Archives of Hydro-Engineering and Environmental Mechanics
Vol. 54 (2007), No. 1, pp. 25–36

Characteristics of Tyre Chips-Sand Mixtures from Triaxial Tests

Lech Bałachowski[*], **Philippe Gotteland**[**]

[*] Civil Engineering and Environmental Faculty, Gdańsk University of Technology,
ul. Narutowicza 11/12, 80-952 Gdańsk, Poland, e-mail: abal@pg.gda.pl
[**] Lirigm, Polytech' Grenoble, Joseph Fourier University, Maison des Géosciences – BP 38041,
Grenoble Cedex 9, France, e-mail: philippe.gotteland@ujf-grenoble.fr

(Received November 23, 2006; revised March 21, 2007)

Abstract

Civil engineering and mainly geotechnics and pavement engineering are the possible domains of application for the end of life tyres. They are used in geotechnical applications as backfill or lightweight fill material in substitution or in combination with natural soils. The mechanical behaviour of tyre chip-sand mixtures was studied in a series of CD triaxial tests. The study was focused on random distribution of tyre chips within the mixture. Initial modulus of deformation, angle of internal friction and cohesion were evaluated for each series of test. A composite conserves a good shear resistance at large strains. The mode of failure depends on the tyre content. The internal shear mechanism and the reinforcement mechanism of the composite are discussed as a function of tyre content, chips orientation and stress level.

Key words: triaxial tests, waste tyres, recycling, backfill

1. Introduction

Tyre disposal is a huge challenge in waste management, as the tyres do not decompose. Used tyres occupy large volumes in already overcrowded landfills, waste tyre storage can cause fire and can provide a breeding ground for vermin. In this context, the European Union is progressively banishing the disposal of tyres in landfills through the directive 1991/31/EC that applies to all countries within the European Union, including the new members. This directive promotes the recycling of the tyres at the end of their life time and their reusing in civil engineering applications. Mixed with a soil, the tyres can lower the weight of the mixture, increase its thermal insulation, vibration insulation and shock resistance, improve its strength and deformation characteristics. They can be used as lightweight material for the embankment body, as a backfill of retaining structures, drainage layer, thermal or vibration insulation layer and reinforcement layer (Foose et al 1996, Pisarczyk 2002). Lower stress transmitted to the subsoil of the embankments built with lightweight material appears especially advantageous for soft subsoil, where it permits reduction of settlements. The tyre content within the mixture can provide a material with high deformability and strength. While a brittle failure mechanism is observed for dense sand, the tyre-soil mixtures can conserve high shear resistance at large strains. Such a mixture can be used to absorb the impacts of falling rocks in road protection facilities or to accommodate ground subsidence in mining areas or in karst regions.

Two types of waste of tyres are used in engineering applications: tyre chips and tyre shreds. The shear strength of tyre chips was studied in triaxial apparatus by Wu et al (1997) and Edil et al (1994), where high values of internal friction angle from 45 to 60 degrees with a zero cohesion intercept are reported for the confining pressures less than 40 kPa. Any peak strength was observed in these tests, so the strength characteristics were calculated for the assumed failure criterion – axial strain of 10% or 20% typically. Mechanical properties of shredded tyres were evaluated by Yang et al (2002) with isotropic and confined compression, using direct shear and triaxial tests. The compressibility of the shredded tyres increases with a shreds size. Small size shreds are characterized with smaller initial void ratio than larger size and individual small shreds are less compressible than the large ones. Zero cohesion intercept and internal friction angle equal to 32 degrees was obtained in direct shear test for a normal stress less than 83 kPa. Triaxial tests give zero cohesion intercept for the confining pressures less than 55 kPa, while the tests performed at higher confining pressures show 82 kPa cohesion. This can be related to non-linear failure envelope and the behaviour of the tyre chips/shreds and the composite should be tested in the wide range of confining pressure.

Mechanical properties of the soil-tyre shreds mixtures were studied in triaxial tests by Youwai and Bergado (2003), Zornberg et al (2004), Bergado et al (2005). They analysed the shreds of different shape, the mixtures with different tyre content, at different confining pressure and sand density. Higher shear strength was obtained for the shreds with elongated shapes. The shear strength of the composite was studied to find the optimum tyre content with the maximum shear strength of the mixture. They found that the optimum tyre shred content is close to 35% by weight. A similar value – equal to 34% – was found by Gotteland et al (2005) at the confining pressure of 75 kPa. They studied horizontal, vertical and random distribution of tyre chips within sand mass at the confining pressures limited to 100 kPa. It was found that the best reinforcement mechanism is assured for the combination of mixed horizontal and vertical chips arrangement. Horizontal arrangement, vertical and random distribution of the tyre chips in the sand mass will provide lower reinforcement.

