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Effect of Waste Rubber-Tire Crumbs on the Behaviour of Expansive Clay for the Application of Landfill Liners

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ABSTRACT

Engineered landfills have become an inevitable solution for the safe and effective disposal of Municipal and Hazardous Solid Wastes (MHSW). Compacted Clay Liners (CCLs) are extensively used as barriers due to their low hydraulic conductivity ($k < 10^{-9}$ m/s) and self-healing capacity to hinder the contaminant transport. On the other hand, the rubber-tires pose a significant threat to the environment due to the high increase in their production rate. This study aims to improve the mechanical stability of the CCLs using rubber-tire crumbs. To achieve this objective, an expansive clay was mixed with tire-rubber crumbs passing 425 µm sieve in different proportions ranging from 5% to 30% and their Atterberg limits were determined. Standard and modified Proctor compaction characteristics were determined for the clay (RC0) and clay-tire crumb mixtures with 5% rubber crumbs (RC5). Further, the hydraulic conductivity was found at optimum water content using flexible- and rigid-wall permeameters. It was observed that the Atterberg limits decreased marginally with the increase in rubber content, and the workability of clay improved. The rigid wall permeameter tests revealed that the hydraulic conductivity of the clay-tire rubber mixture meets the EPA liner criterion ($k < 10^{-9}$ m/s) when compacted only at modified Proctor compaction conditions. Based on the flexible wall permeameter tests, RC0 specimens compacted at standard Proctor compaction conditions met the EPA criterion only at high effective confining pressures. This implies that there is a huge potential to use the waste rubber-tire crumbs beneficially for clay liner applications.

Keywords: Compacted Clay liner, tire-rubber crumbs, hydraulic conductivity.

1 INTRODUCTION

Due to rapid industrialization and enhanced standard of living, there is a significant increase in the disposal of Municipal Solid Waste (MSW), thus causing several environmental problems in many countries. On a global scale, the production of MSW is expected to increase to 2.2 billion tons by 2025 from 1.3 billion tons recorded in 2010 (Hoornweg and Bhada, 2012). Dumping of MSW in engineered landfills is one of the best suitable techniques adopted in many countries (Qian et al., 2002).

Engineered landfills have become an inevitable solution for the effective disposal of solid waste (both municipal and hazardous), considering their inherent advantages. Compacted expansive clays function as barriers for waste containment, and they are mostly preferred as base/cover liner materials due to their low hydraulic conductivity ($k < 10^{-9}$ m/s) and excellent self-healing capacity. Additionally, the liners should possess adequate shear strength to carry the load and a low volumetric shrinkage (Daniel and Benson, 1990; Daniel and Wu, 1993). In pursuit of attaining low permeability in the compacted liners, they are typically compacted on the wet-side of optimum water content (Mitchell et al., 1965; Herrmann and Elsbury, 1987), which may increase their shrinkage potential. In arid and semi-arid regions, due to the seasonal moisture variations and the heat generated from the waste, the liners are subjected to alternate wetting and drying cycles. According to Benson et al. (1999), the liner thickness has a significant influence on their hydraulic conductivity, with thicker liners having lower hydraulic conductivity. They suggested a liner thickness of 0.6-0.9 m to obtain a hydraulic conductivity value lower than 10^{-9} m/s.

