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Mechanical Parameters of Rubber-Sand Mixtures for Numerical Analysis of a Road Embankment

Magdalena Kowalska [1], Maciej Chmielewski [2]

[1] Department of Geotechnics and Roads, Faculty of Civil Engineering, Silesian University of Technology, ul. Akademicka 5, 44-100 Gliwice, Poland
[2] PPI Chrobok S.A., ul. Kowola 11, 43-220 Bojszowy Nowe, Poland

magdalena.kowalska@polsl.pl

Abstract. Waste production is one of the greatest problems of the modern world. It is inevitably related to the increase of industrialization. One of the most difficult, and growing in amounts, waste is scrap tyres. The most common method of utilization of end-of-life tyres by their incineration raises much concern in terms of air pollution. More sustainable seems to reuse the tyre derived products – rubber in particular – in civil engineering, where the interesting properties of this material may be effectively utilized. This paper presents results of direct shear strength tests on sand-rubber mixtures, which were next applied to a numerical FEM (finite element method) model of a road embankment built on soft ground. The laboratory tests, conducted for two types of scrap tyre rubber granulates (0.5 – 2 mm and 1 – 5 mm in size) mixed with medium fluvial sand in various proportions (5, 10, 30 and 50% by weight), proved that the unit weight of the mixtures is distinctly smaller that the unit weight of sand alone and at 50% rubber content it drops by half. The internal angle of friction stays almost unchanged for the mixtures with up to 10% of rubber (33 - 37°), but decreases by about 10° when the rubber content increases to 50%. In most of the cases analysed, the cohesion intercept is higher in case of sand-rubber mixtures when compared to sand alone. The numerical model simulated a 4.5 m high embankment with a 3 m thick layer made of sand-rubber mixtures, containing 0%, 10% or 30% of the waste product, founded on a weak subsoil (with a 3 m layer of organic soil). The results showed that stability factor of the structure built with the layer containing 30% of the coarser rubber granulate has increased from 1.60 – for sand only, to 2.15. The embankment was also able to carry load increased from 32 kPa to 45.5 kPa and its base showed much smaller settlement. The results prove that the use of tyre derived aggregates in embankment construction is not only an effective way of utilization of this problematic waste, but can also improve behaviour of such a structure.

1. Introduction

Scrap tyres constitute one of the most difficult types of wastes. Their stockpiling has been completely banned in Europe (since 2006) and other parts of the world because of number of reasons: biodegradation of end-of-life tyres is very long (more than 100 years), they create breeding ground for disease carrying vermin, in case of (self)ignition the tyres emit black thick and toxic smoke, which is very difficult to fight. Additionally, they occupy too much space in landfills. The European legislation now requires that 75% of the produced tyres must be recovered and 15% recycled. In Poland most of the waste is incinerated in cement kilns. Much more sustainable way of recovery though, in which the positive aspects of scrap tyre rubber (durability, elasticity, low weight, damping of vibrations, etc.) can be utilized, is shredding of the tyres and the use of such a product in various applications. According to Pyskło and Parasiewicz [1] in 2003 the European production of Tire-Derived-Aggregates (TDA) consisted in: 63% of granulate (1 – 10 mm), 12% of shreds (40 – 300 mm) and chips (10 – 50 mm), together, and 8% of rubber powder. They were used mostly for sports and children-playground mats or as additives to other rubber goods. The production of the granulate is usually higher than demand – this is why the tyre shredding companies are actively looking for new markets for rubber granulates. Very promising, in terms of utilization of great amounts of this product, are civil engineering or geoengineering. Rubber granulates, similarly to rubber chips, mixed with natural soil, can be used to e.g. build embankments, backfill retaining walls, form insulating, damping or draining layers [2]–[6].

In each of these applications shear strength and deformability of the material needs to be evaluated in order to design the planned structure or element. Most of the published research results prove that the values of internal angle of friction φ and (apparent) cohesion intercept c may be increased when TDA is added, resulting in a mixture characterized with similar or better shear strength and lower unit weight γ. The shear strength parameters, obtained by various authors for rubber granulates and sand-rubber granulate mixtures are presented in Table 1. The optimum (in terms of the highest φ) mixtures have been marked with grey colour.

