Constitutive modeling of a municipal solid waste considering the effects of creep and temperature using composite theory

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Abstract:

In this paper, a constitutive model for the stress-strain response of municipal solid waste (MSW) is presented, considering the effects of temperature and aging. Our goal is to provide a model for predicting the behavior of these materials. The models used to predict the behavior of waste have used the theory of soils, and in this research, a composite based model has been developed. A Cylindrical sample is modeled and loaded under triaxial loading conditions as observed in the experimental specimens. A fresh MSW, as our sample was investigated with specific composition. The constant of the relation between stress-strain was calculated using optimization technique. The obtained results are compared with previous models' experimental data and results to verify the proposed model. At the lower strains, a good agreement can be reported between the numerical and experimental results. The root mean square percentage of the relative error between the present model and the model of other researchers has shown acceptable results. It is also revealed that, as the temperature of the MSW increases, the stress on the waste is increased.

Keywords: Constitutive model; Municipal solid waste; Finite element method; Temperature; Creep.

1. Introduction

Landslides have caused significant problems in landfills., including irreversible damages to adjacent structures, severe environmental pollution, demolition of urban infrastructures, and most importantly, human casualties [1-5]. It is important to provide a reliable behavioral model in various fields of science, mechanical [6, 7], civil [8-10], biological [11-13], and other applications. In this regard, it is required to develop an appropriate constitutive model to predict the behavior of Municipal Solid Waste (MSW) materials subjected to a different type of loading and various conditions [14-21]. The main application of this research is to predict the behavior of wastes with different properties and over time and at different temperatures. By using the behavioral model presented in this research, it is possible to predict unexpected changes in landfills before the occurrence of unfortunate events. Researchers showed that the composition of the MSW can greatly impacts its behavior [22-25]. Researches on the waste behavioral model consider waste as a soil that has a combination of plastic materials and are not considered as a single material [14, 26-30]. Due to the chemical interactions inside the waste and the biological and creep changes, the temperature of waste has many changes during time. Machado et al. concluded that the waste elasticity modulus declines over time [31]. The researchers found that the age of waste and the interactions created over time have a significant effect on waste behavior. Machado et al. were able to validate their proposed model with their experimental results using a correction factor due to the deformation of the waste ingredients and the pore water pressure created in the waste sample [32]. They also compared the results of the behavioral model and empirical findings of waste with 25% fiber content at confining pressure of 50 and 300 kPa. They found that in confining stresses more significant than 100 kPa, the discrepancy of the proposed model and experimental results were high. In Machado et al. study, the effect of temperature on waste has not been investigated, and the predicting behavioral model involved soil material with the composition of plastic materials. Researchers evaluated the waste bahavior using Cam-Clay (MCC) model [33, 34]. They studied 1.5-year, fresh and artificial waste. In the same line of thought with the research done by Marques et al., they considered that the overall deformation to be a result of instantaneous strains creep, biological strains, and strains occurred because of consolidation [35]. In the research, the waste material is not considered as a composite and the effect of temperature and time on the waste is not studied. Krase et al. also used the theory of fibers and paste to propose their behavioral model [36, 37]. Later, Zhange et al. examined the behavioral model of MSW by dividing the waste into different phases [38]. They considered the latex waste as the MCC soil and developed a 1-D model. Moreover, Feng et al. analyzed the MSW behavior based on Babu's behavior model and developed their model based on biological behavior [39]. They speculated a new factor for this effects and compared their behavior model. The soil behavior model in their study was the cam-clay model. Shariatmadari et al. analyzed the mechanical properties of MSW using tri-axial tests and investigated the effect of pore water pressure [27, 40]. They found that the changes in the effective stress and total stress, and pore water pressure depend on other parameters and do not follow the laws of soil mechanics. Also, the MSW age has a significant effect on stress-strain behavior. Gharabaghi et al. proposed a diagram showing the result of tests on MSW materials using various published sources [17]. These researchers stated that not only the Mohr-Coulomb criterion shows considerable natural variability for the strength parameters of the non-homogeneous MSW material, but also the proposed Mohr-Coulomb theory (borrowed from soil mechanics) lacks the ability to properly simulate the failure mechanism for MSWs that have undergone different elasto-plastic deformations and consolidation before fracture. In 2017, Hubert et al. examined temperature changes in a landfill [41]. They showed that at greater depths and in the lower layers, the temperature increases. A behavioral model for waste is not predicted in work, and merely, the landfill settlement changes due to time are obtained. Faitli et al. also examined changes in the temperature of waste in a landfill [2]. The researchers measured the effect of temperature on the waste components using a 1.5 m^3 box and dumping it. It was found that the temperature of the waste has changed a lot over time. In some other researches, the dynamic behavior of waste has been examined, and in these studies, waste is considered as soil [42]. Modeling the dynamics of waste using the behavioral model of soils as a homogeneous material has caused errors in predicting the dynamic behavior of landfills in their research.

