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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF LOOSE SAND-SCRAP TIRES MIXTURE STIFFNESS

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ABSTRACT: Rubber-sand mixtures have many applications in geotechnical engineering. Considerable literature exists on the mechanical behavior of dense sand shredded rubber mixtures, but up to the author's knowledge, there are no such studies on sand-filled used whole car tires. The latter is ubiquitously used in developing countries to create cheap and quick backfill. The paper presents results from three-dimensional finite element models and plate load tests on layers of loose sand and whole tire mixtures in a steel tank. The finite elements program ANSYS is used to compare between a true 3D realization of the tire shape and a homogenized representation of the mixture. Numerical and laboratory results show how interpreted stiffness values depart from literature and physical laws of mixing soft and stiff components because the whole tire is used instead of shredded chips. The paper applies the equivalent thickness method to interpret the plate load test results and compute mixture stiffness for different thicknesses and shows good agreement with numerical back analysis. The application of plate load tests in the field and using the proposed approximate method is recommended to assess mixture stiffness rather than using assumed values from the literature. The paper presents an empirical correlation between the normalized layer thickness and the mixture stiffness for first-order predictions.

Keywords: numerical back analysis; plate load tests; rubber sand mixture; equivalent thickness; cheap reinforced backfill

1. INTRODUCTION

The applications of sand rubber mixtures are ubiquitous in geotechnical engineering. Initially, they have been used to induce settlement above on ground tunnels and underground conduits to invoke the imperfect ditch conditions [1–3]. Rubber has high elastic compressibility which can withstand considerable differential settlement. The compressibility of the rubber mobilizes soil movement above the conduit which reverses the Marston effect and causes positive arching action. The placement of such layers have to carefully consider the possible settlements at ground surface. Then, it has been used behind retaining walls, and in bridge approaches or road embankments [4–7]. Rubber soil mixture is considered a light and cheap backfill which is easily and quickly constructed. Later on, due to the high vibration - absorption capacity and temperature isolation potential of the rubber, the mixture has been used as earthquake-resistant reinforcement [8] and as absorption bearings underneath structures [9]. In other situations, the mixture is used to improve the strength of fill and reinforce pavements [10–13].

Most importantly, using tires as the rubber component is considered a safe way to consume non-biodegradable waste. The mixture could be a combination of natural soils and whole tires or fragments of tires which could be even in the form of fine powder. The effective use of waste tires as geomaterial has advanced greatly in the United States during the first half of the 1990s. In Egypt, the automobile industry generates about 20 million scrap tires every year, 88% of which is recycled. Half of the recycled tires in Egypt are burned for fuel which causes significant pollution; hence, using old tires would be a more environmentally conscious method of consumption (Galaa, pers. comm.).

A cheap and easy way to create the mixture in developing countries is to fill whole tires with sand or aggregates and lay them within the backfill or the embankment. The technology of shredding tires might not be readily available for small scale works, or the quality control process might not be easily applied to guarantee a uniform mix of natural soil and tire chips. In Egypt, in many situations backfill is hastily laid to support failing structures or inadequate side support systems. There will be limited time to compact the sand properly but whole tires can be used to reinforce the loose sand.

The whole tire soil mixture layer is often represented as a homogenous continuum in design procedures and numerical analyses. The equivalent stiffness of the layer can be assumed based on element tests on shredded rubber sand mixture with similar volume proportions [9]. Another approach is to study the embankment behavior if the embedded mixture layer is assigned a range of possible stiffness values [14]. A stiffness ranging from 10 MPa to 40 MPa is considered based on the thickness of the embedded mixture layer.

A design value for the stiffness and permeability of the mixture is easily controlled when shredded tires are used. There is sufficient literature on the engineering properties of these rubber soil mixtures [15, 16]. On the other hand, defining mechanical properties of whole tires in the mixture poses two considerable challenges:

- Assessing the stiffness of the mixture layer becomes impossible with element tests. The layer must be tested in the field or large scale model tests.
- The deformation mechanism of a whole tire filled with sand is completely different from thoroughly mixed rubber and soil. The tire is expected to confine the sand within an arching action around this unit prevents uniform distribution of the stress on top of the layer. An assumption to homogenize a whole soil-filled tire is not straightforward.

