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Mechanical characterization of municipal solid waste from two waste dumps at Delhi, India

B.J. Ramaiah *, G.V. Ramana, Manoj Datta

Civil Engineering Department, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India

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A B S T R A C T

The article presents the physical and mechanical properties of the emplaced municipal solid waste (MSW) recovered from different locations of the Ghazipur and Okhla dumps both located at Delhi, India. Mechanical compressibility and shear strength of the collected MSW were evaluated using a 300 × 300 mm direct shear (DS) shear box. Compression ratio (C_c') of MSW at these two dumps varied between 0.11 and 0.17 and is falling on the lower bound of the range (0.1–0.5) of the data reported in the literature for MSW. Low C_c' of MSW is attributed to the relatively low percentages of compressible elements such as textiles, plastics and paper, coupled with relatively high percentages of inert materials such as soil-like and gravel sized fractions. Shear strength of MSW tested is observed to be displacement dependent. The mobilized shear strength parameters i.e., the apparent cohesion intercept (c') and friction angle (ϕ') of MSW at these two dumps are best characterized by c' = 13 kPa and ϕ' = 23° at 25 mm displacement and c' = 17 kPa and ϕ' = 34° at 55 mm displacement and are in the range reported for MSW in the literature. A large database on the shear strength of MSW from 18 countries that includes: the experimental data from 277 large-scale DS tests (in-situ and laboratory) and the data from back analysis of 11 failed landfill slopes is statistically analyzed. Based on the analysis, a simple linear shear strength envelope, characterized by c' = 17 kPa and ϕ' = 32°, is proposed for MSW for preliminary use in the absence of site-specific data for stability evaluation of the solid waste landfill under drained conditions.

1. Introduction

Rapid economic growth coupled with increased urbanization has resulted in a phenomenal increase in the generation of municipal solid waste (MSW) in most of the metropolitan cities of India. Although landfilling of solid waste is suggested as the least preferred option in waste management hierarchy (Cossu, 2009), it is still the primary method of managing the MSW in most parts of the world and will remain so for the foreseeable future in developing economies. However, acquiring a suitable land, within an urban area or at the outskirts, for setting up of new waste disposal facilities is increasingly becoming difficult due to many factors associated with socio-economic-cultural-hydro-geological-seismic aspects. This has necessitated increasing the height of existing disposal sites further, but within their initial footprint area, thus resulting in steep slopes. For example, at Delhi, the national capital of India, the solid waste dumps are typically 45–65 m high with steep slopes, posing a threat of slope instability under both static and earthquake loading conditions.

Stability and integrity of waste mass and waste containment system must be ensured during the operation and post closure. Mechanical properties of the emplaced solid waste are required for the stability assessment of solid waste landfills. Significant insights have been gained on the mechanical response of MSW from the dedicated efforts of several researchers across the globe (Landva and Clark, 1990; Jessberger and Kockel, 1991; Grisolia and Napoleoni, 1996; Jones et al., 1997; Kavazanjian et al., 1999; Thomas et al., 1999; Gotteland et al., 2000; Zhan et al., 2008; Bray et al., 2009; Reddy et al., 2009; Singh et al., 2009; Karimpour-Fard et al., 2011; Bareither et al., 2012b; Gomes et al., 2013 among others). Database on the mechanical properties of MSW representative of Indian conditions is very limited (Babu et al., 2015) and none is available for the emplaced MSW from the dump sites/landfills at Delhi.

A comprehensive field and large-scale laboratory studies were conducted to evaluate the physical properties, strength and stiffness of solid waste required for the stability evaluation of existing old dumps at Delhi. This article presents the mechanical compressibility and shear strength properties of MSW collected from two

* Corresponding author.
E-mail addresses: janakiramsvu@gmail.com (B.J. Ramaiah), ramana@civil.iitd.ac.in, gvramanaiitdelhi@gmail.com (G.V. Ramana), mdatta@civil.iitd.ac.in, mdatta55@gmail.com (M. Datta).

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dumps at Delhi. Based on the statistical analysis of the shear strength data obtained from this study as well as the extensive data reported in the literature, a simple linear shear strength envelope is proposed for MSW that can be useful for preliminary stability evaluation of MSW landfills in engineering practice.

2. Background

Mechanical properties of the solid waste play a crucial role during the operation, closure and post-closure phases of the waste containment facilities. Several researchers investigated the influence of various factors such as the composition, density, age or degradation, rate of loading, confining stress, moisture content etc. on the strength and stiffness of MSW. It is well recognized that the mechanical response of MSW is significantly influenced by the composition or the fibrous materials such textiles, plastics, paper and wood (Zhan et al., 2008; Reddy et al., 2009; Bray et al., 2009; Karimpour-Fard et al., 2011; Yuan et al., 2011; Ramaiah et al., 2014, 2015) and fibrous inclusions induce the anisotropic behavior to MSW (Zekkos et al., 2010b, 2013). Additionally, it is reported that the shear strength of MSW is dependent on the relative orientation of the fibrous materials with respect to the shearing direction and is a function of the apparatus employed for testing (Ramaiah and Ramana, 2017).

