Compressibility and Shear Strength of Fresh Municipal Solid Waste from Bharwara Landfill, Lucknow

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Abstract-Cities generate large amount of municipal solid waste daily. MSW if not disposed property can bevery harmful for environment and causes soil, water and air pollution. Landfilling is most populartechnique for waste disposal and widely adopted in India. For successful operation of landfills and to design landfill and its components, solid waste properties are required. Settlement and slope stability are two important parameters that decide the design life of a landfill. In current study, various engineering properties of fresh MSW obtained from bharwara sewage treatment plant site are evaluated. Experimental program includes behaviour assessment of MSW through gradation, specific gravity, compaction, compressibility (primary and secondary compression), hydraulic conductivity, and shear strength. The primary focus of experimental work was to obtain settlementand strength parameters of fresh MSW. Based on obtained properties, numerical analysis was performed using soft soil creep (SSC) and Mohr Coulomb (MC) material models to obtain the settlement and slope stability of a typical landfill. Settlement was also calculated by an analyticalmethod and compared with numerical result. It was found that settlement calculated by modellingMSW using MC material model was found to be significantly less compared to SSC material model. Reason for the lesser value of settlement in MC model is primarily due to the negligence of secondary compression or creep. Settlement obtained by the analytical solution was found to becomparable with the numerical study performed using SSC model. Reduced slope stability was observed as landfill height increased. Settlement and slope stability analysis was performed after providing landfill cover and more settlement and less slope stability was found for covered landfillcompared to uncovered landfill.

INTRODUCTION

Municipal soil waste

Solid waste generation is integrated part of our daily life. In India, big metropolitan cities generatetonnes of waste daily. Large amount of MSW requires very careful and efficient storage, collection, transportation and disposal system to avoid any environmental damage. In India collection and disposal system of MSW is not very efficient as according Sharholy et al. (2007), 90% of waste in India is disposed in open dump sites, and this open dumped MSW is serious threatfor environment as it causes air, water and soil pollution.

MSW generally contains various materials like paper, cloths, kitchen waste, construction waste, chemicals, tyres, polythene etc. These different types of materials need different type of treatment like some wastes are recyclable for example – paper, plastic bag, plastic bottles, card board, woods etc., hence this type of waste is shorted out and send for recycling, other hand kitchen and food waste needs proper biological treatment before disposal, construction and inorganic waste can be disposed without any biological treatment.

These different materials affect environment in different manners, organic waste like unconsumed food or kitchen waste if disposed without proper treatment may decompose on site and causes bad odour and attract insects, harmful chemical generated from industries causes soil pollution, after coming in contact of rain water it generates leachate which seeps to ground water table and causes serious contamination of ground water, electronic wastes contain some very reactive and harmful chemicals like mercury and can't be disposed with normal waste. Air pollution is also greatly associated with MSW, as MSW landfills generates high amount of gases mainly methane and CO2, these gases are very common in uncovered landfills and apart from air pollution these gases mix with vapour and cause acid rains also.

Solid waste management

Most efficient management system of MSW contains four processes these are – generation, storage, collection, transport and disposal. Talking about Indian scenario of waste generation, in year 2004 -05, major 59 Indian cities generated 39031 tonnes of waste daily which increased to 50592 tonnes per day in year 2010 – 11 (CPCB, 2000). Despite of large waste generation, in India waste storage and collection process is badly organised. Due to lack of awareness and proper regulations waste disposal on roads are very common, that waste is further scattered by stray animals. Waste pickup service by municipal corporation is also not regular that causes large pile up of waste on side of roads and streets. Before final disposing of waste in landfills, proper treatment is provided to minimise any chances of environmental damage. Leachate and gas generation are two common problems associated with landfill, to prevent any groundwater contamination due to leachate appropriate lining of landfill is provided.

Considering difficulty and cost associated with waste disposal, a good practice is to reduce,recycle and reuse waste. Reducing waste generation is alone able to cut lots of waste treatment cost. Using daily resources wisely can be helpful to reduce waste generation. Recycling is also very effective measure to reduce amount of waste to be disposed. Large portion of waste can be recycled by using simple or special processes. Plastic bottles, papers, plastic goods, metals are easily recyclable. Some special parts can also be extracted from electronic component to reduce these type of wastes. Reusing means using unusable materials again after little treatment or modification, various organic waste can be decomposed in to manure known as composting.

