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STRENGTH CHARACTERISTICS OF TYRE CHIPS–SAND MIXTURES

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Abstract: Waste tyres are more and more widely used for geotechnical applications as backfill material that is either a substitute for natural soils or combined with them. Beyond the economical and environmental concern, these materials can help solving problems with low shear strength soils. This study aims at investigating a mechanical behaviour of tyre chip–sand mixtures thanks to a triaxial tests campaign. Two factors were studied: (i) the tyre chip content, from 0 to 100% by mass and (ii) the orientation of the pieces of tyre, with four varying orientation conditions. This paper focuses on the stress–strain behaviour of the different mixtures and their volumetric variation during the tests. The angle of friction and cohesion for each mixture are presented. The optimum percentage mass and optimum unit weight, which gives the maximum shear strength, are also determined. The influence of the different parameters is discussed.

1. INTRODUCTION

Tyre disposal is a huge challenge faced by waste management engineers, particularly in more economically developed countries where there exist stockpiles of tyres in alarming volumes. Their disposal proves to be a serious problem as tyres do not decompose. Waste tyres pose a threat to public health and to the environment in terms of current methods of their disposal due to the following three reasons: (i) they occupy large volumes in already overcrowded landfills, (ii) waste tyre storage can be a dangerous fire risk, (iii) waste tyre dumps provide the breeding ground for vermin, including rats and mosquitoes.

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In this context, the European Union is progressively banishing the disposal of tyres in landfills, in any form, through the directive 1991/31/EC that applies to all countries within the European Union. This directive has prompted an interest in new ways to recycle end-of-life tyres, as for instance in civil engineering applications.

Waste tyres have many properties which result in their being of value from a civil or geotechnical engineering perspective: low density, high strength, hydrophobic nature, low thermal conductivity, durability, resilience and high frictional strength. It is due to these properties that the use of tyres has been specifically recommended in civil engineering applications such as lightweight material for backfill of retaining structures, drainage layer, thermal insulation layer or reinforcement layer.

This study is a part of the program investigating the possible use of pieces of tyre as filling material for structures subjected to impact. In the investigation of the suitability of soil–tyre pieces mixtures for geotechnical applications, a shear strength of such mixtures seems to be their most important mechanical property. This study focuses on the characteristics of the shear strength and deformation behaviour of mixtures of sand and tyre ships and aims at determining the influence of their different parameters such as the tyre content and the orientation of the pieces of tyre.

2. BACKGROUND

Of all the studies aiming at characterizing tyre pieces and their mixtures with soils [1] some refer specially to triaxial tests [2]–[5]. These differ in their aim, form and shape of the pieces of tyre and test method, but provide a basis for confirmation of the results obtained throughout this testing campaign while allowing for differences.

The internal angle of friction of waste tyre shreds with soil is 33.7° ± 15° as reported in a statistical analysis of 13 sets investigated by different authors [1]. YANG et al. [5] correlated the initial stress–strain modulus of the specimen E with the confining pressure σ_3 using the following equation:

$$E = 13.2\sigma_3 - 0.0191\sigma_3^2 . \tag{1}$$

ZORNBERG et al. [2] concluded that an optimum percentage of tyre shreds, where a maximum shear strength was attained, occurred at approximately 35% by mass of tyres. The volume variations observed were similar to the results reported by YOUWAI and BERGADO [3].

The factors, whose influence on the shear strength of the material is the greatest, appeared to be normal stress, confining pressure, tyre content and density of mixture. These factors, including the orientation of the tyre chips within the mixture, were investigated in this study in order to confirm the results reported previously and to investigate further the mechanical behaviour of this geocomposite material.

3. MATERIALS

3.1. TYRE CHIPS

The tyre chips (as defined by CEN Workshop Agreement – CWA-14243) used in this investigation were produced using a punching method, where metal cylinders are forced to cut up tyres. The resulting material is composed of rounded pieces (30% in mass) and pieces of indefinable shape or dimension, with or without sticking out steel wires (see figure 1). The number of wire layers within the structure of the pieces varied from zero to six.