The paper presents simulations using the finite element software ANSYS to compare between realizing the actual shape of the tire and considering the mixture as a uniform layer with one value for stiffness. The paper presents the measured load settlement measurements from a physical model of several layers of tires embedded in loose sand filling a steel tank, using plate load tests; and the back analysis of stiffness using numerical analysis. Finally, the paper discusses different analytical and empirical methods to predict the mixture stiffness, and the use of plate load test results to assess this stiffness.

2. HOMOGENIZING SAND-TIRE MIXTURE

Three-dimensional simulations of a plate load test are simulated using the general-purpose finite element code ANSYS. A single layer of sand filled tires is embedded in a body of the same sand. The actual shape of the tire is manifested in the model as shown in Fig. 1 using SOLID185 elements which are 8-node brick elements with trilinear shape functions for displacements and 3 degrees of freedom at each node. The outer diameter of the tire is 400mm and inner diameter is 200mm. The thickness of the tire is 100mm and the wall thickness is 10mm. This constitutes 36.7% of the entire volume filled by the tire and the sand in it. The sand is similarly represented by 3-D solid elements (SOLID65) . The figure also shows the boundary conditions of the model due to symmetry where only the quarter-space of the sand and tires is modeled. The dimensions to the other boundaries of the model provide enough distance such that compression inside the model is not affected, and also the model can be recreated in a laboratory large scale test.

Fig. 2 shows the finite element mesh. The contact behavior between tires and sand is represented by surface-to-surface contact elements. These elements are assigned in pairs for 3D surfaces, where stiffer surfaces are considered the target (TARGE170) and more ductile surfaces are considered the contact (CONTA174). These elements are placed between the surfaces in contact such that the geometry and node ordering is preserved. The sand is represented in the model with the Mohr-Coulomb material model. This is the simplest constitutive model available and does not accurately capture the non-linear behavior of the sand. However, this model would not add to the complexity of the numerical analysis which is already burdened by several contact elements. Also, the goal of the analysis is to investigate single values of stiffness chosen for the mixture layer which can be used in hand calculations; hence, the Mohr-coulomb model is sufficient.

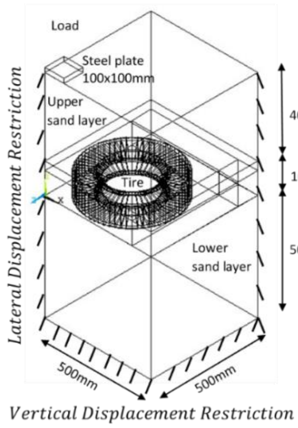

Fig.1 Schematic diagram and boundary conditions of the finite element model.

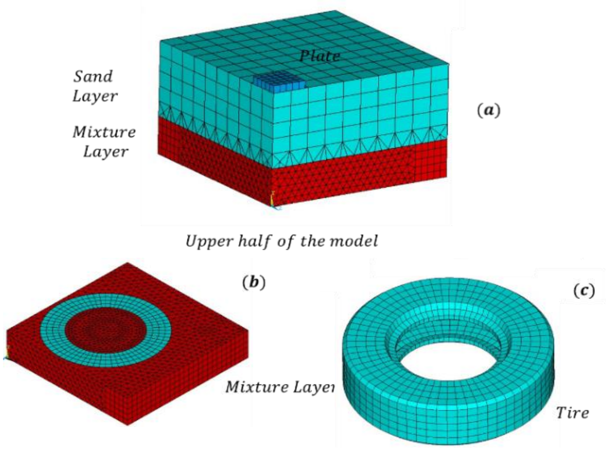

Fig.2 Finite element mesh: a) the combined components, b) the tire and the surrounding sand, c) the 3D shape of the tire.

Table 1 lists the Mohr-Coulomb parameters used to represent sand behavior. The rubber of the tire is represented by a linear elastic model where Young's Modulus, E is 50 MPa, and Poisson's ratio, ν is 0.45. Friction between sand and rubber is also modeled using the Coulomb relationship, where sliding occurs when the shear stress exceeds the sliding resistance with coefficient, μ is 0.4. The values representing the tire and the sand are chosen from typical values for used car tires in Egypt and loose sand often available in Giza, Egypt [17].