In the some In the behavioral models of previous research, waste is not considered as a composite material. The proposed models are compared with the researcher's experimental results too. To the best of the authors' knowledge, the waste temperature has not been considered an influential parameter in waste behavior in previous studies. The main gap of the previous researches is the lack of providing a comprehensive behavioral model that has the ability to predict the behavior of waste in different conditions. This means that in none of the previous studies, the presented behavioral model has not been able to accurately predict the experiments conducted by other researchers. The main goal of this research is to provide a behavioral model based on waste physics that can cover the gaps in previous research.

In this paper, a constitutive model is presented for the stress-strain of MSW, speculating the composite materials approach for the first time. The MSW sample is simulated by the finite element method (FEM), and the waste sample is considered a cylindrical specimen subjected to triaxial loading. The primary purpose of this study is to foresee the behavior of fresh MSW and evaluate the impacts of temperature and aging on the MSW behavior. The waste sample is considered a composite and homogeneous material, and a composite based theory is developed for predicting the waste behavior. In Section 2, the research and modeling methods would be discussed. The composite material theory of fresh waste at constant temperature is investigated, and then the temperature and time changes in the waste sample are demonstrated. In Section 3, the results obtained from the waste behavior and the relationships presented to predict waste in various all-round stresses better are obtained. To validate the results in this section, the obtained results are compared with the experimental data. Also, in the last part of the paper, the conclusions and results are summarized.

2. Methodology

This analysis consists of two parts. The fresh MSW sample is modeled by the FEM and loaded at a constant temperature and time. In this section, using the composite materials theory, the primary model is established for the sample and then using the experimental data, the behavior relationship for the material is predicted. In the second part of this analysis, the waste samples of different ages and different temperatures are simulated. The effect of these two parameters on the MSW behavior is investigated. In this study, we have used a macroscopic viewpoint of a composite material. We assume that our composite material is hemogen and its behavior can be predicted using composite-based constitutive models of materials. It should be noted that the used composite model was not modeled as two or more phases separately.

2.1. Stress-strain response (constant time and temperature)

To predict the strain- stress relation of MSW, the FEM method is usually used. As shown in Figure 1, for predicting these material behaviors, a 20 cm diameter cylindrical sample and 40 cm height with fixed boundary condition at lower surface was modeled according to the the tri-axial tests. the cylindrical model used in this article is a laboratory simulation of landfills and is used to obtain more accurate values of stress and strain in waste .The total force applied to the cylindrical cross-sectional area divided by the total cross-sectional area shows the confinig stress. Additional force applied to the upper surface and includes additional stress.

In the simulations, the Voce material model was employed to define the elastoplastic behavior of the material. This theory, used by Voce et al., describes the behavior of composite materials [43]. The strain hardening law interrelating stress σ and plastic strain ε proposed by Voce is expressed as:

$$\sigma = \sigma_s - (\sigma_s - \sigma_1) + \exp\left[-\frac{\varepsilon - \varepsilon_1}{\varepsilon_c} \right] \tag{1}$$

where σ_s is the saturation stress, σ_1 and ε_1 are the total stress and plastic strain at the onset of plastic deformation, and ε_c is a constant. For initial plastic strain $\varepsilon_1 = 0$.

The implicit FEM based on the unstructured 3D t10 tetrahedral meshes was used to obtain the strain caused by different stresses on the waste sample. As shown in Fig. 1, the mesh sizes are reduced to study the independence of element size on the results. We used Ansys structural 19 to conduct FEM simulation. To achieve this goal, the waste strain is calculated at a total stress of 100 kPa and an additional stress of 150 kPa. Table 1 shows the results of this sensitivity analysis.

