ENGINEERING PROPERTIES OF MSW LANDFILL DAILY COVERS USING WASTE TIRE CHIPS AND PAPER SLUDGE

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SUMMARY: The use of earth materials as daily covers not only consumes valuable landfill space, but also brings a series of operating issues such as fine migration and hetergenity of waste mass. In this study, a mixture of paper sludge and waste tire chips was proposed for daily cover applications in MSW landfills. The engineering properties of the individual tire chips, the sludge, as well as their mixture, were evaluated in this study in terms of the index properties, hydraulic conductivity, and shear resistance of the materials. When compared to traditional soil covers, the proposed cover material was found to be lighter in weight, more impermeable and higher in shear resistance. It was also found that with the addition of tire chips to the paper sludge, the shear strength of the mixture improved considerably. The results suggest that the proposed material has mechanical characteristics that are desirable to be a landfill daily cover.

1. INTRODUCTION

Soils are the traditional materials for municipal solid waste (MSW) landfill daily covers, but their performance is debatable, particularly in consumption of the valuable landfill space (Aivaliotis & al. 1995; Greedy 1995; Haughey 2001; Panagiotakopoulos and Dokas 2001; Aivaliotis & al. 2004) and in contribution to waste mass hydraulic heterogeneity and instability (Hancock & al. 1999, Jang 2000, Dixon and Jones 2005). The use of waste materials, which should be disposed of to landfills, as landfill daily covers encourages the practice of waste recycling and thereby prolongs the life of existing landfills. In addition, it also provides a practical solution to places where suitable soils are not readily available.

Although many waste processing and recovery techniques, such as incineration and composting, have been proposed in the last few decades, the disposal of the remaining non-recyclable materials to landfills is inevitable. As such, the effective use of existing landfill space is very important in sustainable waste disposal practice. It has been reported that for a typical MSW landfill, the total landfill space lost due to the placement of soil daily covers alone can be as high as 25% of the total capacity (Greedy 1995, Wiles and Hare 1997).

Recent literature suggested that paper sludge is capable of adsorpting various heavy metals in contaminated water (Moo-Young & al. 2000; Ochola and Moo-Young 2004). Similar findings were reported by Smith & al. (2001) and Edil & al. (2004) for the sorption of organics on tire derived aggregate. It is hypothesized that with the use of the proposed mixture of paper sludge and tire chip, the quality of leachate can be improved as some of the VOCs and heavy metals

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will be retained by the cover material buried within the waste mass, thereby reducing the associated risks and damages in case of liner failure. This is especially important in the early years of landfill operation, where the leachate strength is considerably higher. In addition, it is believed that by eliminating soil covers in the waste mass, the service life of landfill drainage system may be extended due to lesser amount of washed soil fines (Wiles and Hare 1997).

In this paper, a waste-derived mixture of the tire chips and paper sludge was proposed for daily cover applications in MSW landfills. The key objective of this study was to examine the engineering properties of the mixture of waste tire chips and paper sludge as daily covers in MSW landfills.

2. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Tire chips

The enormous amount of waste tires dumped into landfills every year has always been a great environmental issue to the local government of Hong Kong (Tsoi and Choi 2004). Tire chips used in the study were obtained from a local private company. The tire chips were essentially a blend of rubber chips of different sizes, with particle size ranging from 2 to 40 mm. The shape of particles is highly irregular, varying from round, angular, subangular to flat. By observation, a considerable amount of cotton fabrics were embedded in some of the individual tire aggregate. No metal pieces were found in the tire chips as they were removed from the whole tires in the manufacturing process. Materials were tested as received and no additional pretreatment or sorting was required.

2.1.2 Paper sludge

Recycling and reuse of paper sludge is a topic of international interest in the past few decades. The paper sludge used in the study was collected from a local recycled paper manufacturing company. The sludge collected was a clay-like material consisting of short fibers and other impurities. During the paper recycling process, waste papers were collected and de-inked prior to recovery of the fiber. The sludge used in the study was the fiber sludge generated from the de-inking process, which contains fibers too short to be converted to a finished paper product. The sludge had been partially dewatered before discharge and the texture was soft and limp. Since the plant operated at 24 hours a day, 7 days a week, the sludge was generated continuously throughout the operating year. Freshly collected sludge samples were essentially odorless and no distinct odors were recorded..