Table 1. Internal angle of friction and cohesion of rubber granulates and sands mixed with rubber granulates – literature review

source	size of TDA, mm	Soil type [a]	Rubber content by weight	γ, kN/m³	c, kPa	φ, °
Cecich et al (1996) [7]	1 – 10	-	100%	5.6 – 6.1	7	27
Yang et al (2002) [8]	2 – 10	-	100%	5.7	0 / 5.7 / 8.1 [b]	32 / 42 / 45 [b]
Attom (2006) [9]	< 4.76	Sand A, 8% fines, well graded, G_s = 2.65, $\rho_{d.max}$ = 1.55 I_s = 0.95	0%	-	-	25
			10%			30
			20%			37
			30%			41
			40%			45
		Sand B, 5% fines, well graded, G_s = 2.66, $\rho_{d.max}$ = 1.59 I_s = 0.95	0%	-	-	28
			10%			35
			20%			42
			30%			47
			40%			49
		Sand C, 10% fines, well graded, G_s = 2.66, $\rho_{d.max}$ = 1.66 I_s = 0.95	0%	-	-	36
			10%			42
			20%			45
			30%			48
			40%			49
Edinçliler et al (2010) [10]	1 – 3	medium dense sand; uniformly graded,	0%	13.8	0	38.7
			5%	13.4	1.3	41.2
			10%	13.0	0.2	41.4
			20%	12.4	1.1	42.6
			30%	11.8	1.2	40.0
			100%	5.4	4.6	31.0
	2.5 – 4			I_D = 30 / 60 / 90	I_D = 30 / 60 / 90	I_D = 30 / 60 / 90

Glinicka (2013) [11]		medium sand, uniformly graded; G_s = 2.65	0%	16.1 / 16.6 / 17.0	0 / 0 / 0	32.7 / 35.5 / 38.2
			10%	15.1 / 15.5 / 16.0	12.4 / 12.5 / 15.0	32.3 / 34.7 / 37.6
			20%	13.6 / 14.0 / 14.4	~ 16 / 23 / 26	32.0 / 33.4 / 34.6
Marto et al (2013) [12]	1 - 4	fluvial coarse sand; well graded; I_D = 70; G_s = 2.74; d_{50} = 0.8 mm	0%	-	-	32.8
			10%			33.5
			20%			34.2
			30%			32
			40%			31
			50%			29
			100%			17
Mohamad et al (2013) [13]	1 – 4	fluvial coarse sand, well graded; G_s = 2.66; d_{50} = 0.8 mm		I_D = 75 / 35	-	I_D = 75 / 35
			0%	16.2 / 15.1		31.3 / 25.5
			10%	14.1 / 13.4		32.8 / 29.3
			20%	12.3 / 11.8		30.5 / 27.0
			30%	11.0 / 10.3		27.5 / 24.5
			40%	9.9 / 9.3		23.0 / 21.0
			50%	8.9 / 8.3		21.0 / 20.0

[a] G_s = relative unit weight [-], I_D = relative density [%]; I_S = relative compaction [-], $\rho_{d.max}$ – maximum dry density [g/cm^3]; d_{50} = the value of the particle diameter at 50% in the cumulative grain size distribution
[b] parameters obtained for shear strains equal to 10% / 20% / 30%

Ghazavi [14] tested waste garden hose grains mixed with sand and observed behaviour similar to the one discussed above. He argued that in the mixtures containing less than 10% of rubber the sand grains encapsulate the rubber particles, so in the shear zone there is so much sand that the presence of rubber is negligible. When rubber content increases to the optimum 15%, the sand and rubber grains begin to interact and thus, apart from the obvious friction between sand-rubber, rubber-rubber and sand-sand particles, an additional horizontal resistance of sand grains penetrating into rubber grains becomes active. This increases the internal angle of friction. With rubber content over 15% the voids between rubber grains cannot be fully filled with sand and the shear strength lowers, since it is governed more by rubber-rubber contacts.

Based on the Table 1 and the above conclusions it may be summarized that there is no universal optimum rubber content in the sand-rubber granulate mixtures. In most of the cited works addition of up to 20% of rubber granulates either increases, or does not change significantly, the value of the internal angle of friction, but generates small apparent cohesion. Interestingly, the shear parameters of rubber grains alone are not much different than the ones obtained for sands, which explains why they are not able to increase the shear strength drastically. However, their unit weight is about 1/3 of the unit weight of sand, which becomes important in these applications, where the soil-rubber mixtures are to exert pressure on soft subsoil or retaining walls.