In Table 1, the relative error is the relative error between the calculated strains, according to the previous one obtained from simulation with coarser mesh edge size. Based on less than 1% error, the maximum size of the element sides is considered 0.5 mm in the numerical simulations.

The surface A in Figure 1 is exposed to the $\sigma_1 = \sigma_d + \sigma_3$. Also, the σ_3 applied on the surrounding surface during the time. These confining stress, are the values used in the laboratory results and these numbers have been used to verify the simulation results with the laboratory results. The boundary condition of the surface F is the fixed boundary condition.

The σ_d and σ_3 are varying with time as shown in Figure 2 a and b. The σ_3 is defined as the maximum of the confining stress which applied on the model at time t_1. The value of the t_1 and σ_3 are listed in Table 2 in three cases.

To predict the stress-strain behavior of the waste, by considering Equation 1, as the basic relation, the simulation results are compared with the experimental data. The modeling is based on the tri-axial loading conditions, and Machado et al. experiment is used to better predict the strain-stress response [26, 32]. In this study, the fiber content in the experimental sample is 12.5% in weight. The MSW temperature is also considered constant at $30\,^{\circ}C$. γ_s is $19\,kN/m^3$, the specific gravity of waste in the experiment, and φ is 19 Degree, the angle of internal friction of waste. Using the optimization methods, the difference between the experimental results and the simulation was minimized. By minimizing the average square of the difference in the results, the coefficients of the strain stress relationship of the MSW is predicted. The algorithm of prediction of the coefficients is shown in Figure 3.

2.2. Stress-strain response (variable time and temperature)

In this section, the effect of temperature and time on the waste behavior is investigated. The waste sample simulation is similar to the previous section, and the analysis is repeated for different ages and temperatures. The results of the research of Hubert et al. is used to validate the obtained results [41]. In their study, the landfill deformations were measured over time, and the landfill temperature was determined in different layers. In the present study, based on the results reported by Hubert et al. The values of deformation in each layer of the landfill were obtained versus time and temperature. Then, the stress in each layer of the landfill was measured. Due to the significant changes in temperature of MSW, a temperature range of 30 $^{\circ}C$ to $80\,^{\circ}C$ was considered. These values are for better simulation of landfills and better prediction of waste behavior. Also, considering the significant behavioral changes in the fresh and perennial MSW samples, various ages were considered for the MSW (e.g., 1 and 6 months, and 1, 2, and 5 years). According to the obtained values, the stress-strain response for the MSW was predicted, and the equation constants were determined using the non-linear least-squares method. The strain-stress response of the MSW is predicted by minimizing the average square error between the experimental results and the desire relation between the waste strain, time, temperature, specific weight, and stress. To compare the results and to examine the effects of temperature and time variations on the MSW behavior, the MSW was first investigated at a fixed time and temperature. Next, at a constant temperature, the behavior of MSW was examined at different ages.

3. Results and Discussion

As mentioned in the previous section, the behavior of waste at a constant temperature and time was investigated using composite-based theory and numerical simulation of waste. In the second part of the analysis, the behavior of waste at different temperatures and ages was examined, and the results of these two stages are presented below. As mentioned, Voce theory has been used as a theory of composite materials [43, 44]. In this paper, results from the tri-axial test of shariatmadari et al. have been utilized in the constitutive model [26, 40]. The mechanical behavior of MSW was evaluated using a tri-axial test. This apparatus includes a loading frame with $300\,kN$ and software capacity, which enables to perform strain-stress controlled tri-axial tests. The composition of the sample waste is shown in the Table 3.