2.1.3 Proposed cover material

The proposed synthetic cover material is essentially a mixture of the tire chips and paper sludge. To assure the quality and consistency of the final products, tire chips was allowed to expose in a room temperature of 24°C for at least 72 hours prior to mixing. On the other hand, the paper sludge was stored in air-tight containers at 4°C room to maintain its natural moisture content until mixing. It was found that the mixture can be easily and economically produced by a mechanical mixer in a short period of time. It was produced by firstly weighting the desired amount of the sludge and the tire chips and then mixed them together in a 400 mm-diameter 200 mm-height rotary mixing drum. Results showed that mixing time of about 1 minute was sufficient for uniform mixing of a 4 kg batch of mixture. The rapid mixing was attainable due to the nature of the materials and it was found that further mixing would not improve the mixing quality. Throughout the testing program, no evidence of segregation was observed in the proposed material. The mixture was stored in an air-tight container at a 4°C room to ensure consistent product quality.

2.2 Methodology

2.2.1 Index properties

To determine the relative proportions of the different particle sizes within the tire chips, sieve analysis was carried out according to ASTM D 422 on air-dried samples. Tests were performed with three representative samples taken from different batches from supplier. About 1.7 kg of the air-dried tire chips was used for each test.

The moisture content of the paper sludge was measured as received according to ASTM D2216. Organic content was determined by combusting the sample and subtracting the ash content according to ASTM D2974. Specific gravity test was conducted on the 100 g sludge samples according to ASTM procedure D854. Digital pH meter was used to determine the pH of the sludge. 20 g of representative sludge samples were mixed with 100 g of distilled water to produce a 1:5 solution by weight. After mixing, the solution was allowed to settle for 10 minutes. Once settled, readings were taken by inserting the probe into the solution until a constant reading was observed.

2.2.2 Flexible hydraulic conductivity tests

One of the major functions of a landfill daily cover is the minimization of mass fluxes between compacted waste and surrounding environment. This can be achieved by selecting a material that has dense and impermeable structure. To determine the hydraulic of the sludge and the mixture, flexible wall permeameters were used according to the ASTM D5084. Flexible wall permeameters were adopted in the study to eliminate the possibility of sidewall leakage due to the heterogeneity nature of the mixture.

Two types of cylindrical specimens (100% sludge and 50:50 mixture, by weight) were prepared and compacted using the standard hammer and mold in 5 layers with 25 blows per layer to achieve bulk density of about 1150 kg/m^3. Sample diameters and average initial heights were about 102 mm and 116 mm, respectively, with an average mass of about 1080 g. Back pressures were applied to the specimens to facilitate saturation and changes in height of the specimen were observed through the transparent cell wall. Flow measurements were taken after the samples were saturated and consolidated. Trials were repeated until at least four values of hydraulic conductivity fall within ±25% or better of the mean value, and in that particular interval of time the ratio of outflow to inflow rate were between 0.75 and 1.25. The hydraulic gradients used in the tests were similar to the field situation with local climatic conditions for realistic measurement of the hydraulic conductivities.

2.2.3 Large scale direct shear tests

It has long been known that different types of shear devices may lead to slight differences in measured values. Triaxial compression tests and large-scale direct shear tests had been the most common ones for measuring MSW shear strength in the past. In the recent work by Dixon and Jones (2005), however, the authors concluded after numerous studies that direct shear tests were the most suitable one for MSW shear strength measurement. Kavazaniian (2001) provided a detailed assessment in a previous study and concluded that triaxial compression tests were inappropriate for MSW. As such, direct shear tests were adopted for shear strength measurement of the materials for direct comparison.

Conventional direct shear tests may not be applicable for the mixture since some of the tire chips used in this study well exceeded 20 mm. Shear parameters of tire chips, sludge and mixture were determined by consolidated undrained direct shear tests with shear box size of 300 mm × 300 mm to minimize possible boundary effects. To better evaluate the immediate stability of the mixture during compaction and application process, undrained shear strength properties were reported. Rapid strain rate of approximately 1.5 mm per minute was selected to simulate undrained field condition. Although drained parameters were useful in determining long term stability of waste mass, undrained parameters were more appropriate for landfill daily cover applications. Long term landfill stability was likely governed by the settlement associated with MSW decomposition (Ling & al. 1998; Jones and Dixon 2005) rather than the consolidation process associated with daily covers..