On the other hand, the solid waste materials occupy a large space in landfills due to the hulking nature and low weight–to–volume ratio. Therefore, to reduce the demand for landfilling, government sectors are currently promoting the concept of recycling and reuse of waste materials as a part of the infrastructure system. Several countries have encouraged the replacement of regular stabilized materials with the addition of solid wastes and/ or by-products of industries such as tire-rubbers, construction and demolition wastes, etc., resulting in the 'sustainable infrastructure'. This eventually results in the reduction in the use of natural resources and also decreases the emission levels of greenhouse gas into the atmosphere. Among other wastes, abandoned waste tires form one of the major volumes of disposal wastes throughout the world and demand more attention (Yadhav and Tiwari, 2017). These materials are one of the most problematic materials for disposal as solid wastes due to their increased level of production and durability. Thus the capacity required for storing and transporting such waste materials and culminating health hazards and associated costs pose a huge challenge. It is quite clear that due to their characteristics; low ratio of weight to volume, durability aspects, and resilient behavior, the abandoned waste tires are not coveted at landfills, which forbids them from being 'flat–packed'. These aspects which make them problematic during landfilling, form them one of the most efficient and reusable waste material for stabilization of expansive soils. The waste rubber-tyres proved to be an effective solution for the soil reinforcement as it improves the geotechnical properties of clayey soils, without affecting the mixture compressibility (Trouzine et al., 2012). As in the fiber–reinforced soils, the inclusion of rubber-tire chips gets randomly distributed in the soil matrix, and due to their rough surface nature, elastic behaviour, and low water absorption tendency, they could create a three–dimensional reinforcement network which gives better interlocking of the soil grains into a more consistent matrix with an increase in strength and ductility and a reduced volume change, thereby improving the overall integrity and stability.

The use of soil–rubber composites over the conventional earth in various engineering applications advantageously contributes to sustainable infrastructure. Recently, the application of tyre fiber mixed with a sand-bentonite mixture for landfills was examined by Mukherjee and Mishra (2019).However, the studies related to the consistency limits (Cetin et al., 2006; Trouzine et al., 2012; Srivastava et al., 2014) and their relation to the engineering properties, such as compaction characteristics, are limited. To complement one more step in the direction of sustainability, the present study aims to examine the rubber-tire crumbs in ameliorating the inferior engineering properties of expansive clays for their utilization in liners in landfill applications.

2 MATERIALS AND METHODS

2.1 Materials

Expansive soil for the current study was collected (from Chennai, India), air-dried, pulverized, and sieved through a 2 mm IS sieve. The index and engineering properties of the expansive soil were determined according to the relevant IS and ASTM codes, and the results are given in Table 1. Based on the grain size distribution and the plasticity characteristics, the expansive soil is classified as CH (inorganic clays of high plasticity) according to the Unified Soil Classification System (USCS). Tire-rubber crumbs of size passing 40 mesh (< 400 µm) were obtained from a local manufacturer. Clay–rubber–tire mixtures were prepared using different percentages of rubber crumbs by weight (5%, 15%, and 30%) and their Atterberg limits were determined.

2.2 Testing Protocol

The clay-tire-rubber mixture was prepared by adding 5% tire-rubber crumbs on weight basis to the clay soil (which is hereafter referred to as RC5), and the mixture was uniformly sprayed with distilled water of predetermined water volume and mixed to obtain a homogeneous clay-tire-rubber mixture at relevant moisture content. The mixture was stored in air-tight bags and placed in desiccators for 48 hours to attain moisture equilibrium. The aforementioned procedure was followed to prepare clay/ clay-tire-rubber mixture at the desired water contents for the compaction and swell tests. The optimum water content and maximum dry unit weight were determined for the expansive clay (hereafter referred to as RC0), and the clay-tire-rubber mixture (RC5) using the standard Proctor (SP) and modified Proctor (MP) compaction energies, and the compaction curves are compared.

Table 1. *Properties of materials*

Property	Code reference	Tire-rubber crumbs	RC0	RC5	RC15	RC30
Specific Gravity	ASTM D854-14	1.25	2.71	-	-	-
Organic content (%)	ASTM D2974-20a	0	0.5	-	-	-
pH	ASTM D4972-18	-	7.67	-	-	-
Atterberg limits	ASTM D4318-17e1					
Liquid limit (%)		-	90	83	83	78
Plastic limit (%)		-	45	42	40	35
Plasticity index (%)		-	45	40	42	42
Shrinkage limit (%)	IS:2720 (Part-6)	-	9	12	14	17
Grain size distribution	ASTM D6913-17					
Sand (%)		-	9	-	-	-
Silt (%)		-	24	-	-	-
Clay (%)		-	67	-	-	-
Unified soil classification symbol (USCS)		-	CH	-	-	-
Free swell index (%)	IS:2720(Part-40)	-	130	-	-	-
Standard Proctor compaction characteristics	ASTM D698-21					
Optimum water content (%)		-	33.0	32.2	-	-
Maximum dry unit weight (kN/m^3)		-	13.3	12.9	-	-
Modified Proctor compaction characteristics	ASTM D1557-12					
Optimum water content (%)		-	25.2	25.0	-	-
Maximum dry unit weight (kN/m^3)		-	15.8	15.1	-	-
Swell potential	ASTM D4546-17					
At 2% wet of optimum of standard Proctor (%)		-	5.95	-	-	-
At optimum of standard Proctor (%)		-	10.2	-	-	-
Water holding capacity (%)		-	26.2	-	-	-
Natural moisture content (%)	ASTM D2216-20	-	10.5	-	-	-