Fig. 1. Sample of raw material and selected circular chips

To be able to characterize tyre chips with laboratory tests it was decided to focus on specimens composed of circular pieces of tyres with sticking out steel wires. Indeed, the raw material is rather hard to define, it presents a risk to the equipment, and mainly to the triaxial membrane, and its variability may lead to a high variability of test results.

The average diameter and thickness values for circular chips were measured to be respectively of 28.1 mm and 10.4 mm. The thickness varies significantly and depends heavily on the number of steel belt layers. Tyres containing no steel belt layers generally have a smaller thickness. The unit weight of the rounded pieces ranged from 11 to 15.4 kN/m^3, also depending on the presence of steel belt layers, with an average value of about 13.3 kN/m^3. These values are consistent with the data reported [1].

3.2. SAND

The sand used in this test campaign is from the Seine river, Class D in French Standards. As this is a fluvial soil its most important characteristics is that it contains well-rounded grains. It is an unconventional sand of a shell basis, with unit weight of 17 kN/m^3. All sand used in tests was sieved using a 5 mm grain-size sieve. The sand was tested dry.

3.3. MIXTURES

Four different types of arrangement of tyre pieces were investigated: (i) alternate horizontal and vertical (H&V specimens), (ii) horizontal only (H specimens), (iii) vertical only (V specimens) and (iv) no orientation (NO specimens). NO specimens are representative of on-site use, whereas H&V lay-out aimed at producing well-defined specimens. Except for NO specimens each piece of tyre was placed manually. Pieces of tyre placed on the perimeter of the specimen were selected in such a way that they do not include steel layers in their structure, which allows us to reduce the risk of puncture of the membrane. H&V specimens were prepared placing alternately pieces of tyre horizontally and vertically. For the same tyre content, the same mass of tyres was placed in the cell together with the same mass of sand, then they were compacted in order to reach similar densities. The relative unit weight of the sand within a series varied from 16.3 kN/m^3 to 17 kN/m^3, depending on the tyre content and orientation, except for the case of 50% by mass tyre specimens where it was 0.5 kN/m^3, hence it was almost impossible to compact satisfactorily the mixture.

4. METHOD

Nine series of consolidated drained, CD, triaxial compression tests were carried out. The tests were conducted in a general accordance with French standard NF P 94-074 [6] at a strain rate of 2 mm/min and they allow measuring the confining pressure, the axial load and the specimen volume variation. Adaptations to the preparation procedure were imposed by the characteristics of the material tested (tyre content and tyre orientation). Tests were interrupted either after the shear strength peak or before a strain of about 20%, due to the limited section of the triaxial cell. The size of the pieces of tyre requires the use of a large-scale triaxial cell to test large specimens: 150 mm in diameter and 300 mm in height, giving an average specimen volume of $5\cdot10^6$ mm^3. The changes in the specimen volume during the test were determined measuring the changes of water level in a burette connected to the cell pressure line and taking account of the loading piston displacement.

For each series a minimum of three confining pressures was investigated, 50, 75 and 100 kPa, so that the strength parameters could be determined. These low confining pressures were applied because the materials tested are to be used in civil engineering projects whose height is up to 4 meters. Each specimen within a series was prepared with the same chips orientation and the same tyre content, hence giving a similar unit weight (see table) as described in the previous section. The deviatoric stress was not adjusted to the cross-sectional area change as is required by the standard. Indeed, this formula is intended for use with uniform materials, e.g., sand only, and using it we assume that a tyre chip–sand mixture or a tyre chip specimen only will behave similarly. Failure of the specimen was deemed to have taken place once a maximum deviatoric stress was attained. However, for series I no peak was obtained, whereas for series H a peak was observed at 14% strain, depending on the confining pressure. For the purpose of comparison it was decided to consider for series I and H the deviatoric stress at 14% axial strain, while other authors consider 15 [2], 10 or 20% strains [5].

Angle of friction φ and cohesion C were calculated after plotting Morh's circles. An equivalent angle of friction φ_{eq} was also calculated considering the cohesion as being zero. This data can be used in order to simplify the comparison between the series [2].