3. EXPERIMENTAL STUDY

3.1 Stress-strain relationship and shear resistance

3.1.1 Tire chips

To examine the shearing responses of the tire chips under typical landfill conditions, four different scenarios were investigated and they were summarized in Table 1. Air-dried samples at low and high overburden pressures (test DL and DH) were stored in room temperature for at least 72 hours prior to the tests, whereas the soaked samples (test SL and SH) were soaked in tap water for at least 120 hours prior to tests. Unlike the soaked samples, air-dried samples were sheared in the absence of water. DL and SL samples were tested at low overburden pressures (10-80 kPa) whereas DH and SH samples were tested at high overburden pressures (70-380 kPa). Two different ranges of pressures were studied because a recent study suggested that materials derived from recycled rubber tires may exhibit non-linear shear strength envelop (Strenk & al. 2004).

The experimental objectives in this part were: (i) to investigate the effect of soaking on the tire chips shear strength, and (ii) to verify the applicability of the linear Mohr-Coulomb failure approximation on tire chips under different ranges of normal stresses commonly experienced by landfill daily covers. All samples were carefully hand packed into the shear box to achieve initial bulk densities of about 470 kg/m^3 (air-dried) and 530 kg/m^3 (soaked), respectively.

3.1.2 Paper sludge and Misture

The proposed mixture were compacted in the shear boxes by a standard hammer to achieve bulk density of about 660-1130 to kg/m^3, depending on the relative proportion of sludge and tire chips. Mixture with different tire chips to sludge ratios were studied one by one. The 90 mm height specimens were compacted with 30-35 blows per layer, 5 layers per sample. Compacted samples were placed in the shear box filled with tap water for consolidation prior to shearing.

Table 1. Experimental conditions of tire chips shear strength on the effects of hydrological conditions and overburden pressure.

Test ID	Hydrological Condition	Overburden Pressure	Typical landfill scenarios
DL	Dried	Low	Freshly compacted cover on sunny days
DH	Dried	High	Buried daily cover layer without leachate circulation
SL	Soaked	Low	Freshly compacted daily cover in rainy days
SH	Soaked	High	Buried daily cover layer with leachate circulation

Consolidation pressures were applied to provide two-way drainage and the vertical dial movement was monitored until the end of 90% primary settlement, as determined by the square-root-time method. The samples were then sheared to failure to obtain the shear strength parameters. Preparation of the pure sludge samples was similar to the mixture samples.

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3.2 Applied normal stress and definition of failure

The magnitude of normal stresses used in the study was carefully selected according to field situations. A recent study by Zekkos & al. (2005) on MSW landfill unit weight profile suggested that MSW density increases with landfill depth, ranging from 510 kg/m^3 to about 1730 kg/m^3. Assuming the density of freshly compacted MSW in landfill was about 700 kg/m^3, vertical stresses ranged from 30 kPa to 360 kPa were selected.

For soft materials such as the tire chips and sludge, failures are difficult to determine from the stress-strain curves, as they exhibit no sharp yield point. This phenomenon is typically found in soft compressible materials and the normal practice is to arbitrarily define failure at some reasonable strain of 10-15% (Holtz and Kovacs 1981). In this study, the higher end of the range is taken and failure is defined at 15% of strain. If the material is stressed to its natural yield point, the associated deformations are not acceptable.

4. RESULTS AND DISCUSSION

4.1 Index Properties

Sieve analysis was conducted on the tire chips to determine the particles size distribution. The quality of the tire chips was found fairly uniform. The coefficient of uniformity, Cu, was about 4.20 and the coefficient of curvature, Cc, was about 1.92. The tire chips can be described as "Well-graded" as Cu was greater than 4 and Cc between 1 and 3.

The index properties of the paper sludge, together with other waste sludge samples found in literature, were summarized in Table 2.

Paper sludge was characterized by high water content, large amount of organic fibers, neutral pH and lighter than typical cover soils. The results agree well with published data and were in the high range of the seven paper sludge samples reported by Moo-Young and Zimmie (1996). The moisture and organic content of the Japanese sludge was slightly different from the Hong Kong and the US sludge, probably because the properties of sludge were affected by the raw material quality and operation conditions of the manufacturing process.

Table 2. Index properties of various waste sludge samples.

