Geotechnical and environmental properties of tire shreds in landfill drainage applications

Propriétés géotechniques et environnementales de lambeaux de pneus utilisés dans des drains de décharges

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ABSTRACT: In this paper an experimental study conducted to examine geotechnical and environmental properties of tire shreds is presented. Tire shreds of the size 50x50 mm^2 were investigated regarding compressibility, density and permeability. For this purpose a new apparatus with a diameter of 0.64 m was developed. The shear strength was tested for granulate of the tire material using a conventional direct shear apparatus. Tire granulates, < 10 mm, was investigated from environmental point of view. Leachability of PAHs, sulphur and metals was studied in neutral and strong basic environment. The results show that tire shreds is a low density material (440-990 kg/m^3) with a high compressibility (40% at 400 kPa) and a very high permeability (3-8 cm/sec at 400 kPa). The friction angle is lower compared to material such as sand and gravel. Tire shreds contain leachable PAHs and metals, however in proper application the leached amount of these elements will be negligible. The conducted laboratory tests indicate that the investigated material has a good potential to be used in civil engineering applications, e.g. as landfill drainage material.

RÉSUMÉ: Cet article présente une étude expérimentale conduite pour examiner les propriétés géotechniques et environnementales de lambeaux pneus. Des lambeaux de pneus de taille 50 x 50 mm^2 ont été étudiés concernant la compressibilité, la densité et la perméabilité. A cette fin, un nouvel appareil d'un diamètre de 0,64 m a été développé. La résistance aux cisaillements a été testée sur des granulés de pneus en utilisant un appareil de cisaillement direct conventionnel. Les granulés de pneus, < 10 mm, ont été étudiés du point de vue environnemental. La lixiviation des PAH, des composants soufrés et des métaux a été étudiée en environnement neutre et fortement basic. Les résultats montrent que les lambeaux de pneus ont une faible densité (440-990 kg/m^3), une grande compressibilité (40% à 400 kPa) et une très grande perméabilité (3-8 cm/sec à 400 kPa). L'angle de friction est faible comparé à des matériaux comme le sable ou le gravier. La lixiviation des lambeaux de pneus libère des PAH et des métaux, mais la quantité de ces éléments libérés est négligeable lors d'une utilisation appropriée. Les tests de laboratoire montrent que le matériel a de bonnes possibilités d'être utilisé dans des applications de génie civil, par exemple dans des drains de décharges.

1 INTRODUCTION

1.1 *General*

New knowledge is required in order to transform our society into a long term sustainable one. This knowledge has to cut across traditional academic boundaries and research areas and therefore has to be multidisciplinary. There is a need for technical, environmental sound and practical solutions that will help achieve a closed loop/circle society.

Used tires are regularly used as construction material in some states in USA, some provinces in Canada and in France but almost not at all in Germany, Great Britain and Japan. In Finland research is going on and a few field test sites with tire shreds have been constructed. Up to now, used tires have only been used to a very limited extent in Sweden.

Not long ago used tires were deposited at landfills, but how should it be managed most efficiently from an environmental point of view? In this paper a promising recycling alternative for a material based on used tires for civil engineering applications is thoroughly studied.

The objective of the study presented in this paper was to determine geotechnical and environmental properties of tire shreds. Tire shreds of the size 50x50 mm^2 were investigated regarding compressibility, density and permeability. The shear strength was tested for granulates, < 13 mm, of the tire material. Tire granulates, < 10 mm, was investigated from environmental point of view. Leachability of PAHs, sulphur and metals was studied in neutral and strong basic environment.

1.2 *Geotechnical end environmental properties*

High leachability of a regulated element, e.g. heavy metals and some organic compounds, can lead to contamination of soil, surface and ground water. If background levels are exceeded, humans, animals and plants can be exposed to elevated levels of a contaminant. Some by-products have promising engineering properties, and can be used e.g. in road constructions. When a by-product is used in a soil environment, total contents and leachability of regulated elements as well as engineering properties must be taken into consideration. Strength and deformation properties of the by-product should be identified in order to be able to calculate settlements, bearing capacity, stability, etc. Conditions like permeability, water flow velocity, pH, etc., are of equal importance. Leaching conditions can vary depending on application, e.g. leachability is not the same in an application where shredded tire is used as lightweight fill under unsaturated condition in a road construction, as in a drainage layer under a landfill containing fly ash.