The present study considers the shear strength and deformation of pure chips and tyre chips-sand mixtures and is focused on the composites with a random distribution of tyre chips, being of the most practical importance. The triaxial tests on the mixtures and on the tyre chips/shreds are performed for the confining pressures exceeding 100 kPa.

2. Test Description and Sample Preparation

Seven series of consolidated drained triaxial compression tests were carried out (Table 1). For each series of test at least three confining pressures were investigated: 100, 200 and 300 kPa. The procedure of sample preparation was adapted to the material to be tested (tyre content and tyre orientation). The dimensions of the tyre chips require the large triaxial specimen to be used in order to minimize the influence of a single chip. In this study, the largest available specimen 100 mm in diameter and 200 mm high was formed. The samples were prepared in a rigid split-mold and a suction of several kPa was applied. After removal of the mold the dimensions of each sample were measured on three levels. While the measurements of the initial size of the sample are quite precise for tyre chips-sand mixtures, they are approximate in case of tyre chips or tyre shreds samples (see Fig. 1 and Fig. 2). The suction was progressively released and the sample was saturated with de-aired water. The confining pressure, axial load with immersed load cell, vertical displacement and volume change of the sample were measured during the test. The tests were conducted under a displacement controlled mode with a strain rate adjusted to the material to be tested – from 0.04 mm/min in sand to 0.4 mm/min for the tyre chips samples.

Table 1. Testing program and shear strength parameters

Series	Tyre chips content (% by mass)	Tyre chips orientation	Unit weight (kN/m^3)	Internal friction angle ϕ	Cohesion intercept c (kPa)	Remarks
A	0	na	16.21	42.9	0	Sand only
B	14.2	NO	15.50	34.5	37	Sand-chips/shreds mixture 50/50
C	15.2	NO	14.52	35.5	32	Sand-chips mixture
D	23	NO	13.95	33.9	55	Sand-chips mixture
E	30	NO	13.30	33.6	60	Sand-chips mixture
F	100	NO	6.59	12.2	42	Chips/shreds 50/50
G	100	H	7.72	39.3	34	Tyre chips only

Note: na – not applicable, H – horizontal, NO – no orientation

First test series (A) were realized on sand only. The sand used is fine uniform (U = 1.41) Lubiatowo sand (d_{50} = 0.21 mm), having the minimum and the maximum dry unit weight:

