig. 13 is created by using the EPR model as defined by equation (3), to predict the vertical strain for the input parameters in the range adopted in the experimental program and graphing the predictions against

the input parameters. The results are presented from three different angles. In these figures the top curve corresponds to  $Dr=40\%$  while the bottom curve pertains to  $Dr=80\%$ .

As seen from Fig. 13, an increase in the percentage of EPS generally increases the one-dimensional strain. The rate of increase is much higher for higher levels of vertical pressure. The effect of vertical pressure on the vertical strain is negligible at low EPS content, but as more EPS is added, the effect of overburden pressure is highlighted. As seen from Fig. 13, the threshold of this change in the prominence of the effect of overburden pressure occurs at an EPS content of 0.2 to 0.3 %. The effect of relative density appears to not be as prominent since both curves are very similar in shape and are also very close to one another. It appears that the EPS phase



determines the vertical strain, particularly at higher contents and therefore, the sand phase and its relative density do not play as significant a role.

4-4- Multivariate parametric analysis of the sand-TDA EPR model

Similarly, parametric analysis is carried out graphically for the sand-TDA model. Fig. 14 is created by graphing the predictions of the EPR model for sand-TDA mixtures as defined by equation (4), against the input parameters. The results are presented from three different angles. Once again, the top curve corresponds to  $Dr=40\%$  while the bottom curve pertains to  $Dr=80\%$ .

As seen from Fig. 14, the effect of TDA is more prominent at higher levels of vertical pressure, particularly at a lower relative density. Therefore, the lowest strain occurs at the highest relative density, lowest vertical pressure and lowest TDA content. In addition, a more significant effect of the vertical pressure is observed at the lower level of relative density, where the rate of the increase in vertical strain with vertical pressure is higher. This rate is also higher at higher TDA content.

4-5- Sensitivity analysis of the models

Sensitivity analysis according to the Cosine Amplitude Method (CAM) has been carried out on the developed EPR models in order to determine the effect of the input parameters and to evaluate the dependency of the target function on the input parameters. To this end, first all the predicted data are turned into dimensionless values in a range of 0 to 1, according to equation (5) [27].

$$\text{Dimensionless Value} = \frac{\text{Value} - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}} \quad (5)$$

Next, each of the input parameters is presented as an element in the array  $X$ , as presented in equation (6).

$$X = \{x_1, x_2, x_3, \dots, x_n\} \quad (6)$$

where each element is a vector of length  $m$  as presented in equation (7).

$$x_i = \{x_{i1}, x_{i2}, x_{i3}, \dots, x_{im}\} \quad (7)$$

Next the relationship between  $x_i$  and  $x_j$  is determined according to equation (8).

$$r_{ij} = \frac{\sum_{m=1}^k x_{i_m} x_{j_m}}{\sqrt{\sum_{m=1}^k x_{i_m}^2 \sum_{m=1}^k x_{j_m}^2}} \quad (8)$$

This method determines the most and least effective

parameters on the vertical strain. Fig. 15 presents the dependency of the vertical strain on the input parameters for the two models.

According to Fig. 15, for the sand-EPS model, the EPS content is the most significant and effective parameter among the input parameters, while relative density was the least influential parameter on the vertical strain. For the sand-TDA model, both TDA content and vertical pressure have the most effect on the outputs. Similar to the sand-EPS model, vertical strain has the least dependency on relative density.

5. CONCLUSION

In this study, one-dimensional oedometer tests were carried out on different mixtures of sand-EPS beads and sand-TDA with varying contents of EPS and TDA. The increase in EPS or TDA content continuously increases the vertical compression of the samples in the studied range. Therefore, for practical purposes, the EPS or TDA content should be selected depending on the purpose of use for the mixtures, since they can provide different benefits including reduction of vertical and lateral stresses, improvement in drainage conditions and higher damping properties. The potential increased settlements that occur due to the lower stiffness of materials is an important factor in the ultimate decision and therefore, the optimum content of such materials would correspond to a content that provides the desired benefits while not lowering strength or increasing settlement to unsatisfactory values. To provide simple equations that can be beneficial in choosing the optimum content for design purposes, results of one-dimensional oedometer tests on mixtures of sand-EPS beads and sand-TDA were used to develop EPR models that can predict the vertical strain of the mixtures for different levels of overburden pressure, relative density and unconventional material content.  $R^2$  values for the sand-EPS mixture model and the sand-TDA mixture model were determined to be 99.12% and 98.80%, respectively showing reasonable accuracy. Results of multivariate parametric studies carried out on the sand-EPS model showed that with the increase in EPS content, vertical strain increased. In addition, the rate of the increase in vertical strain with vertical pressure increased with the increase in EPS content. In addition, based on the results of multivariate parametric analysis conducted on the sand-TDA mixture, increase in relative density intensifies the effect of vertical pressure where the rate of the increase in vertical strain increases with the increase in vertical pressure. This rate is also higher at higher TDA contents. In addition, increasing the TDA content increases the rate of increase in vertical strain with vertical pressure. Results of the parametric studies showed that relative density had a more significant effect on the settlement of sand-TDA mixtures in comparison to sand-EPS. Results of sensitivity analyses on the sand-EPS model showed that the EPS content and relative density were the most and the least influential parameters on the settlement respectively. Results of sensitivity analysis on the sand-TDA model showed that despite the fact that both TDA content and vertical pressure are highly influential on the vertical strain of the mixtures. On the other hand, relative density had

the least significant effect on vertical strain.

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