1.3 *Environmental regulations*

Guideline values for regulated elements have been developed in order to evaluate the extent of a contaminant in a soil or ground water environment, and to set remediation goals at a contaminated site. The degree of contamination of soil or ground water is assessed from national Maximum Containment Levels (MCL) and/or background values. A Swedish MCL regulation for ground water contamination is pending. The lack of a finalised Swedish MCL regulation for ground water is unfortunate, as leachability of a contaminant is an important pollution factor. The following three soil MCL regulations have been identified by the Swedish Environmental Protection Agency:

- soil with sensitive use (KM), with the lowest allowable contents,
- soil with less sensitive use with ground water protection (MKM GV),
- soil with less sensitive use without ground water protection (MKM), with the highest allowable contaminant levels.

These Swedish MCL regulations are based on:

- models for human health risk, e.g. direct intake of soil and ground water, dermal uptake, inhalation, etc;
- models for environmental risk, e.g. ecotoxicological effects in soils and in aquatic environments.

In the case of contaminated soil, these guidelines can be used in order to decide whether a remediation action is necessary or not. There are no MCL guidelines for using materials e.g. by-products in soil environments. Swedish MCL regulation are therefore only used as comparison in this case.

1.4 *Contamination of soil and ground water*

A polluted soil can be a source of contamination for the ground water. However, a heavily contaminated soil presents a limited exposure risk, if the contaminant is neither soluble nor volatile. Soil and ground water sampling (field conditions) and analyses, background values, drinking water standards and MCL regulations for soil and ground water, as well as long term stability are essential to evaluate a by-product in a construction application. Laboratory leaching tests, conducted on e.g. tires are an important instrument to evaluate the hazards of a "material" in soil environments. However, field-testing is necessary in order to verify laboratory test results.

2 LABORATORY TESTS

2.1 *Testing Program*

2.1.1 Geotechnical properties

The technical properties compressibility, density and permeability have been investigated for tire shreds of size 50x50 mm^2, Westerberg and Mácsik (2000). For this study a new apparatus, with a large diameter, was developed at Luleå University of Technology in order to be able to test large particle sizes, Figure 1. One intention was to use the apparatus also for shear tests and thus have the possibility to evaluate strength parameters. However, up to now the equipment has not worked as expected in shear tests. For this reason, test results from other studies of strength properties of tire shreds have been included in this paper. However, in this study the shear strength of rubber granulates of sizes 1-3 mm and 0-12 mm, has been tested in a conventional direct shear apparatus with a sample diameter of 50 mm.

The newly developed apparatus, Figure 1, is based on the same principles as the conventional direct shear apparatus. The tested material (tire shreds) is placed, without compaction, into a cylindrical reinforced rubber membrane. The diameter is 64 cm and the initial height is 40-60 cm for a prepared sample. The rubber membrane is 9 mm thick and reinforced with a steel wire with a diameter of 2 mm. The membrane can be compressed in the vertical direction with the cross-sectional area (approximately) kept constant, Figure 1.

Tire shreds were tested for vertical pressures up to 400 kPa. This value is based on the estimated maximum pressure that a drainage layer of tire shreds in a landfill will be subjected to. In the compression tests and the tests conducted to determine density, tire shreds were tested under dry conditions, i.e. without water in the voids. However, the voids were water saturated before the permeability tests were conducted.

Figure 1 The recently developed apparatus, arranged for permeability tests on tire shreds.

2.1.2 Total constituent analyses (TCA)

In *TCA* the samples are leached out under oxidising conditions in a microwave oven with 7-M Nitric Acid in sealed teflon containers. Released metals are then analysed by plasmaemission spectrometry ICP-AES, according to EPA-methods 200.7 and 200.8. Polyaromatic hydrocarbon (PAH) analyses were conducted according to High Performance Liquid Chromatography (HPLC).