$$\gamma_{d\,\min} = 14.52 \text{ kN/m}^3,$$

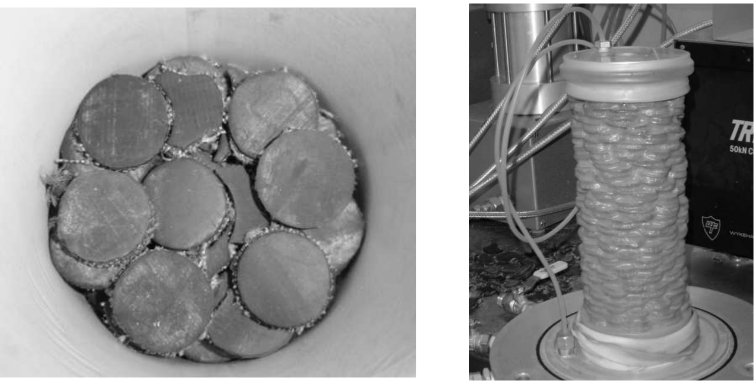

Fig. 1. Tyre chips and a specimen prepared for triaxial test

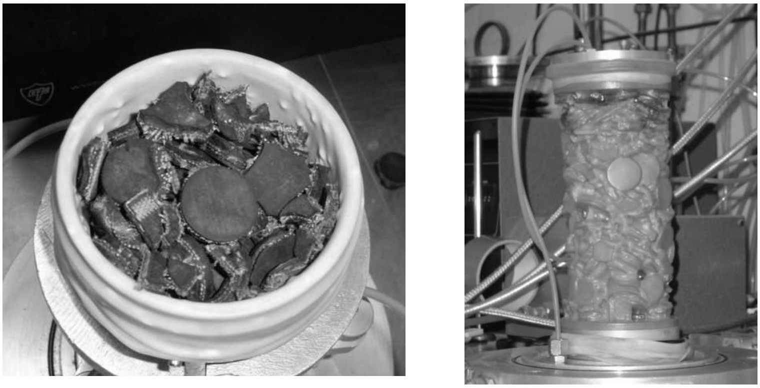

Fig. 2. Tyre chips and shreds mixture and a specimen prepared for triaxial test

$$\gamma_{d\,\max} = 16.38\ \text{kN/m}^3.$$

The sand was placed dry in 20 layers, each of them was compacted with falling mass.

The tyre chips used in this investigation were produced using a punching method, where metal cylinders are forced to cut through tyres. Circular chips with two rows of textile fibers within their structure were used. In some tests also some shreds with irregular shape were studied. The average diameter of the chips is about 28.2 mm and the specific weight of the chips is about 11.0 kN/m^3. The chips with two different thicknesses, i.e. 5.2 mm and 7.5 mm, were used in this study.

Random distribution of the tyre chips within the sand matrix was used (series C, D, E) with three tyre contents by weight (15.2%, 23%, 30%). Additionally, a random distribution of the tyre chips and the tyre shreds (mixed in a proportion 50/50) with a tyre content of 14.2% was studied (series B). This mixture was placed dry in 10 layers, each of them was compacted to dense state with a falling mass. The triaxial tests were also made on tyre chips/ tyre shreds material (series F, G). Two arrangements were used: horizontally placed circular chips (Fig. 1) and random distribution of 50% circular chips and 50% of shreds (Fig. 2). Unit weight of the prepared samples and the testing program are given in Table 1.

For each series of tests the Mohr circles were plotted and internal friction angle and cohesion intercept were calculated (see Table 1) for the confining pressures from 100 kPa to 300 kPa. An example of the strength parameters determination is given in Fig. 3, where internal friction angle (ϕ) and cohesion intercept (c) were calculated by means of Mohr circles.

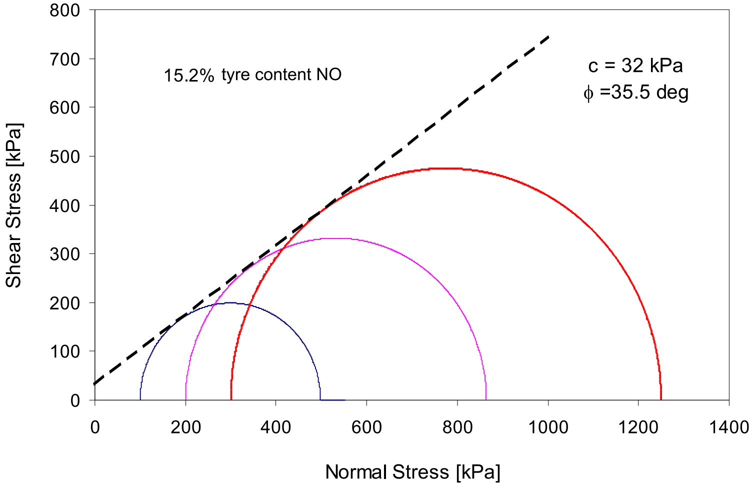

Fig. 3. Failure envelope for tyre chips-sand mixture at the tyre content 15.2%

The initial cross-sectional area and the height of the sample was corrected for a water volume expulsed from the sample during isotropic consolidation, which could be quite important (up to 12% of initial volume of the sample at the confined pressure of 300 kPa) for chips/shreds samples. During the shearing the cross section of the sample was corrected according to approximate formula:

$$A_i = \frac{V_0 - \Delta V_i}{h_0(1 - \varepsilon_1)}, \tag{1}$$

where:

V_0 – volume of the sample after consolidation,
ΔV_i – volume change (positive in compression),
h_0 – hight of the sample after consolidation,
ε_1 – axial strain.