Compressibility of rubber is higher than the one of mineral sands. On the other hand, rubber exhibits much greater elasticity. As explained by Ahmed [15] this results from coupling of three mechanisms: a) rearrangement/sliding of chips at first loading – small and irrecoverable; b) bending/flattening of rubber grains - major portion of total compression, mostly recoverable at unloading; c) elastic deformation of tire chips - small and recoverable. This indicates that compression of specific sand-rubber mixtures can be reduced by increasing sand content or overburden pressure. The latter may be realized e.g. as a soil cap directly under the pavement – as suggested by Edil and Bosscher [16].

There were two goals for the research described in this paper. The first was to check, based on laboratory tests, the influence of various amounts of rubber granulates on shear strength parameters of sand. The second was to analyse efficiency of the selected mixtures to improve behaviour of a road embankment founded on soft soil.

2. Materials and laboratory tests

2.1. Materials and methodology

The laboratory tests were conducted on fluvial quartz sand, two types of rubber granulates and their mixtures, according to ISO/TS 17892 instructions: sieve analysis (wet method) [17], particle density [18] and direct shear tests [19]. The specimens were given symbols: SA = sand, FR and CR = fine and coarser rubber granulate respectively, FR-SA-x% or CR-SA-x% = rubber-sand mixtures with x% of rubber content. The particle size distribution is presented in Figure 1. All the materials were uniform (coefficient of uniformity $C_u \leq 3$): with d_{50} = 0.36 mm, 1.7 mm and 3.1 mm for sand, fine rubber granulate (0.5 – 2.0 mm) and coarser granulate (1 – 5 mm) respectively. The relative unit weight of the sand was $G_s = 2.65$, while for rubber $G_s = 1.15$. The results of the normal Proctor test for all the materials [20] showed that increase of the water content does not influence their dry density – this is why the shear strength tests were conducted for dry specimens.

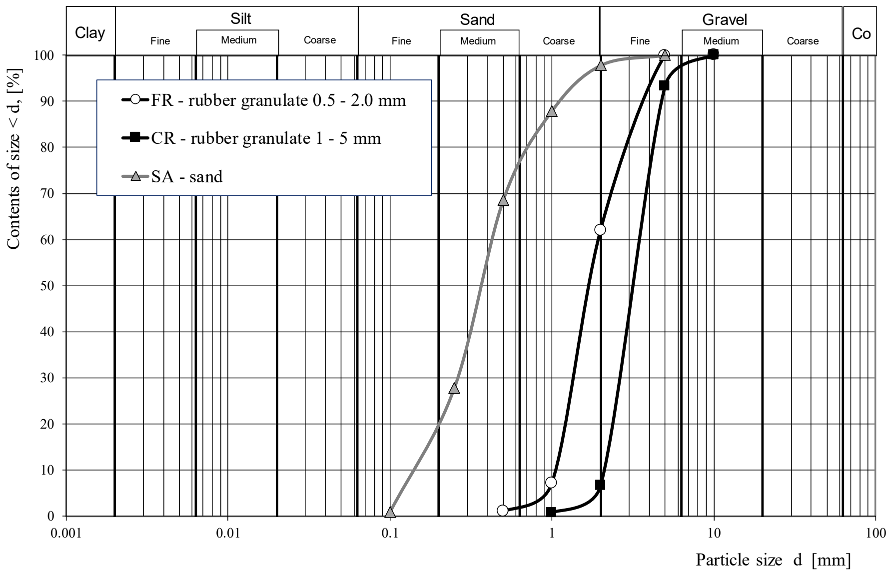
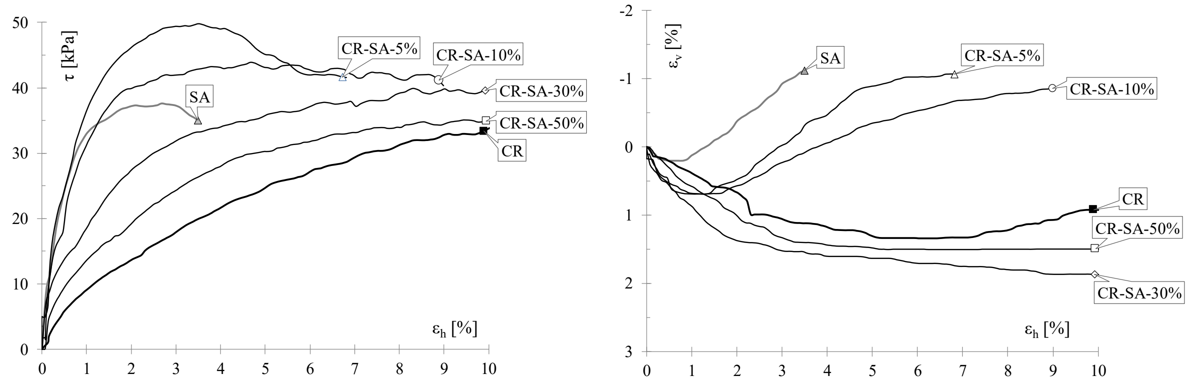