2.3 Hydraulic Conductivity

Hydraulic conductivity of clay-tire-rubber mixture (RC5) was determined on three identical specimens using rigid wall and flexible wall permeameters following the procedure given below.

The clay soil and clay-tire-rubber mixture equilibrated at optimum water content were placed in 30 mm high stainless steel rings of 75 mm diameter and statically compacted to a height of 20 mm using a hydraulic press for attaining the required maximum dry unit weight. A spacer disc of 10 mm high was used during the static compaction process to ensure a sufficient gap for the soil to undergo volume change. Figure 1a shows the top view of compacted RC5 specimen. Compacted specimens were sandwiched between the filter paper and porous stones at the top and bottom. The setup was held firmly in an acrylic perspex holder and placed in a swell assembly as described in Thyagaraj and Zodinsanga (2015), as shown in Figure 1b. The soil specimen was allowed to swell under vertical stress of 12.5 kPa, and the vertical deformation was monitored using a dial gauge of least count 0.002 mm. When no further volume change was observed in the dial reading after a period of approximately ten days, the setup was dismantled, and the hydraulic conductivity of the soil was determined on three identical specimens prepared in this manner.

Figure 1. *(a) Top view of compacted RC5 specimen and (b) swell setup*

2.3.1 Rigid Wall Permeameter

As per ASTM D 5856 – 15 (ASTM, 2015), the hydraulic conductivity was determined using the fully swollen specimens in the rigid wall oedometers under a vertical stress of 12.5 kPa and the hydraulic gradient of 20. The falling head method was adopted, and the hydraulic conductivity was obtained for the steady flow condition. The hydraulic conductivity for RC5 specimen at optimum water content of standard (SP OMC) and modified Proctor (MP OMC) conditions was determined.

2.3.2 Flexible Wall Permeameter

As per ASTM D 5084 – 16a, the hydraulic conductivity was determined at three different confining pressures of 20, 50 and 100 kPa using the flexible wall permeameters on the swollen specimens prepared at SP OMC. The RC5 specimens extracted from the circular rings were placed between the saturated filter papers and porous stones at top and bottom. The specimens were enclosed in a flexible membrane with O rings and the flexible wall permeameter cells were setup. The pressure difference between the top and bottom of the specimens was maintained in such a manner to maintain a hydraulic gradient of 20. The test was continued until the steady flow condition was attained at each effective confining pressure.

3 RESULTS AND DISCUSSION

3.1.1 Effect on Atterberg Limits

Atterberg limits were determined for clay-tire-rubber mixtures with different percentages of tire-rubber (5%, 15% and 30%). Figure 2 presents the variation of liquid limit, plastic limit and plasticity index with rubber content. Figure 2 shows that with an increase in the percentage of tire-rubber crumbs, there is a marginal decrease in the liquid limit for 5% tire-rubber content which remains the same up to 15% tire-rubber content and then it slightly decreases for 30% tire-rubber content. Similar observation was also made by Cetin et al. (2006), in which the liquid limit remained unchanged till 30% of rubber crumbs. Plastic limit decreased with increase in rubber crumbs. However, the workability improved with the addition of tire-rubber crumbs to the expansive clay. Younus and Sreedeep (2012) suggested a plasticity chart for selection of material for liners. They have shown that material with LL > 65 and PI > 50 satisfies the hydraulic conductivity. Therefore, the rubber contents of 15 and 30% does not satisfy the above mentioned criteria.