The representation of the mixture layer as a homogenized body with a single value of stiffness is also recreated in the numerical simulation considered as isotropic elastic material. This single stiffness value is determined by trial and error until the initial slope of the plate pressure settlement curve coincides with the observed in the detailed 3D analysis as shown in Fig. 3. The figure shows the variation of contact pressure beneath the plate and the plate settlement. The dimensions of the plate are 200 mm x 200 mm which are the typical dimensions of a loading plate in the market. This approach has been employed in using plate load tests to assess the stiffness of constructed stone columns by numerical back analysis [18]. The results of a full-scale plate load test performed in the sand-filled tank with an actual single layer of a whole tire – loose sand mixture is included in the figure. The curve from the detailed numerical analysis (Tire - sand) agrees well with the one observed in the experiment verifying the numerical model conditions. The curve from the numerical analysis considering the equivalent layer matches the other curves in its initial slope when the equivalent Young's modulus used is 15 MPa and Poisson's ratio is 0.35. This value is higher than the range observed in element tests [16].

Table 1. Mohr-Coulomb Parameters for the sand material used in the analysis.

Parameter	Value
Unit Weight, γ $(\mathbf{KN/m^3})$	18
Cohesion, c (KPa)	0
Friction Angle, $\boldsymbol{\phi^o}$	33
Dilation Angle, $\boldsymbol{\psi^o}$	0
Young's Modulus, E (MPa)	10
Poisson's Ratio	0.3

The plate load tests are conducted in the Soil Mechanics and Foundations Research Laboratory of the Faculty of Engineering in Beni-Suef University, as shown in Fig. 4a. The whole analog tire – the loose sand mixture is set up in a steel tank with dimensions of 1000 mm x 1000 mm x 1000 mm. The tank is filled with siliceous sand in two stages only to preserve a loose structure. Sand cone tests are performed to ensure a relative density of 40% (E = 10 MPa, ϕ=300) which is consistent with non-compacted Giza Sand properties. The first stage fills the bottom 500 mm of the tank. The second stage places the tires and fills within and around the tires, as shown in Fig. 4b. Four tires are laid side by side to a thickness of 100 mm. The stiffness of the used tires is 50 MPa as considered in the numerical analysis.

A 200 mm x 200 mm square steel plate is placed on the sand and tire mixture as shown in Fig. 4c. Then, the loads are applied via a system comprising a hydraulic jack and reaction and loading frame. Initially, a seating load of 0.35 kN for leveling. The settlement of the plate is measured for each increment of stress by two dial gauges with 0.01 mm accuracy. The dial gauges are attached to a steel bar mounted on the tank sides to maintain a horizontal position. The load is measured by a calibrated proving ring and the average of the dial gauge measurements gives the settlement. Hence, a plate pressure settlement curve in Fig. 3 is constructed for comparison.

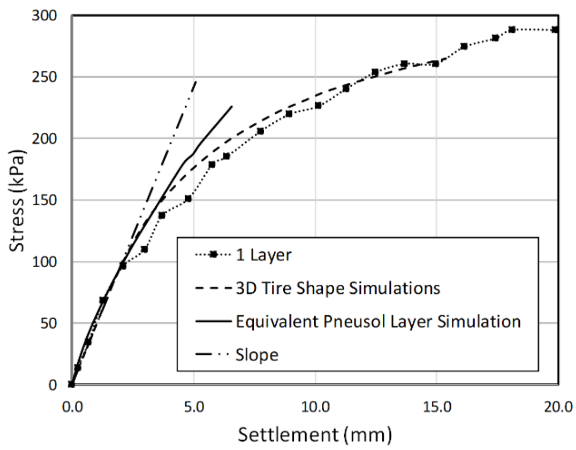

Fig. 3. Comparison between the homogenized and detailed simulation of whole tire sand mixture with experiment results.

Fig. 4. Laboratory set up for the plate load test experiments.