2.1.3 Leaching tests

All laboratory tests were performed at Luleå University of Technology, Sweden, Westerberg and Mácsik (2000). Laboratory leaching tests were conducted according to leaching standard prEN-12457. The leaching tests were conducted during 24 hours on a shaker, 150 rpm. The weight of the tire sample leached, was 70 g and liquid/solid (L/S) ratio was 10. The leachates were centrifuged and filtered through 45 μm Millipore filter. The filtered leachates metal content was analysed by plasmaemission spectrometry ICP-AES, according to EPA-methods 200.7 and 200.8. PAH analyses were conducted according to HPLC standard. All analyses were conducted by SGAB-Analytica AB.

In order to control the pollution potential and leachability of shredded tires, leaching tests were performed on tire fractions < 10 mm. Contents of metals and PAH, which are considered as possible pollutants, were compared with Swedish Maximum Containment Level (MCL) standards. Analyses of metal, sulphur, and polyaromatic hydrocarbons (PAH), and pH measurements were carried out on the leachates. Different pH conditions were established in these tests, distilled water and 1 M NaOH solution were used as leachants, in order to control the leachability of metals and the leachability of PAH.

2.2 *Results - Geotechnical Properties*

2.2.1 Compression characteristics

In Figure 2, four compression curves, describing vertical strain as a function of vertical stress for the tested tire shreds, are presented. The two lower curves represent first time loading and the two upper curves represent reloading (following after first time loading and unloading). The tire shreds were not compacted before first time loading. From the results it can be seen that the tire shreds compress more at first time loading compared to at reloading. This implies that a permanent deformation occurs during first time loading. The tire shreds have been rearranged to a denser state after first time loading and unloading and therefore a stiffer response takes place at reloading.

Tire shreds show a large compression at loading. At a vertical stress of 400 kPa the vertical strain is about 40% and at 100 kPa

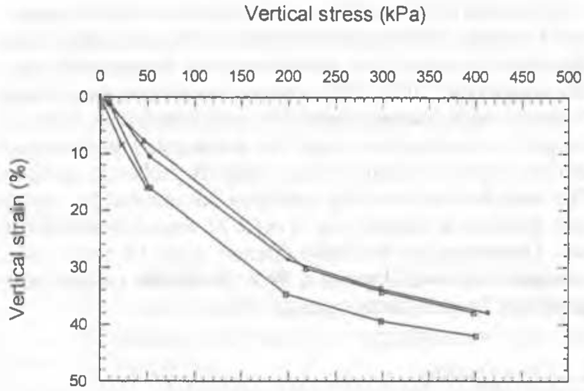

Figure 2 Results of four compression tests conducted on tire shreds ($50x50mm^2$).

Table 1 Density at different compaction states and pressures for tire shreds ($50x50mm^2$).

Loose state (no load)	At vertical stress 30-50 kPa	At vertical stress 400 kPa
440-450 kg/m^3	500-700 kg/m^3	810-990 kg/m^3

about 20%. At lower pressures significant deformations occur, about 10% strain at 30 kPa. The relation between vertical stress and vertical strain is non-linear and the largest deformations take place at the lowest stresses.

2.2.2 Density

The density of a volume of tire shreds at different compaction states and pressures is presented in Table 1. Values of density vary from 440 kg/m^3 for loose state (and no load applied) to 990 kg/m^3 at very high pressures (vertical stress 400 kPa). For stresses between 30 and 50 kPa the density is 500-700 kg/m^3.
The value of 440 kg/m^3 was determined at the 'loosest' state and should thus be the lowest possible density at dry conditions. The 'loosest' state was determined by carefully pouring tire shreds into a cylindrical membrane.

2.2.3 Permeability

The permeability of the tire shreds was determined for a high vertical stress, 400 kPa, which corresponds to about 40% vertical compression (the situation shown in Figure 1). Based on six tests with different pressure gradients the vertical permeability was found to be 3-8 cm/sec. This is a high permeability and of the same order or higher than the permeability of gravel. The drainage capacity of a layer of tire shreds is thus very high even at high pressures.