Table

Scope of the testing program and shear-strength parameters

Specimen description				Shear strength parameters		
Series	Content of tyre chips (% by mass)	Orientation of tyre chips	Unit weight (kN/m^3)	Φ (°)	C (kPa)	φ_{eq} (°)
A	0	na	16.7	40.9	0	40.9
B	15	H&V	15.5	41.1	10	44.5
C	14	H	15.9	42.6	15	44.5
D	14	V	15.9	41.7	7.5	43.5
E	14	NO	15.5	39	13.8	43
F	22	H&V	15.3	36.1	50	45
G	50	NO	11.4	41.5	7.5	43.5
H	100	H	6.8	31	28	38.5
I	100	NO	6.1	19	16.3	25

Note: na = not applicable, H = horizontal, V = vertical, NO = no orientation.

5. RESULTS AND DISCUSSION

Figure 2 shows pictures of different specimens at the end of the test. Tyre chip–sand specimens tend to have many rupture planes that follow closely the lay-out of the chips within the specimen, particularly where there are vertically placed chips around the perimeter of the specimen (figure 2a and b). Figure 3a gives an example of stress–strain curves obtained varying the content of tyre chips; it will be discussed in the following section.

(a) Series B, 50 kPa (b) Series F, 75 kPa (c) Series C, 50 kPa

Fig. 2. Specimens at the end of the tests

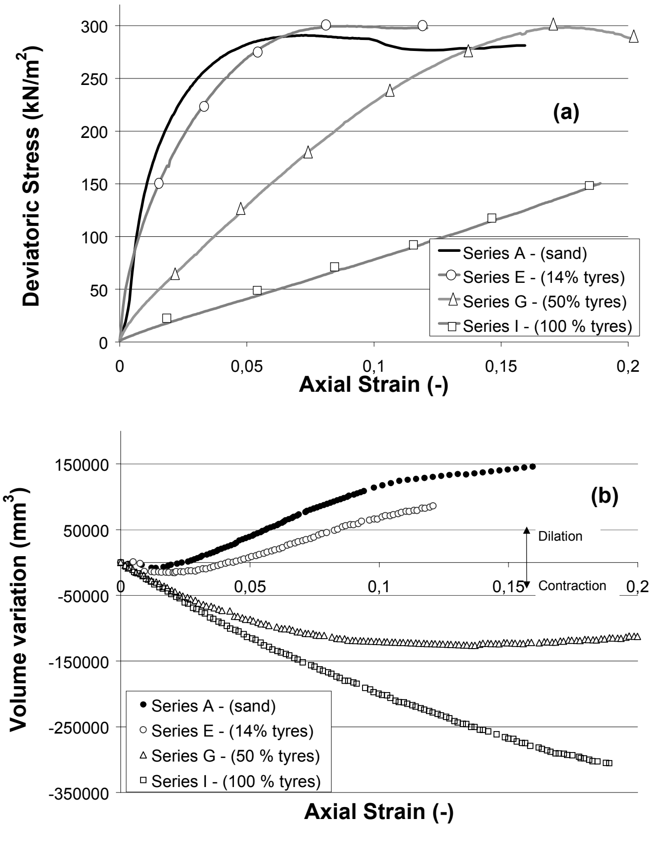

Fig. 3. Influence of the tyre content on the behaviour of NO specimens (75 kPa confining pressure tests)

Shear-strength parameters are given in the table. Angles of friction vary from 19 to 42.6°. Cohesions vary from 0 to 50 kPa. It is not a real cohesion but an intercept cohesion resulting from the simplistic Mohr–Coulomb linear model. The cohesion is not negligible for series E, F, H, and I mainly, affecting φ_{eq} values. Thus, considering φ_{eq} values rather than φ and C values to characterise the shear strength of the various specimens may lead to different conclusions. Whatever, it appears that the shear strength of the specimen of a tyre chips only is much less than that of a sand or a sand–tyre chip mixture up to 50% mass. These shear and stress results are in a good agreement with results reported by ZORNBERG et al. [2] regardless of the size and shape of pieces of tyre.