3. EFFECT OF HOMOGENIZED LAYER THICKNESS

Two more plate load test experiments are performed to investigate the performance of two and three layers of tires on top of each other. Each layer comprises four side by side tires as shown in Fig. 4b. Fig. 5 shows a schematic diagram of the experimental setup for the multiple layers. The back analyses for the 2 and 3 tire layers results are done using only the homogenized representation in the numerical model. Fig. 6 shows the back analyses for these results. The initial slopes match 2- and 3-layers curves at Young's moduli, 20 MPa and 45 MPa, respectively. The same Poisson's ratio (ν=0.35) is used in all the analyses.

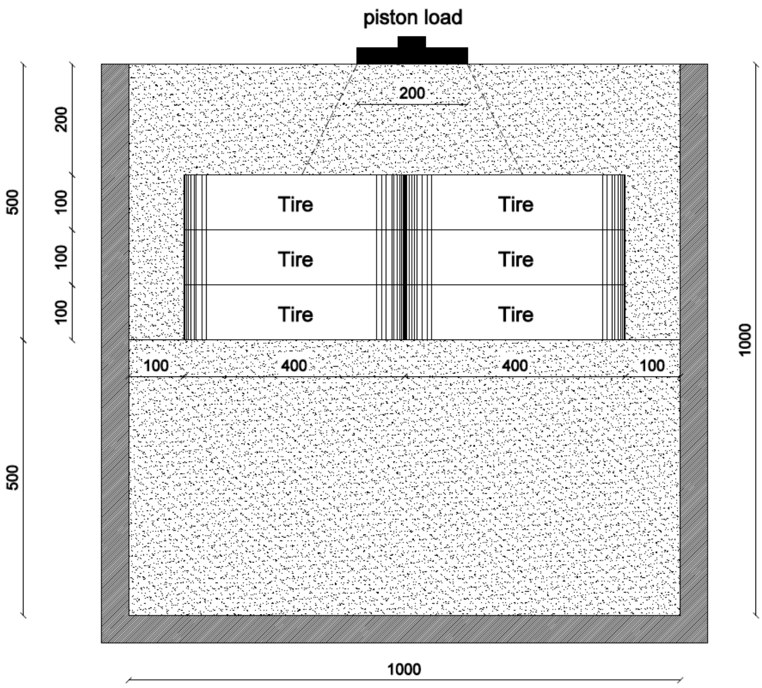

Fig. 5. Schematic diagram of the lab set up for multiple layers (dimensions are in mm).

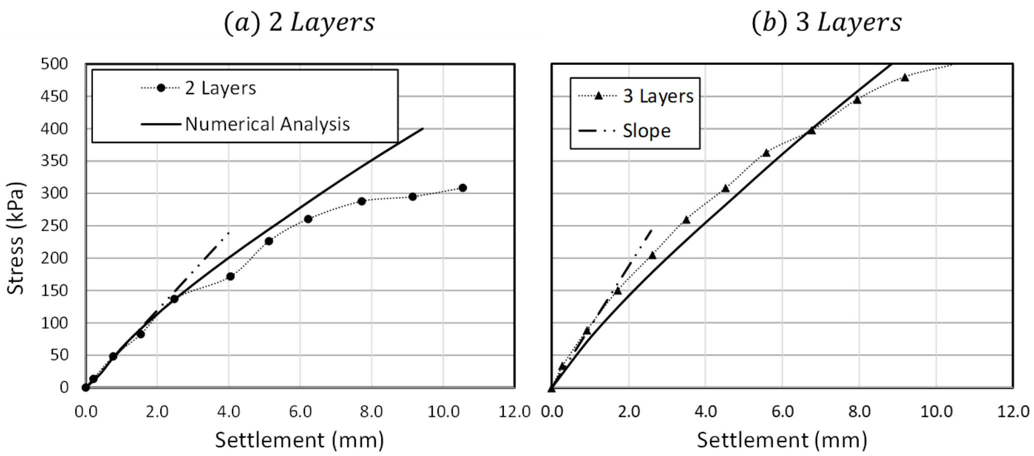

Fig. 6. Back analysis of the mixture layer stiffness for a) 2 layers of tires, and b) 3 layers of tires.