To obtain the waste relation between strain stress, the experimental results are compared by composite method, and its constant parameters of the equation are obtained using optimization. The relation obtained for the dimensionless stress-strain is in the form of Equation 2. Then, the simulation is performed for fresh waste in constant temperature.

$$\bar{q} = a_1 + b_1(1 - e^{-\varepsilon/c}) + b_2(1 - e^{-\varepsilon/c}) \tag{2}$$

where, $\bar{q}$ as the dimensionless … and other constant parameters are defined as:

$$\begin{aligned}
&\bar{q} = \frac{q}{\sigma_{3-ref}} \\
&\sigma_{3-ref} = 100\,kPa \\
&\bar{\sigma}_3 = \frac{\sigma_3}{\sigma_{3-ref}} \\
&a_1 = -0.02 - 0.07\bar{\sigma}_3 - 0.20\bar{\sigma}_3^{\,2} \\
&b_1 = 0.002 \\
&b_2 = -9.17\bar{\sigma}_3 \\
&c = -0.08
\end{aligned} \tag{3}$$

In the Equation 3, ε and σ_3 represent the waste total strain and confining stress, respectively. The experimental results are compared with the results of this equation in Figure 4. In this comparison, the experimental results for different stress levels were investigated. Experimental results of Machado et al. were used to compare the results.

As shown in Figure 4, there is a relatively good agreement between the experimental results and the proposed model. The error between the experimental data and the obtained results is 4.235%, 17.256%, and 3.552% at the confining stress of 110 *kPa*, 240 *kPa*, and 308 *kPa*. The errors between the experimental and numerical results include experimental errors, regardless of some specific numerical and computational results. As shown in figure 4, up to a strain of 5%, there is a passeble consistency in the results. Moreover, the lower σ_3 in the waste leads to more consistensy. One of its reasons is the less stress effect on the waste chemical interaction. Also, the waste biological variations is more less and the lower stress levels.

Due to internal interactions within the MSW, the internal temperature of MSW is one of the significant parameters affecting its behavior. Therefore, the behavior of MSW is investigated under different temperatures at different ages. In this study, the stress-strain values are obtained at any point in the landfill, and according to the obtained results, the total stress and confining stress are calculated at each point of the landfill. Equation 4 is developed for MSW as follows:

$$\varepsilon = 1.2 + 1.1(\frac{\sigma_d + \sigma_3}{\gamma}) - 0.125T + 24t + 0.004T(\frac{\sigma_d + \sigma_3}{\gamma}) - 0.8t(\frac{\sigma_d + \sigma_3}{\gamma}) + 0.074Tt - 0.007tT(\frac{\sigma_d + \sigma_3}{\gamma}) \quad (4)$$

In this equation, $\varepsilon\, mm/m$, stands for strain, $\gamma\, kPa$ represents specific weight, *t* represents the aging, $T\, °C$ denotes temperature, and $\sigma_d\, , \sigma_3\, kPa$ represents stress.

To validate the applied method, the results are compared with the results of the tri-axial specimen of experiments in other studies[32]. The experimental data employed in the verification of Figure 5 is corresponding to fresh MSW at 30 $°C$.

The mean square error of the total stresses calculated by the experiments and equation 4, are 8.25% and 15.65% for the confining stresses equal to 100 *kPa* and 200 *kPa*. The consictency between of the results indicates the validation of our developed equation. The main reasons of these errors may be the computationally or the effects of the other influential factors in the strain stress response, which have not been considered; experimental errors may also influence this difference. Overall, since waste is composed of different materials, biological and chemical changes in the MSW composition are one of the parameters affecting the behavior of MSW, causing substantial errors in the results. Many biological and chemical changes occur over time that indicate the effect of time on the stress-strain behavior of the MSW.

To validate the applied method, the results are compared with the results of the tri-axial specimen of experiments in other studies (Babu et al, 2015). The experimental data employed in the verification of Figure 6 is corresponding to fresh mechanicaliy biologically treated (MBT) without fiber.

As shown in Figure 6, there is a relatively good agreement between the experimental MBT results and the proposed model. The error between the experimental data and the obtained results is 17.13%, 9.67%, and 17.89% at the confining stress of 50 *kPa*, 100 *kPa*, and 150 *kPa*. Errors between the experimental and numerical results include experimental errors, regardless of some specific numerical and computational results. A simplified model is also presented in this paper that is more consistent with the experimental results of fiber-free waste.

The results are compared with the another results of the tri-axial specimen of experiments in other studies at the confining stress of 100 *kPa* (Athma Ram et al, 2013). The mean square error of the total stresses is 29/48%. As shown in the figure 7, near to a strain of 25%, there was more good agreement between the results that indicate the MBT behavior. Strains greater than 30% have been considered large strains in previous research, and the model presented in this paper is designed for smaller strains.