Investigating the influence of the tyre content and the chips orientation allows far-reaching comparison of the different series.

5.1. INFLUENCE OF THE TYRE CONTENT

Figure 3 shows the influence of the tyre content on the behaviour of NO specimens during 75 kPa confining tests giving results for series E, G, and I together with the results for series A. The tyre content greatly affects the deviatoric stress–strain and volumetric strain behaviour.

The sand shows contraction, then dilation characteristic of a medium of dense sand. The peak on the stress–strain curve is well defined at approximately 6% axial strain, although it is unexpectedly high compared to peak obtained at 50 and 100 kPa. The difference in the behaviour of 100% tyre specimens and that of sand is obvious. The curve representing the stress–strain of 100% tyre NO specimen shows approximately linear behaviour with an initial modulus of 790 kPa. This value is smaller than that predicted by Yang's equation (1) giving 882 kPa in these conditions. The volumetric strain is contractive following an approximately linear relationship. This linear behaviour of tyre specimens only is consistent with previously undertaken research [2]. In the case of a mix of 14% by mass of tyres and sand, the specimen behaviour is similar to that of a medium to dense sand, although the tyres provide greater shear strength to the mixture, allowing a higher peak strength to be achieved at approximately 8% axial strain.

The behaviour of a 50% tyre specimen corresponds more closely to that of the 100% tyre series, but the stress–strain curve exhibits a peak when an axial strain reaches 15%, which occurs much later than for sand only. Although the behaviour of the specimens whose tyre content ranges between 14% and 50% varies considerably, it should be noted that their peak shear strengths achieved are similar, hence it is proposed that between these two percentages a greater peak strength can be achieved.

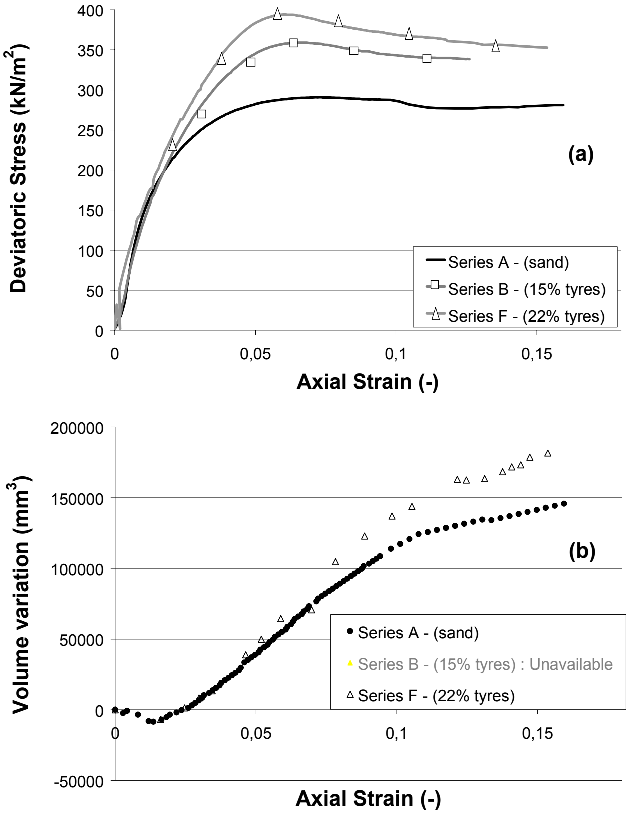

Fig. 4. Influence of the tyre content on the behaviour of H&V specimens
(75 kPa confining pressure tests)

The same conclusions can be drawn from the results obtained with H&V specimens, as shown in figure 4 giving the same presentation for series B and F, together with series A. It provides a complementary information about the results for a 22% tyre specimen. An increase in the tyre content from 15% to 22% brings about an increase in the peak shear strength from 359 to 394 kPa. The volume variation for the 22% tyre specimen is similar to that of a dense sand in a dilatant behaviour following a short contractive period. Hence it is thought that an optimum percentage mass does not exceed 50% of tyres which would give a maximum peak shear strength for a particular confining pressure. This is illustrated clearly in figure 5, corresponding to the idea of internal shear and reinforcement mechanisms proposed by ZORNBERG et al. [2]. The composite shear strength envelopes were defined by the second-order polynomial with $R^2 > 0.98$, hence by a good correlation. The relationship between unit weight and shear strength was defined by the third-order polynomial.