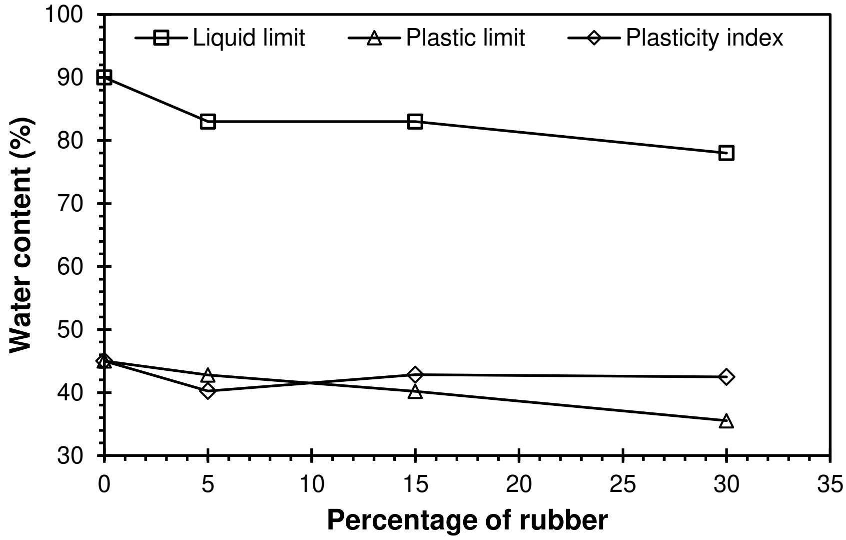

Figure 2. *Effect of tire-rubber crumbs on Atterberg limits of expansive clay*

3.1.2 Effect on Compaction Characteristics

Figure 3 presents the standard and modified Proctor compaction curves of expansive clay (with 0% rubber content, RC0) and 5% clay-tire-rubber mixture. It is evident from the figure that with the addition of tire-rubber crumbs, the maximum dry unit weight decreased, whereas the variation in the optimum water content was negligible at both standard and modified Proctor compaction energies. This could be attributed to the low specific gravity (Table 1) of the tire-rubber crumbs and their hydrophobic nature. Also, this insignificant effect on optimum water content justifies the limited effect of tire-rubber crumbs on the plastic limit of soil.