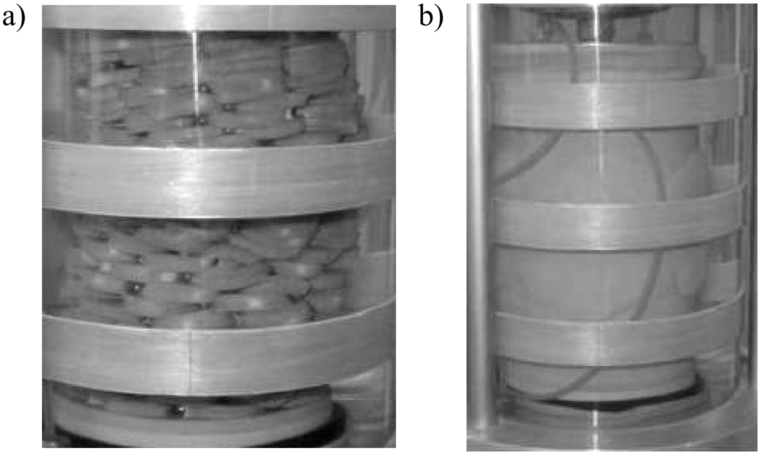

Fig. 4. Failure modes in triaxial tests: a) tyre chips only – horizontal distribution, b) tyre chips-sand mixture with 15.2% tyre content

The specimens at failure are presented in Fig. 4. Some shear zones, deformations of individual chips and bending of the sample are observed for tyre chips/shreds samples (see Fig. 4a). As it was noticed by Gotteland et al (2005) the tyre chips-sand specimens tend to have many rupture planes, that follow closely the lay-out of the chips within the specimen (see Fig. 4b). The failure of the sample was assumed either at the peak of the shear strength for sand and chips-sand mixtures or at 20% of axial strain for the tyre chips/ shreds specimens. Initial secant deformation modulus E_{50} corresponding to the half of the deviatoric stress at failure $q = \sigma_1 - \sigma_3$ was evaluated for each test.

3. Results and Discussion

The results of triaxial tests on tyre chips and shreds only are given in Fig. 5. For horizontally distributed tyre chips a distinct peak shear strength appears at large strains, higher than 15%. Axial strain at failure increases with confining pressure. The samples with non-oriented tyre chips do not exhibit a peak strength, so the failure criterion at axial strain equal 20% was assumed. Shear strength parameters from the triaxial tests on tyre chips (G series) and on tyre shreds (F series) are given in Table 1. While a small internal friction angle (12.2°) is found for randomly distributed tyre chips/shreds, relatively high internal friction angle (39.3°) is deduced for horizontally distributed tyre chips. Nearly linear relation between the deformation modulus E_{50} and the confined pressure was found for the tyre chips/shreds samples (Fig. 6). This linear behaviour of tyres only specimens is consistent with previous research.

The influence of the tyre content on the shear strength and volumetric strain developed in triaxial test is presented (Fig. 7) for random distribution of the chips.

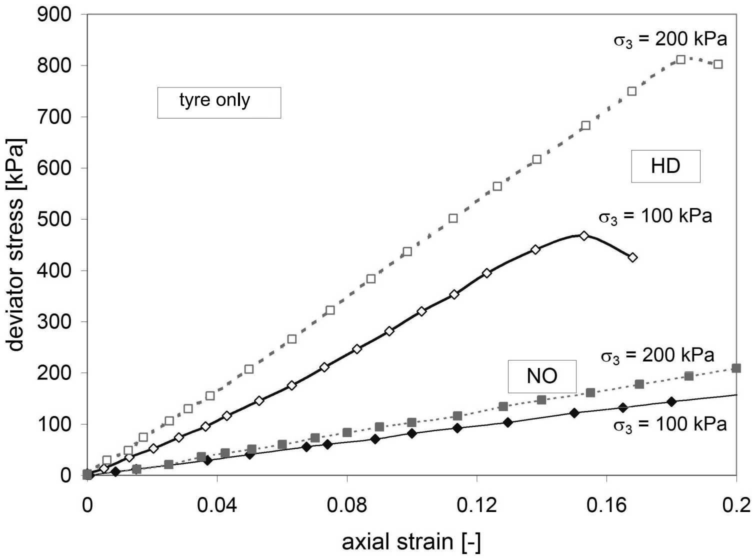

Fig. 5. Influence of chips/shreds orientation on the shear behaviour: HD – horizontal distribution, NO – non-oriented (random) distribution