Shear strength of MSW is evaluated using several techniques including: (1) the back analysis of failed or stable slopes, (2) large-scale in-situ testing (direct shear or load bearing tests) and (3) laboratory testing of intact or reconstituted MSW. Triaxial compression (TXC), simple shear (SS) and direct shear (DS) apparatus are used for evaluating the shear strength and stiffness parameters of MSW. However, DS apparatus is the most popular one employed for the shear strength characterization of solid waste (Stark et al., 2009; Bareither et al., 2012b) due to simplicity in the specimen preparation and testing procedure compared to other devices. Shear strength of MSW measured using DS apparatus is generally conservative compared to that measured using TXC apparatus. This is because of the predominant orientation of fibrous elements parallel to the shearing direction in DS device, wherein the reinforcement action from fibrous elements is not significantly engaged (Bray et al., 2009). Shear strength of MSW evaluated using the DS apparatus is reported to be similar to that estimated from the back analysis of stable and failed landfill slopes (Kavazanjian et al., 1995; Eid et al., 2000).

Stress-strain or stress-displacement behavior of MSW is strain hardening without a definite peak stress (rupture or failure) both in the field (in-situ DS tests) and laboratory tests (DS, TXC or SS). Hence, the shear strength parameters i.e., the apparent cohesion (c') and friction angle (ϕ') are computed at a specified level of strain or displacement to limit the excessive deformations in the containment system (Jessberger and Kockel, 1991; Grisolia et al., 1991; Pelkey et al., 2001; Reddy et al., 2009; Stark et al., 2009; Bray et al., 2009; Karimpour-Fard et al., 2011; Gomes et al., 2013; Babu et al., 2015). Stark et al. (2009) recommend using 10% axial strain for TXC tests or 25 mm horizontal displacement for DS tests as the limiting strain criteria to maintain strain compatibility between MSW and other components of landfill system exhibiting strain-softening behavior (geosynthetic interfaces and foundation soils). Several empirical shear strength envelopes for MSW are recommended in the literature beginning 1995 and are summarized in Table 1. The most recent strength envelope is a non-linear model proposed by Bray et al. (2009) and Zekkos et al. (2010b) based on the statistical analysis of 109 large-scale DS tests.

Effect of age or degradation of MSW on shear strength parameters reported in the literature is contradictory. Some researchers reported a decrease in both c' and ϕ' with decomposition (Landva and Clark, 1990; Konig and Jessberger, 1997). Caicedo et al. (2002) observed a decrease in ϕ' and insignificant change in c' with the aging of MSW. Bareither et al. (2012b) reported an increase in ϕ' with an increase in the degree of decomposition and did not find any conclusive correlation between c' and decomposition of the waste. An increase in ϕ' and a decrease in c' with the aging of MSW were reported by some other researchers (Zhan et al., 2008; Gomes et al., 2013). On the other hand, a decrease in ϕ' and increasing trend in c' with increasing age or degree of degradation is observed by some researchers (Gabr et al., 2007; Reddy et al., 2015). Contradictory observations related to the effect of age or degradation on the shear strength of MSW requires further investigations.

Table 1
Summary of the shear strength envelopes recommended for MSW by different researchers.

Reference	Envelope type	Strength envelope details
Kavazanjian et al. (1995)	Bi-linear	c' = 24 kPa, ϕ' = 0° for σ_n < 30 kPa and c' = 0 kPa, ϕ' = 33° for 30 < σ_n < 300 kPa
Manassero et al. (1996)	Tri-linear	c' = 20 kPa, ϕ' = 0° for σ_n < 20 kPa, c' = 0 kPa, ϕ' = 38° for 20 < σ_n < 60 kPa and c' = 20 kPa, ϕ' = 30° for 60 < σ_n < 250 kPa
Jones et al. (1997)	Linear	c' = 5 kPa, ϕ' = 25° for σ_n < 400 kPa
Eid et al. (2000)	Linear	c' = 25 kPa, ϕ' = 35° for σ_n < 400 kPa
Stark et al. (2009)	Bi-linear	c' = 6 kPa, ϕ' = 35° for 0 < σ_n < 200 kPa and c' = 30 kPa, ϕ' = 30° for 200 < σ_n < 500 kPa
Bray et al. (2009) and Zekkos et al. (2010b)	Non-linear	c' = 15 kPa, $\phi' = \phi'_o - \Delta\phi'$ [log(σ_n/p_a)] where: ϕ'_o = 36° and $\Delta\phi'$ = 5° and p_a = 101.3 kPa

The purpose of this article is to evaluate the compressibility and shear strength of emplaced MSW collected from two waste dumps at Delhi and to contribute to the database on mechanical properties. Data from the large-scale DS tests conducted on MSW from this study is analyzed to examine the influence of various parameters such as the composition or fibrous materials, normal stress, age or degradation, density and horizontal displacement on the shear strength of MSW.

3. Dump sites for the present study

The Ghazipur dump site and the Okhla dump site, both located in Delhi, are unlined facilities and have been receiving the MSW and construction and demolition waste (often co-disposed together) since last three decades. The tipping over method of disposal is practiced at these dumps and results in a relatively loose state of MSW. Slopes forming the periphery of the dumps are relatively steep. The repose angles of the slopes are in the order of 38–47°. Vertical cuts ranging from 3 to 5 m, which are made for providing/widening the access roads or for making the benches are observed to remain stable for long periods. Occasional fires and smoldering at some locations were also observed mainly during summer seasons.

The Ghazipur dump site (Fig. 1a), covering an area of about 28 hectares (~283,578 m^2), is about 680 m long and 360 m wide. The dump is underlain by the fluvial deposits of sandy silt to silty sand. Disposal operations at this site began in 1984 and at present, the site receives about 2600 Metric tons of solid waste per day. Significant ponding of leachate at the southern side of the dump was observed during field visits. The base of the dump is about 3 m below the surrounding ground level. The total height of the dump from its base to the crest varied between 45 and 47 m as on August 2012. Slopes forming the periphery of dump varied between 37° and 75° with horizontal. The Okhla dump site (Fig. 1b), covering