Fig. 7 shows the finite element (FE) mesh representing three layers of sand filled tires as a homogenized body. The figure also shows the contours of settlement and vertical stresses inside the sand and the mixture layers. These distributions are computed at a vertical plate pressure of 400 kPa. Directly underneath the plate, the stress distribution is not uniform and shows high-stress concentrations at the plate edges. However, at relatively small depths inside the sand, the stress distribution becomes uniform and propagates with an approximate slope of 2V:1H. The distribution of vertical deformations shows that most of the compression occurs in the top sand layer, and the mixture layer exhibits a stiffer response.

The back analyzed stiffness values of the homogenized layer from numerical analysis are compared with those calculated using the averaging laws of the mixture. Research shows that the stiffness of a mixture of material ranges between the isostress case (Reuss average of stiffness) and the isostrain case (Voight average of stiffness) [19, 20]. The isostrain case, where stiff and soft components are equally strained, produces higher stiffness values as shown in Eq. 1a. The isostress case, where stiff and soft components are subjected to equal stresses, gives the lower bound of possible stiffnesses. Fig. 8 shows schematics of the isostress and isostrain cases, and the variation of the Voight and Reuss average stiffnesses (E_{Mix}) with the possible percentage of rubber tires (P_{tire}).

$$\boldsymbol{E_{Mix} = E_{tire} * P_{tire} + E_{sand} * (1 - P_{tire})} \quad \textbf{(1a)}$$

$$\boldsymbol{E_{Mix} = \frac{1}{\frac{P_{tire}}{E_{tire}} + \frac{1-P_{tire}}{E_{sand}}}} \quad \textbf{(1b)}$$

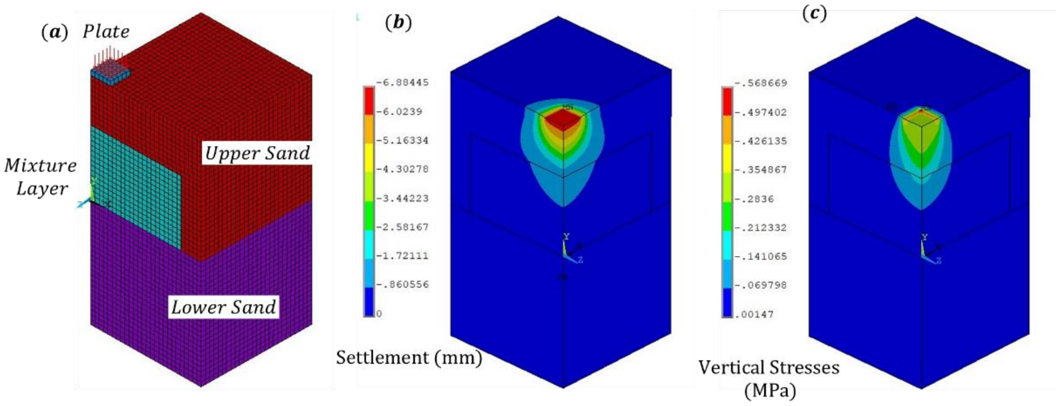

Fig. 7. Numerical analysis of homogenized mixture layer, a) FE mesh, b) Settlement contours, c) Vertical stress distribution.

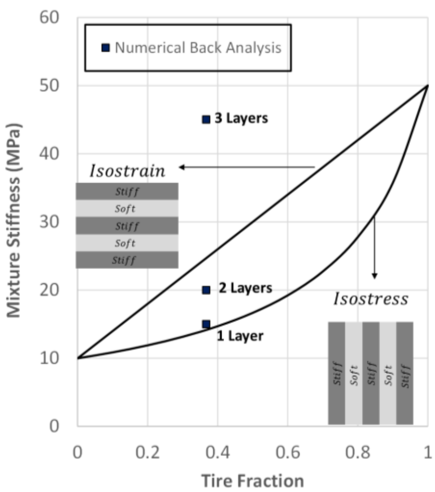

Fig. 8. Values of back analyzed stiffness of the homogenized layer compared with the isostress and isostrain averages.