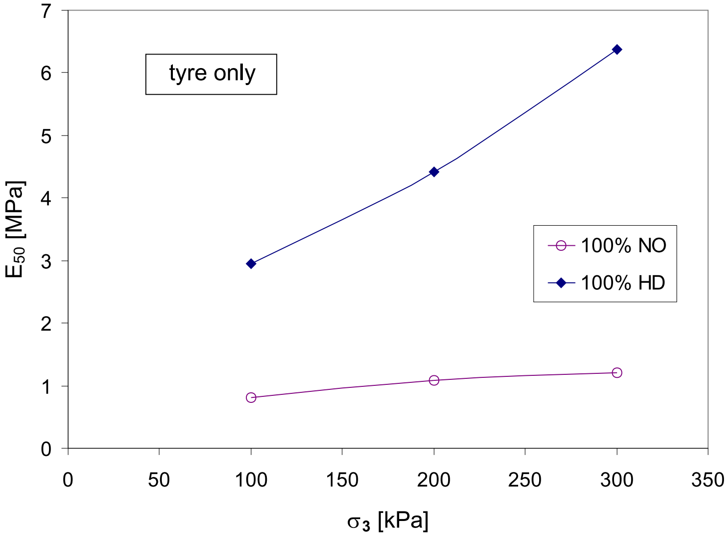

Fig. 6. Deformation modulus for the tyre chips/ shreds samples tested in triaxial test: NO – non-oriented distribution, HD – horizontal distribution

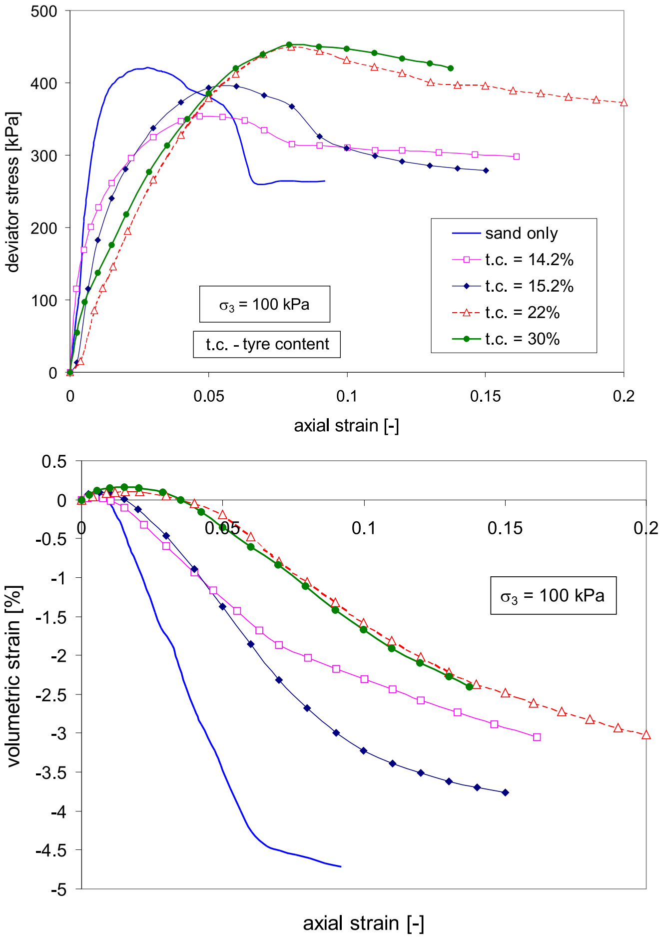

Fig. 7. Behaviour of the tyre chips-sand mixtures (NO) for different tyre content

The maximum deviatoric stress for dense sand is reached at axial strain of about 3%. For the sand-tyre chips mixtures the maximum deviatoric stress and the corresponding axial strain at failure increase with the tyre content. The axial strain at failure is about 8% for the tyre content of 30%. The optimum tyre content found in this study is close to 30%. The maximum (contractive) volumetric strain is observed for high tyre content. Dilative volumetric strain is getting reduced with higher tyre content.