Figure 1. Particle size distribution of sand and rubber granulates

For both the granulates there were four sand-rubber mixtures prepared with varying rubber content: 5%, 10%, 30% and 50% - relatively to the mass of the whole specimen. Each specimen was compacted in three 1 cm thick layers in the shear box (10 cm / 10 cm) with standard Proctor energy. During this process segregation of rubber and sand particles was observed, similarly as described by Mohamad et al [13] – to prevent that the distribution of grains in each layer was corrected by means of a brush. The normal stresses applied during the tests were equal to σ = 25, 50, 100, 200 and 300 kPa. The compressibility of the rubber-only specimens at 100 kPa was too high to continue the direct shearing test, so additional tests at normal stresses 15, 35 or 75 kPa were conducted. The tests were terminated either after the peak shear strength was achieved or at horizontal strain equal to 10%.

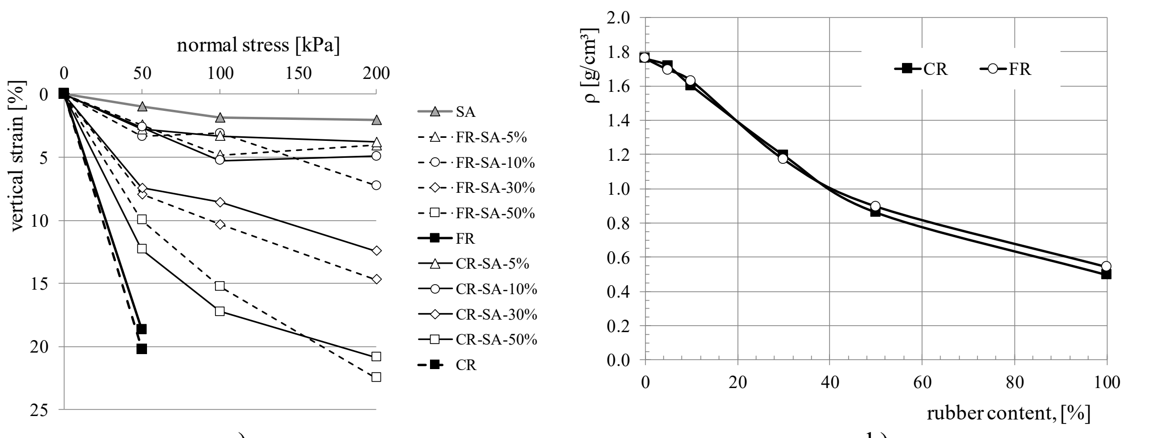
2.2. Results and discussion

Sand specimens showed peak strength at about 2% shear strain and dilative behaviour: initially small contraction and from about 0.5% strain – increase in volume. At the increasing amount of rubber in the mixtures, the mode of failure was gradually transforming into the constant increase of shear strength with only compressive behaviour. Interestingly, at higher horizontal strains the rubber-only specimens begun to show some dilation, however the final height of the sample was never greater than at the beginning of the test. As an example, the evolution of shear stress and dilatancy of sand, CR and CR-SA specimens at 50 kPa normal stress are presented in Figure 2. These observations are consistent with [14].



a) b)