In the experiments, the percentage of rubber to sand in a single sand-filled whole car tire is 36.7 %. This percentage does not change when more tires are added laterally or vertically. Fig. 8 shows that the Reuss average act as a lower bound to possible values of the mixture stiffness.

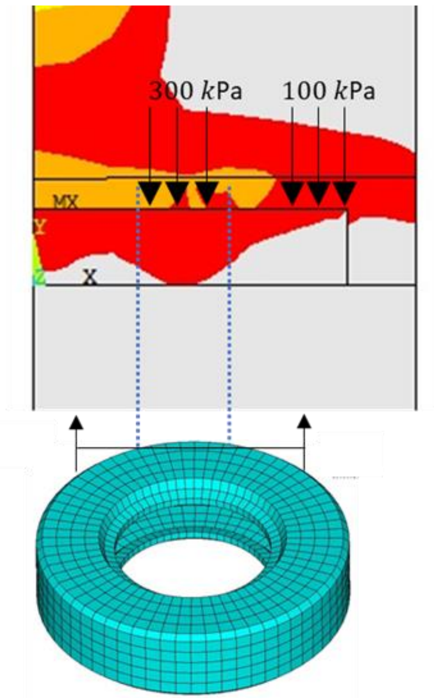

Fig. 9. Redistribution of vertical stresses around the tire.

However, the increase in tire layers leads to an increase in the mixture stiffness even beyond the Voight average (the typical upper bound). The logical explanation for this is when the mixture thickness increases, and the distance between the mixture and the plate decreases, the mechanism departs from both isostress and isostrain cases. The bodies of the tires attract more stresses without being constrained with the same strains as the sand.

Fig. 9 is an excerpt of the vertical distribution in the numerical model realizing the actual shape of the tire. The contour lines show that the edge of the tire is loaded with higher stresses (approximately 3 times) than the surrounding area where only sand exists. This arching action voids our ability to use the typical average laws to calculate mixture stiffness.

4. STIFFNESS OF THE MIXTURE

A single value of stiffness representing a homogenized mixture of sand and whole tires cannot be inferred from theoretical methods or using the element tests in the literature. A plate load test can be easily and quickly applied in the field, but the 3D numerical analyses needed for the back analysis of its results is cumbersome and not regularly available. Hand calculation methods typically used to investigate the load-settlement performance of improved grounds [21] can be used to interpret plate load test results instead. One of the most important methods to analyze a double layer system where a weak layer is underlain with a stronger one is the equivalent thickness method [22]. This method is a suitable representation for the considered case herein where the loose sand is reinforced with tires of rubber at a certain depth from the surface subjected to the plate load. As presented in Fig. 10, an equivalent thickness for the top weak layer, H_{1e} is calculated as a function of the Young's Modulus and Poisson's ratio of the weak Layer (E_1 and ν_1), and of the strong layer (E_2 and ν_2) as in Eq. 2.

$$H_{1e} = \left(\frac{E_1(1-\nu_2^2)}{E_2(1-\nu_1^2)}\right)^{\frac{1}{3}} \qquad (2)$$

The relationship between plate contact stress, ΔP, and settlement, S can be calculated using Eq. 3. An approximate method assumes that stress propagates through both layers with the same slope (1V:2H) after modifying the thickness of the weak layer as shown in Eq. 3a [21]. The equivalent pressure causing both layers to compress, ΔP_e is that acting at the middle of the layer with modified dimensions (Eq. 3b) as also shown in Fig. 10.

$$S = \frac{1}{E_2}\Delta P_e(H_2 + H_{1e}) \qquad (3a)$$

$$\Delta P_e = \frac{\Delta P}{B+\left(\frac{H_{1e}+H_2}{2}\right)} \qquad (3b)$$

In this scenario, the stiffness of the strong layer, E_2 is a representative value of the rubber tire and the sand confined within. By trial and error, an appropriate value of E_2 is chosen so that the slope, ΔP/S matches the initial slope observed in the experiments. Table 2 shows the E_2 values that when used in the above equations similar slopes to those indicated in Fig. 3 and Fig. 6 are produced. The values are close to those back analyzed from numerical analysis with a difference of ±5 MPa.