Conclusion

Predicting waste behavior is very complex and providing a simplified model in landfill design is very important. Numerical analysis has become increasingly important in predicting the behavior of MSW landfills, and a constitutive model for MSW is fundamentally required. Municipal solid waste is composed of various materials, including plastics and pulps, and the these material interactions affects behaviors. The research conducted on waste model considers waste as a soil, which is very different from waste materials. Using composite based theory, the waste deformation has been predicted. In this paper, constitutive modeling was carried out using the composite materials approach. The model was verified through comparisons with the triaxial test results. Further parametric studies were also conducted, and the model's performance at different ages was analyzed.

Our goal in this paper is to provide a model for predicting the behavior of these materials and their use in geotechnical engineering. In this model, the waste is developed by confining stress. It was found that the effect of confining stress is very high and determines the waste behavior. The results showed that in the lower strain, there is good agreement between the numerical and experimental results. At higher confining stresses, hardening appears in the model. The age of the MSW has a significant influence on the stress-strain behavior of landfills; so, it must be considered in their stability. Moreover, the MSW temperature varies in different layers of a landfill with different stresses; so, it should also be taken into account. According to the results, assuming MSW as a composite material is reasonable and can be extended to future studies.

Declaration of conflicting interests

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Figure captions

Figure 1. a: The MSW sample modeling; Surfaces A and F are upper and lower surfaces of the waste sample exposed the deviator stress and fixed boundary conditions. b: The MSW sample modeling

Figure 2. The variations of the stresses on the model, a) the confining stress, and b) the deviator stress; the confining stress increases linearly with time until t_1, Then it takes a constant value. The deviator stress is applied on the model from time t_1 and varies linearly with time.

Figure 3. The algorithm for coefficients calculation of the constitutive equation

Figure 4. Comparison of the presented model result with the experimental data[32]

Figure 5. The stress vs the strain at the $\sigma_3 = 100, 200\ kPa$ [32]

Figure 6. The stress vs the strain at the $\sigma_3 = 50, 100\ and\ 200\ kPa$. (Babu et al, 2015).

Figure 7. The stress vs the strain at the $\sigma_3 = 50, 100\ and\ 200\ kPa$.. (Athma Ram et al, 2013).

Table captions

Table 1. Results of the mesh sensitivity analysis

Table 2. The time and maximum of the confining stress applied on the model in different cases

Table 3: The waste physical composition [40]

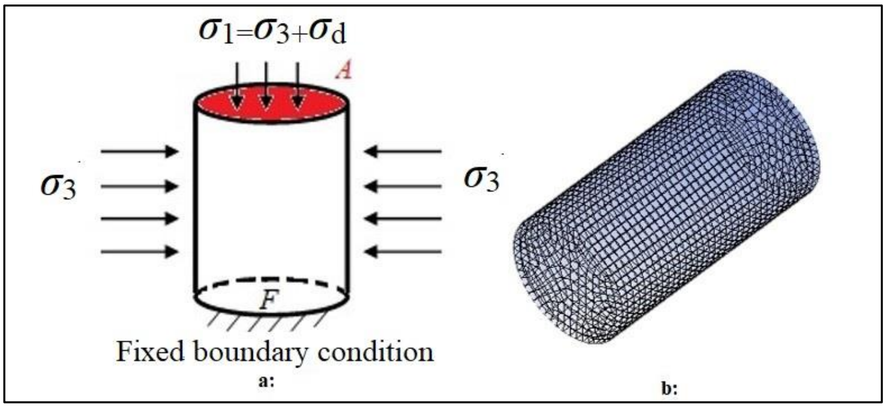
$\sigma_1=\sigma_3+\sigma_d$
A
σ_3
σ_3
F
Fixed boundary condition
a:
b:

Figure 1.