Figure 2. Shearing characteristic (a) and dilatancy (b) of the CR-SA mixtures at 50 kPa normal stress



a) b)

Figure 3. Compressibility (a) and density ρ (b) of the specimens

The unit weights, shear strength parameters, together with the stiffness moduli $E_{0\text{-}0.1}$, evaluated from compressibility of the specimens during application of σ = 100 kPa are presented in Table 2. As expected, the sand-rubber mixtures showed lower bulk density ρ than sand only (see also Figure 3) – at 50% rubber content it dropped by half. The difference in the results of fine and coarser granulates was not significant. The sand-rubber mixtures were characterized with lower stiffness (see also Figure 3) and higher apparent cohesion (with the exception of the specimen FR-SA-10%) when compared to sand, which is consistent with the results cited in the literature review. The highest internal angle of friction was observed for the mixtures containing 10% of the fine rubber granulate. The Mohr-Coulomb envelopes were linear.

Table 2. Unit weight and shear strength parameters obtained in laboratory tests, together with parameters of organic soil assumed in numerical analysis

parameter	SA	FR-SA-5%	FR-SA-10%	FR-SA-30%	FR-SA-50%	FR	CR-SA-5%	CR-SA-10%	CR-SA-30%	CR-SA-50%	CR	organic soil
γ_0, kN/m^3	17.6	16.9	16.3	11.7	8.9	5.4	17.1	16.0	11.9	8.6	5.0	14
c, kPa	4.9	11.5	1.0	13.5	11.9	9.4	15.3	10.4	16.7	13.6	6.2	10
φ, °	36.3	33.7	37.2	27.7	26.3	24.4	33.3	35.2	29.1	23.9	29.4	10
$E_{0\text{-}0.1}$, MPa	5.47	2.08	3.27	0.97	0.66	0.55	3.01	1.90	1.17	0.58	-	0.5

3. Numerical model

3.1. Materials, dimensions and scope of analysis

The results of the laboratory tests were used in a numerical analysis of an embankment built on weak ground. The model was created with the use of the FEM software ZSoil.PC (v. 2016 Student). The embankment's dimensions, together with the size of the model are presented in Figure 4. Construction of the embankment was simulated in 5 steps (layers), with gradual increase of the layers' weight. All the materials were described with elastic-perfectly plastic Mohr-Coulomb constitutive model and parameters' values as shown in Table 2 (marked with frames). Five versions of the R-SA MIX layer were analysed: SA, FR-SA-10%, FR-SA-30%, CR-SA-10%, CR-SA-30%. For φ > 30° the dilatancy angle ψ was assumed as $\psi = \varphi$ - 30°, in other cases $\psi = 0$°. The Poisson's ratio was assumed as equal to 0.3. The analysis was focused on stability of the embankment, its bearing capacity (maximum allowable load q), settlement of the central points at the top and base of the embankment (A and B respectively). The stability of the structure was calculated with the use of c-φ reduction method for the stages: just after construction and after application of q = 20 kPa.