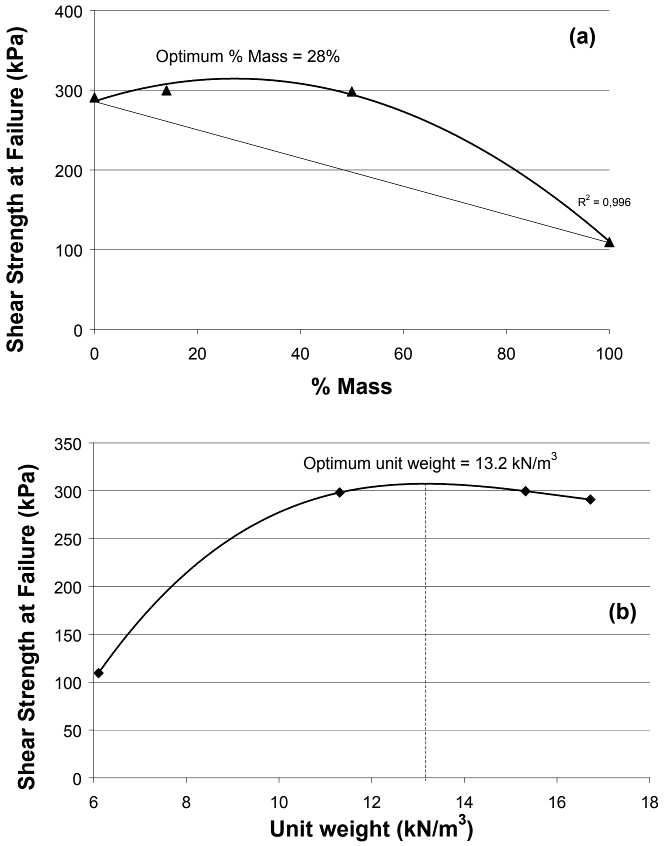

Fig. 5. Influence of tyre content (a) and unit weight (b) on the shear strength at failure for NO specimens (75 kPa confining pressure tests)

These results were obtained in the tests performed at a 75 kPa confining pressure, but the same observations were made at the other confining pressure and an optimum tyre content that changed slightly, i.e. 28 and 36%, respectively, for 50 and 100 kPa. Taking an average of the three, an overall optimum percentage mass of tyres, which gives a maximum peak shear strength, is 34%. An average optimum density is 13.5 kN/m^3. These results correspond closely to optimum percentage mass of 35% reported by Zornberg et al. This optimum is not defined by a well-marked peak; over a range of tyre from 20 to 40% the shear strength is close to the optimum.

5.2. INFLUENCE OF THE TYRE CHIP ORIENTATION

The investigation of the effect of varying the orientation of tyre chips deals solely with 14/15% mass of tyres specimens. This takes into account series B, C, D and E. It appears from figure 6 that orientation has an important influence on the behaviour of the specimen. H specimens reach a higher peak shear strength than that of V specimens. H&V specimens are not similar to NO specimens, the latter having the smallest peak shear strength of all the series. These results were confirmed by shear strength measured under 50 and 100 kPa confining pressure. Friction angle values show that shear characteristics of H specimens are close to H&V ones, and are higher than these of V specimens and NO specimens. In fact, in the case of mixtures, tyre chips act as inclusions whose efficiency is higher when placed perpendicularly to the shear plan, as was previously reported by EDIL et al. [7] who performed direct shear tests on tyre chips–sand mixtures. In our case, pieces of tyre are not perpendicular to the shear plan, but H specimens and V specimens offer more efficient orientation in terms of reinforcement.