2.2.4 Shear strength

In this study, the shear strength was determined for fine-grained tire granulates, i.e. for particle sizes much smaller than the tire shreds ($50x50mm^2$), Westerberg and Mácsik (2000). Two grain sizes were tested, one with fraction 1-3 mm and the other with fraction 0-12 mm. The iron cord was separated from the particles, and thus solely the rubber material tested. In these tests, a cylindrical sample with diameter 50 mm and initial height of 14-19 mm was tested in a conventional direct shear apparatus. In Figure 3 shear stress is shown as function of normal stress at failure. Failure was defined by the peak value of shear stress, and occurred at relatively large deformations, between 0.3 and 1 radians angle deformation. The friction angle ϕ may, for example, be evaluated separately for each of the failure values in Figure 3, by allowing the Mohr-Coulomb failure line to go through origin (i.e. the cohesion intercept c = 0). Following this principle of evaluation, $\phi = 33.6°$ is obtained for the normal stress 20 kPa. For the other failure values $\phi = 23.4°$ (50 kPa), 21.3° (100 kPa),

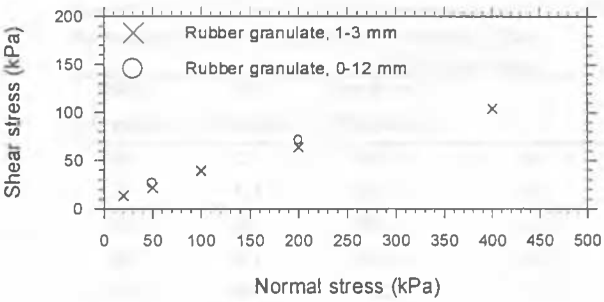

Figure 3 Failure values from shear tests conducted on rubber granulate, 1-3 mm and 0-12 mm respectively.

17.6° (200 kPa) and 14.5° (400 kPa), are obtained for granulate 1-3 mm. For granulate 0-12 mm slightly higher values of friction angle, 27.2° (50 kPa) and 19.5° (200 kPa), are obtained. The friction angle decreases with increasing normal stress, i.e. the failure line is non-linear.

When testing tire shreds the iron cord affects the interaction between the individual shreds and thus the shear behaviour. Further, the shape of the shreds (flat particles) are different from the shape of more rounded granulates. The friction angles evaluated from testing granulate may therefore not directly apply to tire shreds. However, it gives an indication of the strength properties when solely the rubber material is tested.

Typical values of strength parameters of tire shreds of sizes about $50x50mm^2$ are $\phi = 19\text{-}28°$ and c = 0-12 kPa, see e.g. Humphrey et al. (1993) and Repo (1997). For tire shreds a peak value of shear stress is normally not obtained in shear tests. If this is the case, failure is defined by a chosen strain limit. Thus, the values of evaluated strength parameters are dependent on the current shear strain. It is also important to consider the current stress interval when evaluating ϕ and c, while the failure line is non-linear.

2.3 *Results - Environmental Properties*

2.3.1 Constituents

Shredded tire, fraction < 10 mm, were analysed for metals and PAH. The content of regulated metals in the tire samples is lower than the Swedish MCL regulations for contaminated soils. Tire samples contain 24 mg/kg DS (dry solid) cancerous PAH out a total PAH content of 62 mg/kg DS. As a comparison PAH discharge is 28 µg/km DS and 140 µg/km from car tires and truck traffic respectively. The total content of cancerous PAH is higher than MCL regulations for soil with sensitive use (KM), but lower than MCL regulations for soil with less sensitive use (MKM), Table 2. However, tires can not directly be considered as 'soil contamination' case and MCL regulations were only used as comparison values.

2.3.2 Leaching tests

Leaching tests on tire shreds were conducted with distilled water and with 1 M NaOH solution. These tests were conducted according prEN 12457, and L/S = 10. As given in Table 3 the leachate contents of metals and PAH differ depending on what leachant was used. Leachability of S, Al, Cu, Pb, Zn and PAH vary depending on pH of the leachant.

The leachability of Cu and Zn from tire samples is high when leachant with high pH is used. Leachability of Pb is high, however the total content of Pb is low in the tire samples.