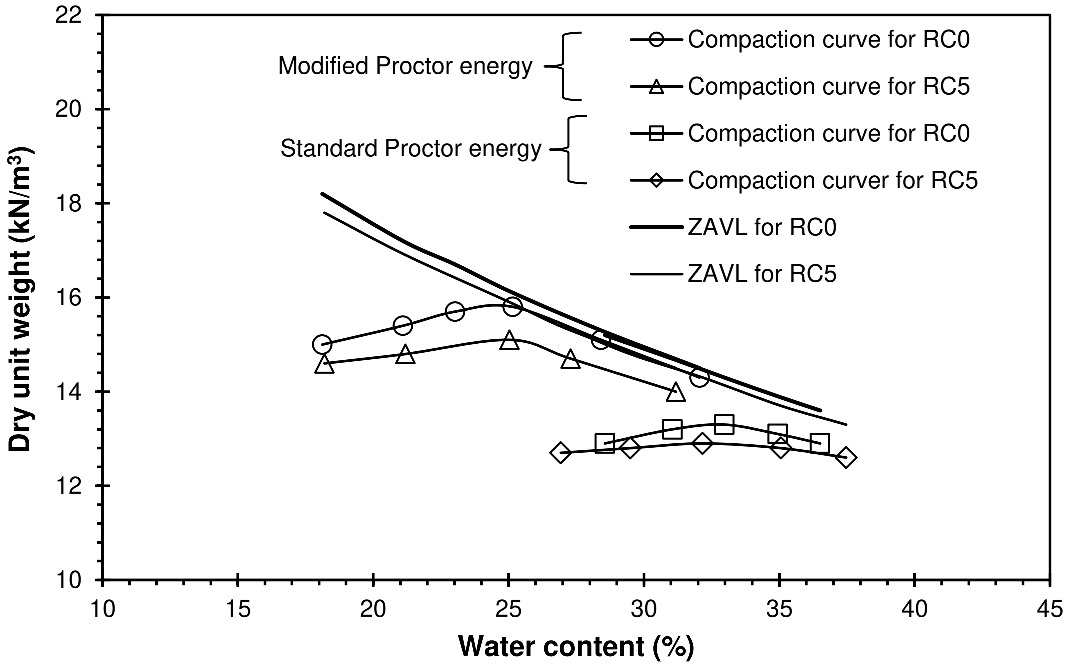

Figure 3. *Effect of tire-rubber crumbs on standard and modified Proctor compaction characteristics of expansive clay*

3.1.3 Effect on Hydraulic conductivity

The rigid wall permeameter test results on RC0 and RC5 revealed that the measured hydraulic conductivity of the expansive clay and clay-tire rubber mixture meets the EPA liner criterion ($k < 10^{-9}$ m/s) when compacted to the modified Proctor compaction conditions only, as shown in Figure 4. The inclusion of rubber crumbs resulted in an increase in the hydraulic conductivity of the clay soil. This is attributed to the additional flow channels introduced by the rubber crumbs. The RC0 and RC5 specimens tested in the flexible wall permeameter at SP OMC condition show that only at high effective confining pressures the hydraulic conductivity of the specimens could meet the EPA liner criterion (Figure 5). Also, it can be noted that with the increase in confining pressure, the hydraulic conductivity decreases. Pierce et al. (1985) found that depending on the type of waste and size of the landfill, the overburden pressure resulting from the placement of waste can impose a very high confining stress of up to 370 kPa. Therefore, it is advisable to compact the liners with clay-tire-tubber mixture using high compaction energy (modified Proctor condition) in order to attain a low hydraulic conductivity. It is clear that the clay-tire-rubber mixtures with 5% tire-rubber crumbs of size less than 425 µm can serve as a liner for engineered landfills when compacted at modified proctor energy. This emphasizes a huge potential for the reuse of waste tire–rubber in the landfill liner construction.

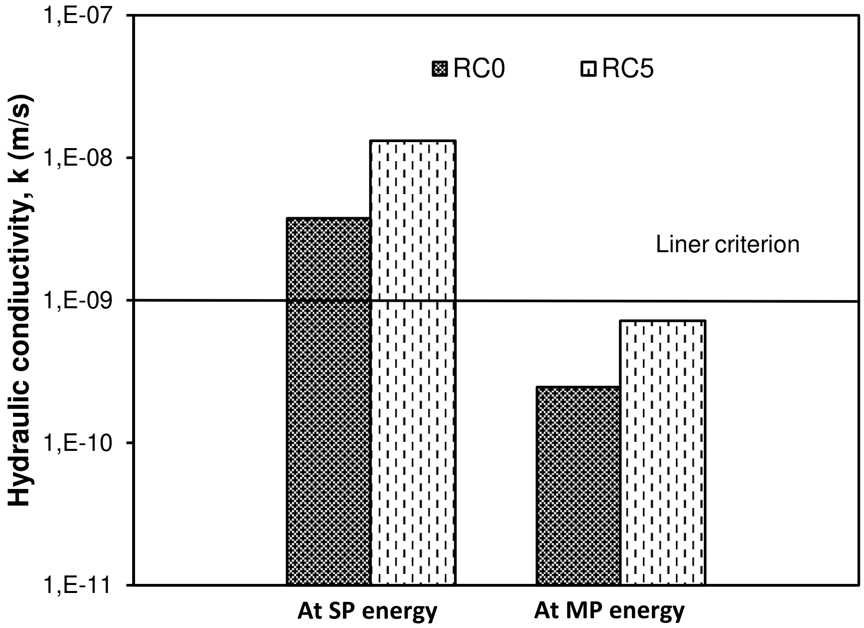

Figure 4. *Hydraulic conductivity of RC0 and RC5 specimens using rigid wall permeameter at standard and modified Proctor compaction energies.*