Shear strength of the composite is due to the contribution of two mechanisms (Zornberg et al 2004): internal shear, i.e. mobilisation of friction angle within the chips-sand mixtures, and reinforcement mechanism due to tensile forces induced within the tyre chips or shreds. The contribution of the reinforcement mechanism of the tyre content is getting reduced with relative density of the soil matrix and with

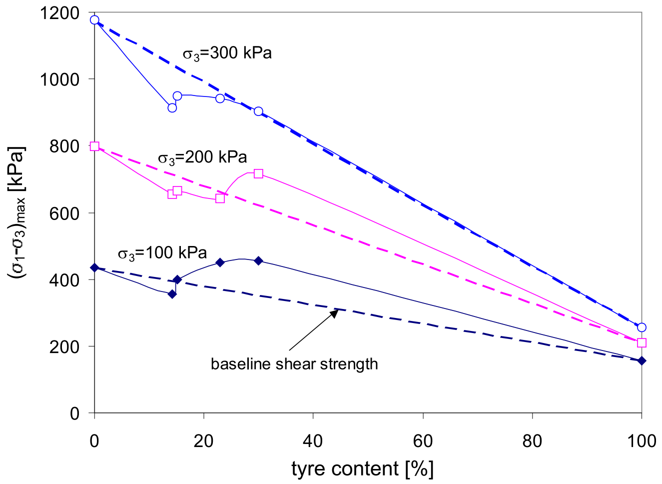

Fig. 8. Shear strength at failure vs. tyre content for different confining pressures

confining pressure. The contribution of the internal shear mechanism is presented in Fig. 8 (dotted line) as a baseline shear strength. The contribution of the second component – i.e. the reinforcement mechanism – attenuates with confining pressure. Finally, for any tyre content, no contribution of reinforcement mechanism was found at the confining pressure equal to 300 kPa. The reinforcement mechanism is getting reduced with sand density. The tests were made for the tyre content in the range from 0 to 30% and for 100%. The form of the curves for the tyre content between 30% and 100% is not related to the experiment, but it comes from the authors' suggestion, only.

It seems that the shear mechanism depends on the tyre content. Due to tyres compressibility, the sand-chip interface presents contractive behaviour, especially at high confining pressures. The friction mobilised in the chip-sand interface is smaller than the friction between the soil grains. For a small tyre content, the failure in form of slip on the chip-sand interface is not compensated by tensile or bending forces within the tyre chips, especially for small circular chips. It gives smaller shear strength of the mixture than for the sand only. A similar behaviour can be noticed in the triaxial tests presented by Zornberg et al (2004) and Gotteland et al (2005), especially for dense sand and at high confining pressure. At higher tyre content, the composite tends to have many local rupture planes within the sand mass, which follows closely the layout of the chips within the specimen (see Fig. 4b). The specimen failure is not in a form of the shear bands, but appears locally within the overall volume of the mixture**.**

The angle of internal friction and cohesion intercept are plotted (Fig. 9) for the sand, the tyre chips/ shreds and the tyre chips-sand mixtures. The maximum internal friction angle is measured for the sand specimens and decreases steadily with the