In an application where shredded tire is used in drainage layer under a landfill with fly ash the drainage water has a high pH.

Table 2 Total constituent analyses of tire samples and Swedish MCL regulations for sensitive soil (KM) and less sensitive soil (MKM).

	Tire shreds [mg/kg DS]	KM [mg/kg DS]	MKM [mg/kg DS]
As	< 9,95	15	40
Cd	< 1,99	0,4	12
Co	< 1,99	30	250
Cr	< 1,99	120	250
Cu	32,1	100	200
Fe	452	£	£
Mo	3,51	£	£
Ni	< 1,99	35	200
Pb	< 9,95	80	300
Zn	174	350	700
Cancerous PAH	**24**[KM]	0,3	40
Other PAH	**38**[KM]	20	40

£ no MCL regulation

3 CONCLUSIONS AND RECOMMENDATIONS

3.1 *Drainage Layer Application*

The leachability of PAH was found to be lower at high pH values. The leachate from an ash deposit has pH ranging between 8 and 13, depending on the age of the ash. The leachability of different elements from fly ash is higher than or equivalent to the leachability from tire samples. Similar leaching tests were carried out on both materials. Tire shreds will not contribute to the metal content of the leachate from an ash deposit. The leachate from the ash landfill will be distributed/re-circulated to the landfill. Leachate from the ash landfill will be monitored/analysed in a field test.

The permeability is very high for tire shreds and thus the drainage capacity is very good, Westerberg and Mácsik (2000). At very high vertical stresses, 400 kPa, the vertical permeability is 3-8 cm/sec. This is a permeability of the same order or higher than that in gravel. Tire shreds are very compressible and this fact should be taken into account when designing necessary thickness of a drainage layer. For tire shreds used in boundary zones of a construction, where the pressure is low from one side and the vertical pressure is high, stability problems might occur. The risks for such stability problems are reduced by applying a side pressure as support, e.g. a layer of coarse grained frictional soil. Depending on the lower friction angle for tire shreds, the maximum allowed slope of a layer should be reduced as compared to a layer of sand or gravel.

3.2 *Tire Quality*

The quality of the shredded tires is of great interest. It is of great importance that:

- in order to minimise release of iron and rust building, free iron cord length is limited,
- the shredded tire is washed and free from contaminants e.g. oil, fine tire particles.

Leaching tests in laboratory must be followed up with field tests in order to verify the suitability of tire shreds in drainage applications.

3.3 *Full Scale Test Sites*

The conducted laboratory tests indicate that the investigated material has a good potential in civil engineering applications. As any other material used in a construction its environmental and technical properties related to the specific construction should be identified.

The studied shredded tire material is going to be tested as drainage layer in landfill test sites in 2001.

4 ACKNOWLEDGEMENTS

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Table 3 Metal and PAH contents of lechates. As comparison German MCL values for contaminated ground water (Berlin list) and Swedish ground water MCL for PAH are listed.

		Tire shreds-Distilled water	Tire shreds-1 M NaOH	Berlin list* I	Berlin list* II	Berlin list* III	Swedish MCL in groundwater
Fe	mg/l	0,284	0,462				
S	mg/l	2,5	10,1				
Al	µg/l	8,49	901				
As	µg/l	2,27	1,69	40	60	80	
Ba	µg/l	10,6	8,08				
Cd	µg/l	0,078	0,12	5	10	15	
Co	µg/l	5,33	5,81				
Cr	µg/l	2,95	5,96	20	30	40	
Cu	µg/l	5,77	**383**	40	60	150	
Hg	µg/l	<0,02	0,0386	1	2	3	
Mn	µg/l	56,4	5,57				
Ni	µg/l	4,31	1,37				
Pb	µg/l	8,44	**48,8**	40	60	150	
Zn	µg/l	***1310***	**7050**	1000	1500	2000	
pH		7	13,6				
Cancerous-PAH	µg/l	0,03	<0,05				0,2
Other PAH	µg/l	11	3,4				10

* I – MCL in water protection area
* II – MCL in river valley/alluvial sediment
* III – MCL in for area without aquifer.
Bold style - MCL values are exceeded.

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