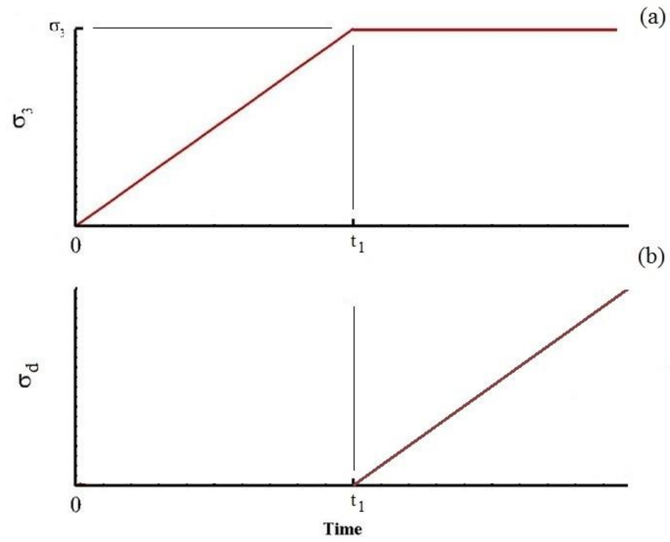

Figure 2.

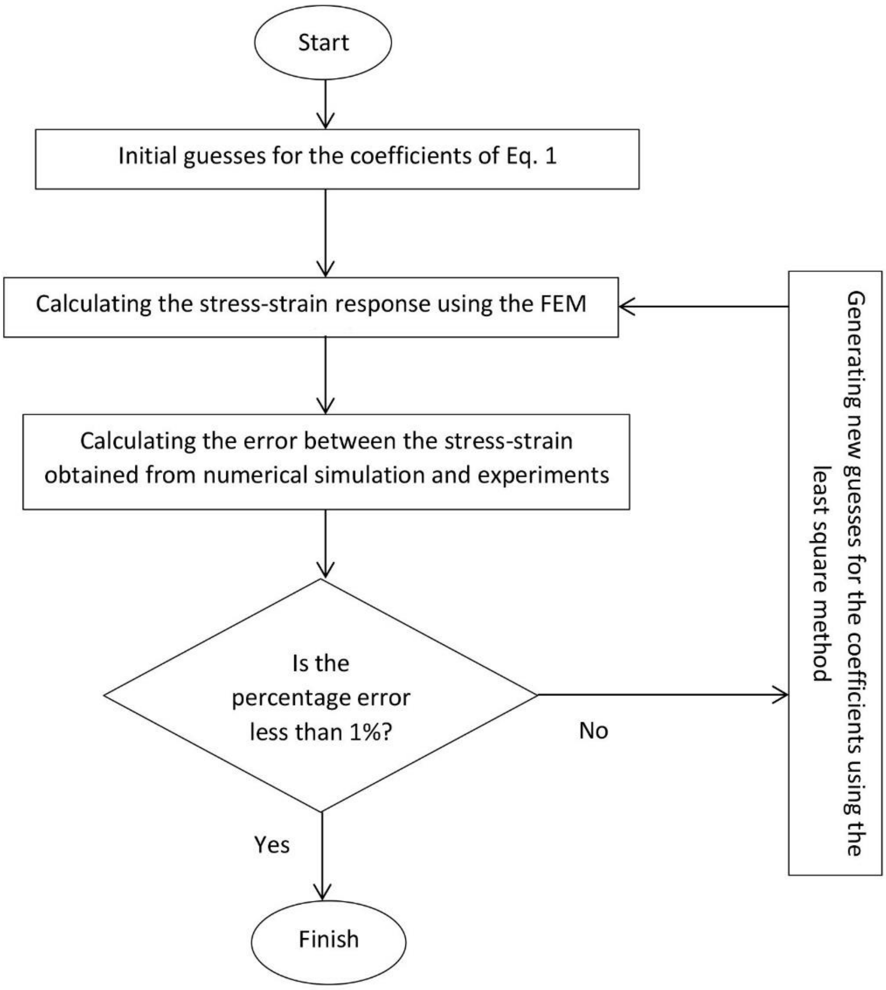
Start
Initial guesses for the coefficients of Eq. 1
Calculating the stress-strain response using the FEM
Calculating the error between the stress-strain obtained from numerical simulation and experiments
Is the percentage error less than 1%?
No
Yes
Finish
Generating new guesses for the coefficients using the least square method

Figure 3.