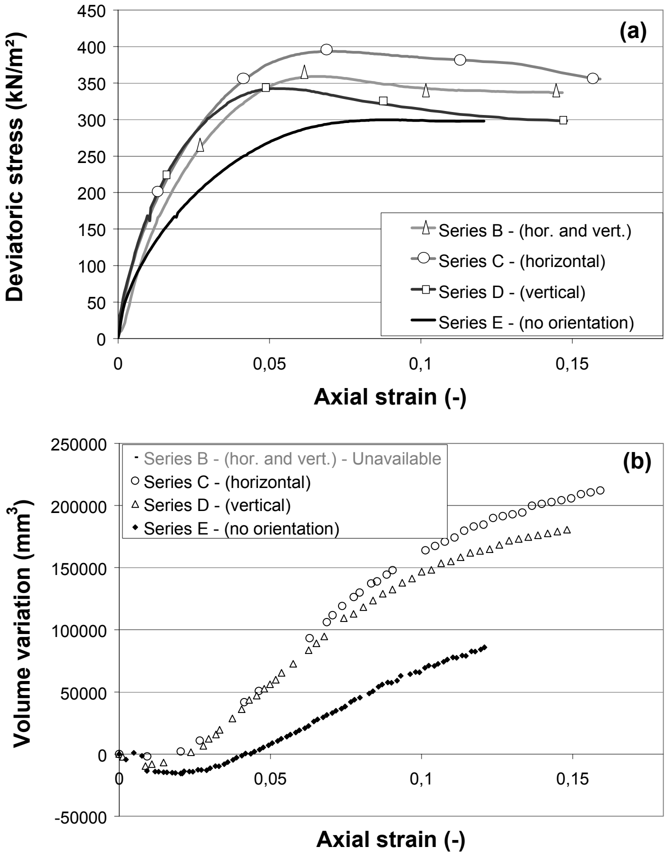

Fig. 6. Influence of the tyre chip orientation on the behaviour of 14/15% specimens
(75 kPa confining pressure tests)

5.3. INFLUENCE OF TYRE SPECIMENS

The table shows that the orientation of tyre chips has an important influence on the shear-strength characteristics. It can be expected that 100% NO specimens are weaker than specimens with horizontal orientation of tyres only.

Volume variations of the three types of mixtures have the same shape but an increase in the volume of NO specimens is smaller. This means that shearing NO specimens requires less rearrangement in the specimen, and also that the shear band is thinner. This is consistent with previously reported observations [7], [8].

As previously mentioned, an important difference was observed between the two series of 100% tyre specimens. Indeed, the stress–strain curves representing H specimen exhibited a well-marked peak at the strain ranging from 14.5 to 17%, depending on the confining pressure. The maximum strength was followed by a rapid strength decrease and almost simultaneously accompanied by a rapid increase in the volume.

6. CONCLUSION

A triaxial test campaign of tyre chip–sand mixtures was conducted by varying the tyre content and the orientation of chips in order to investigate the mechanical behaviour of the mixture: to determine the strength parameters, the angle of friction and the cohesion. In particular, the campaign determined the optimum percentage mass of tyres and the optimum unit weight, i.e. those which give the maximum shear strength.

The results of this research have led to the following conclusions:

1. 100% tyre specimens with no orientation show a linear stress–strain relationship.
2. The percentage mass of tyres has a great influence on the shear strength of the mixture. The strength increases as with the increase of tyre content up to an optimum percentage mass of 34%, after which the shear strength decreases. This optimum corresponds to an optimum unit weight of 13.5 kN/m^3.
3. The tyre content changes the volumetric variation – axial strain behaviour. It appears that the behaviour of mixtures changes from a sand-like-behaviour to a tyre only-like-behaviour at a percentage mass of 34%.
4. The equivalent angle of friction for 100% tyre specimens with no orientation is 25° compared to 41° for the sand.
5. The orientation of the tyre chips has an effect on the shear strength of the mixture. The strength is higher when tyre chips are placed horizontally, followed by the specimens made of alternately placed horizontal and vertical tyres, tyres placed only vertically and finally the specimens where tyre chips have no orientation.

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