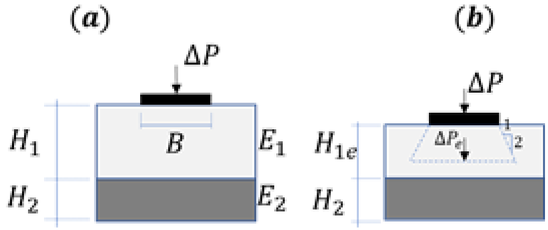

Fig. 10. A schematic diagram showing the a) actual, and b) modified dimensions of the double layer system.

Table 2. Values of mixture stiffness back analyzed from numerical analyses and calculated from the equivalent thickness method.

Number of Layers	Numerical Back Analysis (MPa)	Equivalent Thickness Method (MPa)
1	15	20
2	20	25
3	45	40

In order to come up with a method to give a first-order value for the mixture stiffness before construction, the results of the aforementioned plate load tests are used in a curve fitting process. This empirical correlation computes the mixture stiffness from numerical and semi-analytical back analyzed values. Eq. 4a is an exponential relationship between the $E_{MIX\text{-}Ratio}$ and H, the normalized thickness of the mixture layer (H = thickness/depth of the layer). The R^2 correlation factor is 0.9997, and the E_{MIX_Ratio} is defined in Eq. 4b. The relationship is a clear exponential one indicating the combined effect of increasing thickness and a decreasing distance between mixture and load (weak layer thickness).

$$E_{MIX\_Ratio} = 0.1413e^{1.1693H} \qquad (4a)$$

$$E_{MIX\_Ratio} = \frac{E_{Mix}-E_{sand}}{E_{tire}-E_{sand}} \qquad (4b)$$

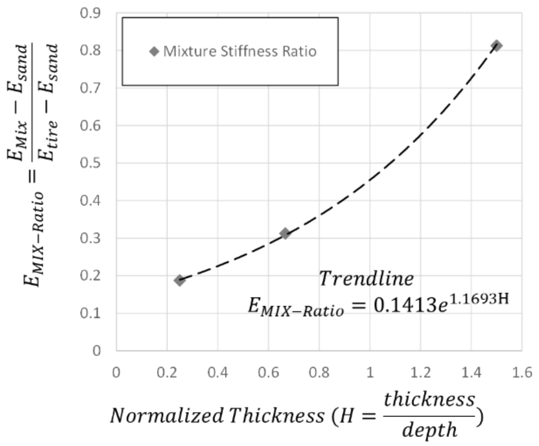

Fig. 11 Predicting mixture layer equivalent stiffness from its thickness and depth.

5. CONCLUSIONS

In developing countries, whole tires rather than processed rubber are mixed with sand to create cheap and quick backfill. This backfill can be used in many applications starting from quickly supporting and excessively deforming side support systems to vibration absorbents around sensitive structures. Typically, the numerical analysis considers the mixture as a homogenized body and assigns stiffness values based on an existing database of element tests. This paper presents a set of numerical and physical experiments using plate load tests on whole tire loose sand mixtures from which the following conclusions are drawn:

a. A simple plate load test can be used to interpret a representative stiffness of the whole tire sand mixture. An approximate method is proposed using the equivalent thickness method and an average distribution of stresses to interpret plate load test results. The mixture layer stiffness is inferred with acceptable accuracy when compared with advanced 3D numerical simulations.
b. Using a uniform homogenized layer to represent the whole tire sand mixture gives the same initial stiffness in the linear portion of the load settlement curve. At large values of deformations, a single value of stiffness cannot be assessed because of the possible plastic strains computed in the model.
c. Results from FE analyses show that contact stresses directly beneath the loading plate is irregular. However, the stresses become uniform and propagate with a slope (2V:1H) similar to the assumption used in the approximate methods.
d. The isostrain average stiffness is considered a lower bound value for the mixture layer. However, the arching around tire edges lead to an exponential increase in mixture stiffness when the thickness is increased and depth from the load is decreased. An empirical correlation between mixture stiffness and normalized thickness is proposed to help designers determine first order stiffness values before using plate load tests.

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