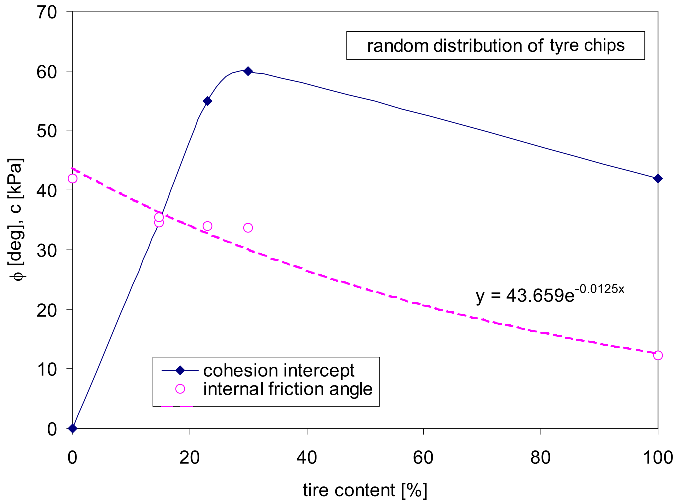

Fig. 9. Internal friction angle and cohesion intercept vs. tyre content

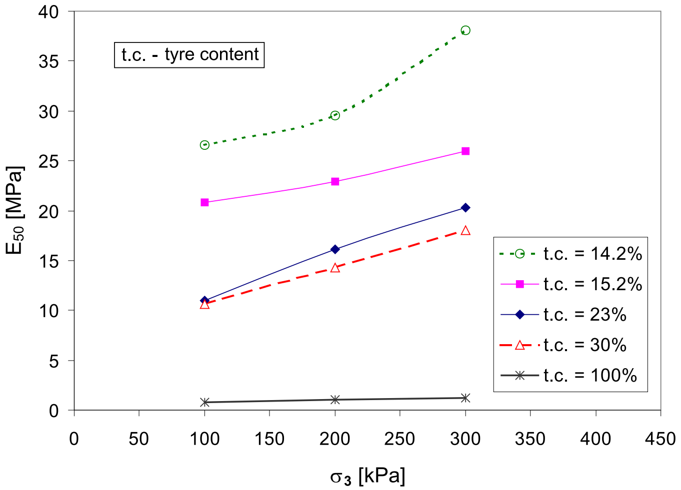

Fig. 10. Deformation modulus vs. confining pressure for different tyre content

tyre content. The maximum cohesion intercept corresponds to the optimum tyre content. The internal friction angle is considerably higher for horizontal distribution of the tyre chips (series G) than for randomly distributed tyre chips/shreds (series F), the cohesion intercept being similar in both cases. The modulus of deformation E_{50} of the tyre chips-sand mixtures highly depends on the tyre content (Fig. 10). Nearly linear increase of E_{50} with the confining pressure is observed.

4. Conclusions

The following conclusions can be drawn from the analysis of the triaxial test results:

1. Pure tyre chips specimens show a linear stress-strain relationship. Randomly distributed tyre chips/shreds have 3 to 5 times lower shear strength than horizontally oriented chips.
2. The strength and dilatancy of the mixture depends highly on the tyre content. For a small tyre content, the shear strength of the mixture is smaller than for the sand only. This behaviour – related to the sand-chips interface – reduces the reinforcement effect of the tyres. An optimum tyre content close to 30% was found.
3. The tyre-chips soil mixture has a high shear strength at relatively large strains. At optimum tyre content, the maximum deviatoric stress corresponds to the axial strain of about 8%. The mixture conserves a high post-peak shear resistance as well.
4. The reinforcement effect of the tyres is getting reduced with high density of the sand and with confining pressure. For a practical application one should avoid to compact the composite backfill to a very dense state.

Acknowledgements

The authors would like to acknowledge Anne-Sophie Malick and Henri Beny at practical training at Gdańsk UT for their experimental work. The authors wish to thank Helios Niko Pneus, Beaucaire, Langeudoc-Rousillon, France for the tyre chips and shreds used in this study.

References

Bergado D. T., Youwai S., Rittirong A. (2005) Strength and deformation characteristics of flat and cubical rubber tyre chip-sand mixtures, *Géotechnique*, **55** (8), 603–606.

Edil T. B., Bosscher P. J. (1994) Engineering properties of tyre chips and soils mixtures, *Geotechnical Testing Journal*, **17** (4), 453–464.

Foose G. J., Benson C. H., Bosscher P. J. (1996) Sand reinforced with shredded waste tyres, *Journal of Geotechnical and Geoenvironmental Engineering*, **122** (9), 760–767.

Gotteland P., Lambert S., Bałachowski L. (2005) Strength characteristics of tyre chips – sand mixtures, *Studia Geotechnica et Mechanica*, **27** (1–2), 55–66.

Pisarczyk S. (2002) Laboratory tests of suitability of synthetic and rubber wastes for the soils used for road embankments, *Drogi i mosty*, **2**, 31–51 (in Polish).

Wu Y. W., Benda C. C., Cauley R. F. (1997) Triaxial determination of shear strength of tyre chips, *Journal of Geotechnical and Geoenvironmental Engineering*, **123** (5), 479–482.

Yang S., Lohnes R. A., Kjartanson H. (2002) Mechanical properties of shredded tyres, *Geotechnical Testing Journal*, **25** (1), 44–52.

Youwai S., Bergado D. T. (2003) Strength and deformation characteristics of shredded rubber tyre-sand mixtures, *Canadian Geotechnical Journal*, **40**, 254–264.

Zornberg J. G., Cabral A. R., Viratjandr C. (2004) Behaviour of tyre shred-sand mixtures, *Canadian Geotechnical Journal*, **41**, 227–241.