Material	Moisture Content (%)	Organic Content (%)	pH	Specific Gravity
Paper sludge in Hong Kong	167	39	7.7	1.89
7 types of paper sludge in United States (Moo-Young and Zimmie 1996)	150-268	35-56	na	1.80-2.08
Paper sludge in Japan (Inazumi 2003)	133	63.7	7.57	1.79
Construction sludge in Japan (Inazumi 2003)	337	6.2	7.34	2.68
Sewage sludge in Hong Kong (Lo & al. 2002)	180	na	na	1.55

4.2 Hydraulic performance

Good daily covers should be able to minimize infiltration and odor emission. The average saturated hydraulic conductivities of the paper sludge and the associated 50:50 mixture (by weight) were 1.11×10^{-8} cm/s and 4.15×10^{-7} cm/s, respectively. Hence, the hydraulic performance of the proposed cover material was at least 2 orders of magnitude more impermeable than traditional soil covers. The earth cover in MSW landfills usually consist of silty and fine sands and the corresponding value is in the range of 10^{-4} to 10^{-5} cm/s. The hydraulic conductivity of MSW was about 10^{-3} cm/s, according to a number of field tests conducted in Canada by Landva & al. (1984). The dense and impermeable nature of the proposed material made it a suitable material for landfill daily covers in terms of controlling excessive percolation and unpleasant odor.

4.3 Stress-strain relationships of the materials

4.3.1 Tire chips

Typical stress-strain curves of tire chips did not show a definite yield point, at least up to 25% of strain. The shear resistances corresponding to 15% strain were plotted against applied stresses to construct Mohr-Coulomb failure envelop by the linear regression method. The results of the study are tabulated in Table 3.

The results confirmed that the failure envelops of tire chips are curved in nature, especially at low applied stresses. This observation agrees with other similar studies (Strenk & al. 2004). However, the results also suggest that the curved envelopes may be approximated by linear lines for practical purposes as the coefficients of determination (R^2) were equal to or better than 0.989 in all cases. In addition, it is also clear that differences in shear strength for air-dried samples (DL and DH) and the soaked samples (SL and SH) were negligible. The results imply that the shear resistances of tire chips are independent of the hydrological conditions and therefore the pore water from the sludge would not probably affect the strength of the tire chips. These observations suggest that the interlocking mechanism of the aggregates is responsible for the shear resistance of the tire chips, as the particle-particle frictional forces would be greatly reduced by the water lubrication effect in the soaked cases.

Table 3. Summary of the shear parameters on the tire chips alone.

Test ID	Average Initial Bulk Density, kg/m^3	R^2 of the M-C linear approximation	Cohesive Intercept (kPa)	Friction Angle (deg)
DL	472.5	0.9890	1.74	32.4
DH	473.3	0.9928	7.84	29.8
SL	532.3	0.9973	0.90	33.5
SH	535.4	0.9947	7.38	29.3

The cohesive intercepts in DL and SL samples were smaller than those of DH and SH samples. The results confirmed that the failure envelops of tire chips are curved in nature, especially at low applied stresses. This observation agrees with other similar studies (Strenk & al. 2004). However, the results also suggest that the curved envelopes may be approximated by linear lines for practical purposes as the coefficients of determination (R^2) were equal to or better than 0.989 in all cases. In addition, it is also clear that differences in shear strength for air-dried samples (DL and DH) and the soaked samples (SL and SH) were negligible. The results imply that the shear resistances of tire chips are independent of the hydrological conditions and therefore the pore water from the sludge would not probably affect the strength of the tire chips. These observations suggest that the interlocking mechanism of the aggregates is responsible for the shear resistance of the tire chips, as the particle-particle frictional forces would be greatly reduced by the water lubrication effect in the soaked cases.

Tire chips had been studied by a number of researchers in the past due to their favorable engineering properties. Based on large-scale direct shear tests, typical shear strengths of tire chips were about 20° to 35° of friction angle and 3.0 kPa to 11.5 kPa of cohesion (Humphrey and Sandford 1993; Foose & al. 1996; Bernal & al 1997). Although there were some variations of the engineering properties of tire chips, they were generally in similar trends.

4.3.2 Paper sludge and mixture

Results from direct shear machine indicated that the Mohr-Coulomb straight line approximations were also appropriate for the sludge and the mixture. The corresponding cohesive intercept and friction angle for the sludge were 5.0 kPa and 16.3°, respectively, with R^2 of 0.9844. The friction angle of the paper sludge in Hong Kong was slightly lower than that of other paper sludge (Table 4), probably due to the higher amount of water presented in the sludge (Table 2).

To determine optimal dosage of tire chips within the mixture, samples with different tire chips content (0 TC, 20 TC, 40 TC, 60 TC, 80 TC, and 100 TC) were studied. “0 TC” denoted 100% sludge, whereas “20 TC” denoted 20% of tire chips by wet weight (in their natural moisture contents). The Mohr-Coulomb failure envelopes for all cases were well characterized by linear relationship. The friction angles of the synthetic mixture ranged from 16.9° to 32.4°, whereas the cohesive intercepts ranged from 3.2 kPa to 24.0 kPa (Table 4 and 5).