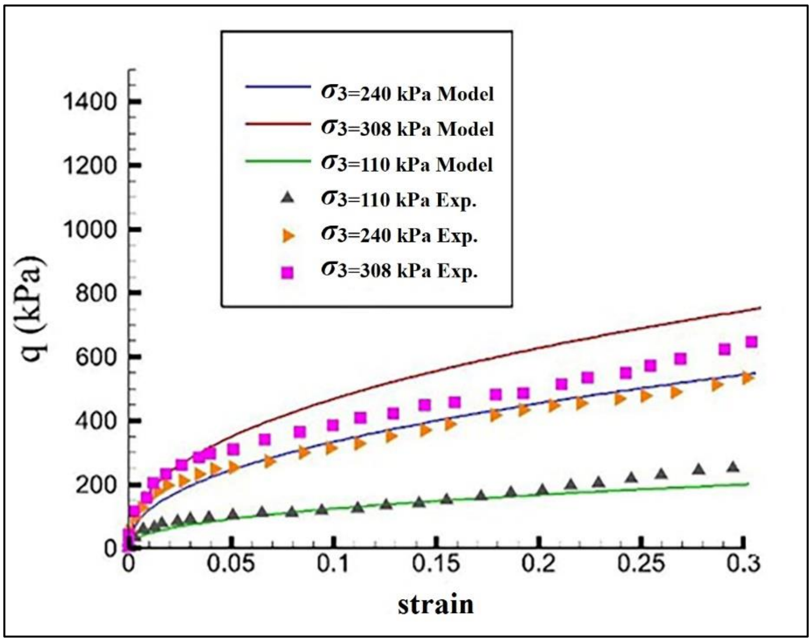
σ_3=240 kPa Model
σ_3=308 kPa Model
σ_3=110 kPa Model
σ_3=110 kPa Exp.
σ_3=240 kPa Exp.
σ_3=308 kPa Exp.
q (kPa)
1400
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
0.25
0.3
strain

Figure 4.

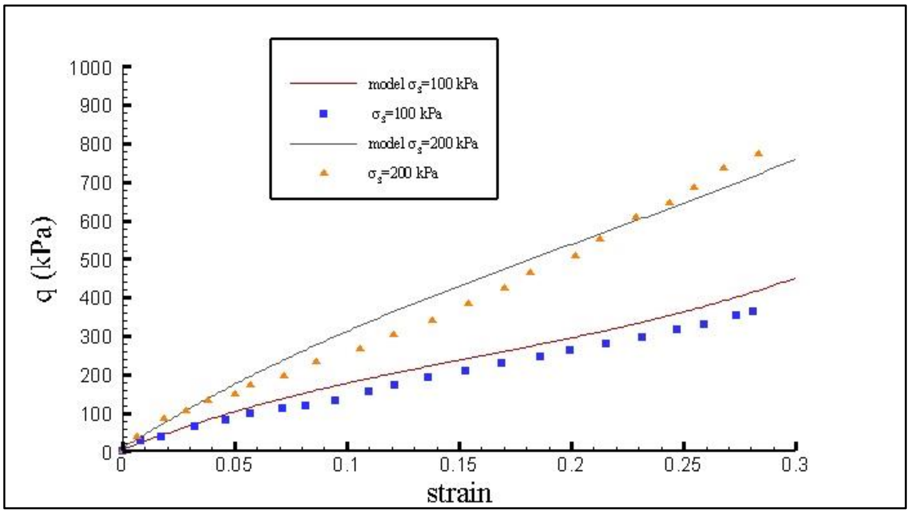
model σ_3=100 kPa
σ_3=100 kPa
model σ_3=200 kPa
σ_3=200 kPa
q (kPa)
1000
900
800
700
600
500
400
300
200
100
0
0
0.05
0.1
0.15
0.2
0.25
0.3
strain

Figure 5.