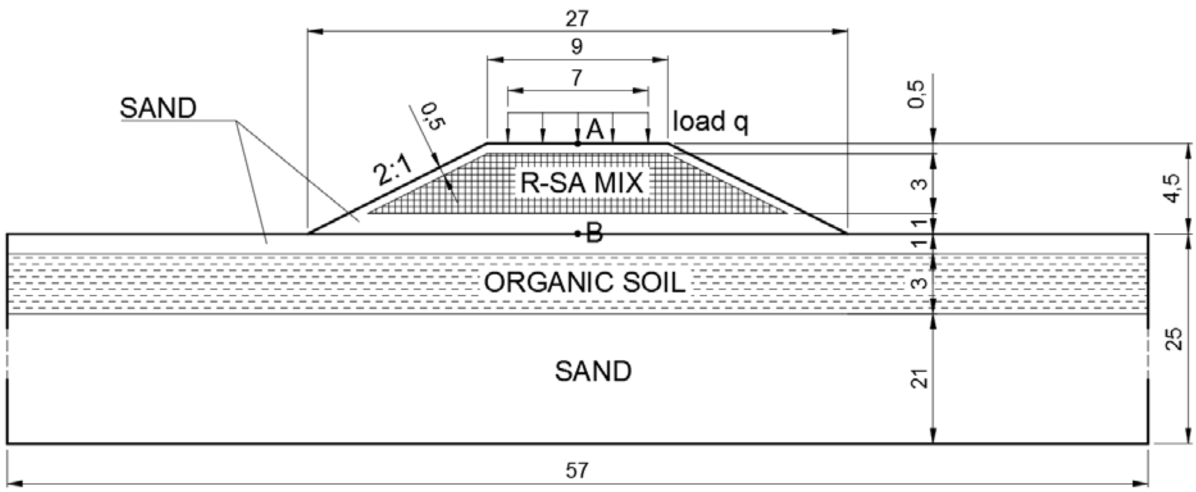


Figure 4. Numerical model

3.2. Results and discussion

The results of the numerical analysis are presented in Table 3. The results better than (or equal to) the ones for embankment built entirely of sand are marked with grey colour (higher SF or q_{max} and lower settlements).

Table 3. Results of numerical analysis

Results[a]:	SA	FR-SA-10%	FR-SA-30%	CR-SA-10%	CR-SA-30%
SF_0	1.60	1.60	2.10	1.65	2.15
SF at q = 20 kPa	1.5	1.25	1.7	1.35	1.65
q_{max}, kPa	32	29	28.5	34.5	45.5
s_{B0}, m	0.636	0.606	0.490	0.600	0.494
s_B at q = 20 kPa, m	0.748	0.717	0.611	0.718	0.614
Δs_A, m	0.145	0.148	0.178	0.152	0.169
Δs_B, m	0.112	0.112	0.122	0.118	0.120
$\Delta H = \Delta s_A - \Delta s_B$, m	0.033	0.036	0.057	0.035	0.049

[a] *SF* = safety factor; q_{max} = maximum allowable load [kPa]; s_A / s_B = settlement of the top / base central point of the embankment; subscript $_0$ = refers to situation after construction of the embankment and before external loading; Δs = settlement caused by increase of *q* from 0 to 20 kPa

When stability and bearing capacity of the embankment is considered, the optimum sand-rubber mixture turned out to be the one containing 30% of the coarser (1 – 5 mm) granulate. The SF values were raised by 34% and 10%, depending on the value of the external load *q*. The maximum allowable load was increased by 42%. The stability of the embankment before and after loading got higher also for the filling containing 30% of the finer rubber. Addition of 10% of any of the two types of granulate did not influence, or slightly increased, the initial stability of the embankment and, in case of the coarser TDA, increased the q_{max}.

Due to the presence of the very soft organic soil in the ground, the evaluated settlement of the sandy embankment's base (s_B) was very large – almost 64 cm – just after its erection, and 75 cm after application of the external load q. Introduction of the sand-rubber mixtures enabled lowering the ground deformation. Compression ΔH of the embankment caused by increase of the load from 0 to 20 kPa, was the smallest in case of the structure without the TDAs, however the differences are not greater than 2.5 cm, which makes only 0.5% of the initial embankment's height.

It should be remembered that in terms of deformations, this numerical analysis has to be considered only qualitatively - not quantitatively. Reliable estimation of the settlements requires more advanced constitutive material model, such as e.g. Hardening Soil model, and more precise results of the specimens' compressibility – e.g. based on triaxial or oedometric tests with loading-unloading loops.

4. Conclusions

Admixture of scrap tyre granulate to sand lowers the unit weight of the material in a substantial manner. Additionally, when up to 10% of the rubber by weight is used, it may positively influence the shear strength of the sample. The results of laboratory tests on sand and its mixtures with rubber grains (10 and 30% of fine and coarser granulates), applied in numerical analysis of an embankment on soft soil, proved that incorporation of sand-rubber layers into the embankment's structure may increase its stability and bearing capacity. It also causes less settlement of the weak ground underneath. The specimens exhibiting the maximum shear strength in the shear box tests turned out, however, to be less effective than the ones with 30% of rubber content. It means that, in case of applications similar to the one discussed in this paper, the mechanical parameters of sand-rubber mixtures (c, φ) are just as important as the physical ones (ρ). Taking into account that the results considering the shear strength of the sand-rubber mixtures, published in several papers, are often different, the conclusion has to be drawn that each practical application of TDA needs an individual approach.

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