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Table 4. Comparison of the shear parameters on various daily cover materials.

	Cohesive Intercept (kPa)	Friction Angle (deg)	Reference
Paper sludge in Hong Kong	5.0	16.3	Present study
7 types of paper sludge in United States	2.8-9.0	25.0-40.0	Moo-Young and Zimmie 1996
Paper sludge in Japan	3.9	40.5	Inazumi 2003
Sewage sludge in Hong Kong	8.3-14.4	26.1-31.9	Lo & al. 2002
MSW in Hong Kong	10.0	25.0	Cowland & al. 1993
Tire chips in Hong Kong	0.9-7.8	29.3-33.5	Present study
Tire chips with particle size ranged 12-50mm	0.0-11.5	20.0-35.0	Humphrey and Sandford 1993; Foose & al. 1996; Bernal & al 1997; Strenk & al. 2004
Proposed mixture	3.2-24.0	29.3-32.4	Present study
Sandy soil typically used as daily covers	0.0	27.0-30.0	Das 1998

For any given normal stress, shear stress can be computed using the above cohesive intercept and friction angle values. In the range of normal stresses considered, the results indicate that shear stress increases with increasing tire chips content, reaching a maximum in the vicinity of 55%, and then decreasing beyond this value. The results imply that additions of tire chips improve the engineering properties of the mixture considerably. These reinforcement mechanisms taking place within the mixture may be explained as follows: the soft and highly compressible sludge deformed under an applied load and squeezed into the voids of the tire chips matrix. The relocation of the sludge would be instantaneous as the tire chips themselves were soft and deformable. As sludge filled the voids, the mixture essentially behaved as a dance block. The dense and consolidated sludge supported each individual tire aggregate and bound them together. If tire chip content is too low, the mixture essentially behaves as a lump of sludge mass, which is soft and limp. On the other hand, if too much of tire chips are added to the mixture, there is not enough sludge to fill the voids and support the individual tire aggregates, thereby reducing bulk density and shear resistances of the mixture

Table 5. Effect of tire chip content on the mixture shear strength.

Tire Chip Content	Friction Angle (deg)	Cohesive Intercept (kPa)	R^2 of the Approximation
0 %	16.9	5.0	0.9844
20 %	29.3	3.2	0.9961
40 %	32.4	15.4	1.0000
60 %	31.3	24.0	0.9869
80 %	31.3	12.1	0.9998
100 % (SOAKED)	29.3	7.4	0.9947
100 % (DRIED)	29.8	7.8	0.9928

Among the many practical issues of restoration of closed landfill sites, settlement of the waste mass might be the most challenging ones (Wall and Zeiss 1995; Ling & al. 1998). It is generally believed that the waste types, cover materials, waste compaction ratios, geographical and physical conditions are the key contributing factors of landfill settlements. Final settlement as large as 30 – 40% of the initial fill height is not uncommon in MSW landfills (Ling & al. 1998). The driving force of settlement, or any other form of instability, is the self-weight of the materials. The moist unit weights of the proposed materials were about 6.5 kN/m^3 – 11.1 kN/m^3, which were 2-3 times lighter than typical soil covers. Given about a quarter of total landfill space would be occupied by daily covers, the use of the proposed mixture would reduce the severity of settlement and induce less lateral pressure against underground structures such as vertical gas extraction and leachate circulation pipes.

The results in this study showed that engineering properties of the mixture were satisfactory for daily cover applications, at least for the cases considered here. Although not included here, preliminary results on sorption capacity of heavy metals by the mixture were highly favorable. It is important to note that the use of waste materials in landfill construction and operation (such as daily cover applications) should not be confused with disposal. These waste derived products actually replace other valuable virgin construction materials that would have to be purchased.

5. CONCLUSIONS

The engineering properties of the proposed mixture have been evaluated by a series of experimental studies for the determination of the index properties, hydraulic conductivity and shear resistance of the materials. The paper sludge was characterized by high moisture and organic content, low specific gravity with neutral pH. The addition of tire chips to the sludge improved the shear resistance considerably. For all studied cases, the failure envelopes could be approximated by straight lines. Comparisons had been made between the proposed materials with the traditional soil covers and other alternatives. When compared to traditional soil covers, the proposed mixture was lighter in weight; less permeable; and higher in shear strength. The primary objective of evaluating the mixture in terms of its mechanical behavior was met. The optimal tire chip content for shear resistance were found to be 55% by weight. The results suggest that the proposed mixture has mechanical characteristics that are desirable to be a landfill daily cover.

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