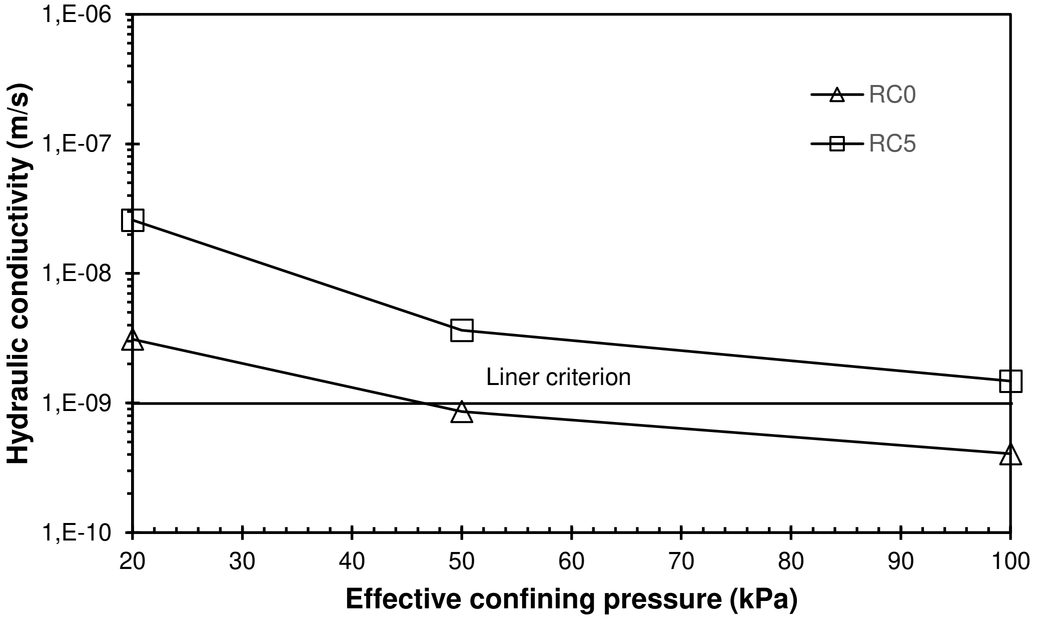

Figure 5. *Effect of confining pressure on hydraulic conductivity of RC0 and RC5 using flexible wall permeameter at standard Proctor compaction condition*

4 SUMMARY AND CONCLUSIONS

The primary objective of this study was to find the suitability of clay-tire-rubber mixture as a landfill liner material for which it has to meet the EPA liner criterion of hydraulic conductivity ($k < 10^{-9}$ m/s). Clay-tire-rubber mixtures were prepared by adding three different percentages (5%, 15%, and 30%) of tire-rubber crumbs of size less than 425 µm and their Atterberg limits were determined. It was observed that the rubber content has only an inconsiderable effect on liquid and plastic limits. Based on the Atterberg limits, it was found that RC5 mixture is more suitable as a liner material. Also, the shrinkage characteristics of the expansive soil improved with the addition of tire-rubber crumbs. The standard and modified Proctor compaction tests on RC0 and RC5 specimens revealed that there was a slight decrease in the maximum dry density whereas negligible effect on the optimum moisture content. RC0 and RC5 specimens met the EPA hydraulic conductivity criterion for liners only when compacted using the modified Proctor energy, even when tested in rigid wall permeameters. Based on tests conducted in the flexible wall permeameter, it was found that RC0 specimen compacted at SP OMC satisfied the EPA liner criterion only at high effective confining pressure. Therefore, it is recommended to compact the clay-tire-rubber mixture liners at modified Proctor energy conditions to satisfy the liner criterion. Thus, it is evident that the clay-tire-rubber mixture with 5% rubber crumbs of 40 mesh size is a promising composite for its application as a landfill liner.

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