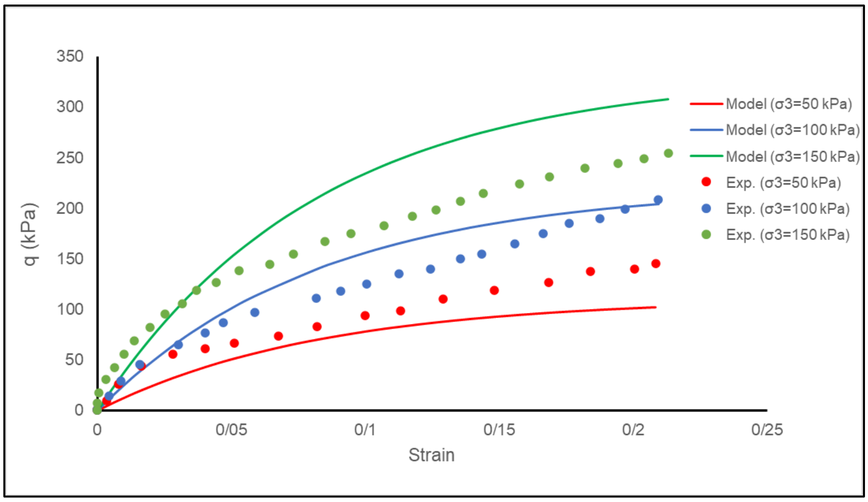
350
300
250
200
150
100
50
0
q (kPa)
0
0/05
0/1
0/15
0/2
0/25
Strain
Model (σ3=50 kPa)
Model (σ3=100 kPa)
Model (σ3=150 kPa)
Exp. (σ3=50 kPa)
Exp. (σ3=100 kPa)
Exp. (σ3=150 kPa)

Figure 6.

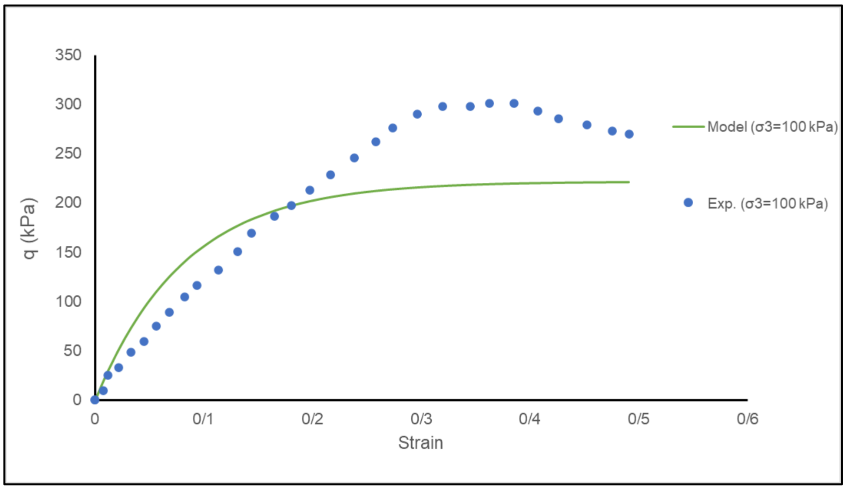
350
300
250
200
150
100
50
0
q (kPa)
0
0/1
0/2
0/3
0/4
0/5
0/6
Strain
Model (σ3=100 kPa)
Exp. (σ3=100 kPa)

Figure 7.

Table 1.

The Maximum size of mesh sides (mm)	Strain	Relative Error (%)
4	0.0095	-
2	0.0112	15.2
1	0.0120	6.7
0.5	0.0125	4.0
0.025	0.0124	0.8

Table 2.

	σ_3 (kPa)	t_1 (min)
Case 1	110	10
Case 2	240	10
Case 3	308	10

Table 3:

Component	Percentage – dry basis (%) New MSW - average
Textile	3.66
Rubber	0.38
Stone	11.47
Plastic	21.13
Glass	3.91
Metal	3.16
Wood	4.86
Paper	16.2
Waste and other non- easily separable materials.	35.23

Technical biography

Mohammadreza yousefi received his M.Sc. degree in Civil Engineering from Sharif University of Technology, Tehran, Iran, in 2012. He is currently a Ph.D. candidate in Iran University of Science and Technology. His research interests include developing behavior models and numerical methods.

Ali noorzad was born in Noor city in 1957. In 1985 he graduated from the University of Science and Technology in the field of Civil Engineering (road and construction) and obtained a master's degree in the same university. Then in 1992, using the scholarship of the Ministry of Research and obtaining a doctorate degree in the field of seismic geotechnical engineering, he went to Canada to teach science while also teaching in his specialized field in the same university.

MohammadJavad Mahmoodi is an associate professor of Civil Engineering at University of Shahid Beheshti, Tehran, Iran. He received his B.Sc. degree in Isfahan University of technology, Isfahan, Iran in 2002. He received his M.Sc. and Ph.D. degrees in Amirkabir University of Technology, Tehran, Iran.