Composting can be done by either aerobic or anaerobic environment. Aerobic process is fast whileanaerobic process is slow in which gas generation is takes place. Solid waste can also be used in energy generation. Some types of wastes have good calorific value and can be burn to produce electricity known as waste to energy (WTE). Bricks and tiles can also be made from fly ash obtained after burring the waste. WTE process is widely adopted in developed countries but due its costly nature, it is not popular in India. Bharwara landfill this process is used to generate electricity, but due to lower calorific value of Lucknow waste and uncertain quality of obtained waste, generated electricity is very less and inconsistent.

Scope of work

Lucknow is big city located in central India. This city has some big institutes, hospitals and industries; thus, population of this city is around 4.5 million (census-2011), with population densityof 1449 persons/square km., this city generates 1600 tonnes waste daily (CPCB, 2000) that is 0.62 kg/person/day. Lucknow municipal corporation authorised A2Z company for collection, transportation, treatment and disposal of waste. Bharwara landfill site is located in outskirt of city where large integrated solid waste management plant is developed by company.

Considering very large volume and high rate of waste generation various engineering properties of solid waste is required for proper disposal of waste. In current study, fresh MSW sample is collected from Bharwara landfill site and various engineering properties of fresh MSW is obtained in geotechnical laboratory Snow fountain. Compaction test is conducted to obtain the moisture content effect on dry unit weight of solid waste. This compaction test result is used as baseline to perform other tests on different compaction levels.

A primary aim of this work is to determine compressibility characteristics of fresh MSW. Primary and secondary consolidation tests have been conducted on fresh MSW at various moisture contents by direct and step loading methods. Secondary consolidation test is conducted to obtain long-term settlement in landfills, which is very useful to predict the age of MSW landfill and to design various landfill components like leachate and gas collection systems, liner, landfill cover etc. Shear strength of fresh MSW is important factor, which governs the slope stability of landfill. Shear strength parameters are obtained by conducting consolidated undrained (CU) triaxial test.

To simulate potential of obtained results, numerical analysis is conducted for a typical landfill configuration using FEM and various parameters like settlement, pore pressure vertical stress has been obtained. In this analysis, soft soil creep and Mohr Coulomb soil models are used.The parameters of SSC and MC model are calculated from compaction, consolidation and CU triaxle tests. Apart from numerical method, settlement of landfill is also calculated using analyticalsolution given by Sowers (1973) and both results are compared.

RESULTS AND DISCUSSION

Compaction

Compaction is the process in which the soil particles are rearranged and packed together into a closer state of contact by mechanical means in order to decrease air voids of the soil and thus increase density, shear strength and bearing capacity, and reduce settlement and control hydraulicconductivity. According to Holtz and Kovac (1981), compaction is the densification of soil by theapplication of mechanical energy. It may also involve modification of water content as well as gradation of soil. The standard Proctor compaction test as explained in chapter 3 was repeated multiple times at varying moisture contents to form the basis for the compaction curve, which illustrates the relationship between dry unit weight and moisture content. The results of compaction testing are generally plotted as dry unit weight versus moisture content. Figure 4.1 shows the compaction curve of fresh MSW obtained from three trials. A good repeatability of thetest results can be noticed.

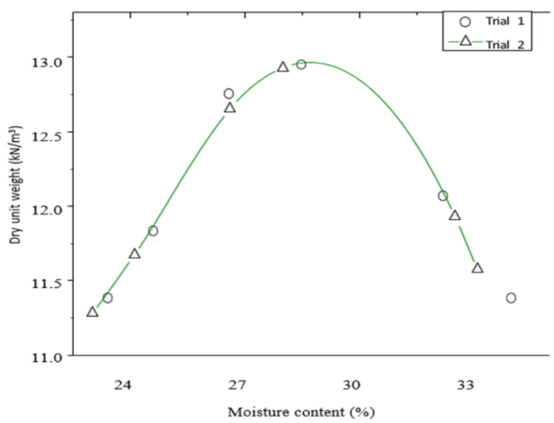

Figure 1.1 Variation of dry unit weight of fresh MSW with water content

It can be noticed that as water content increases, dry unit weight also increases. As the water content increases the particles develops larger and larger water film around them which tend to lubricate the particles and make them easier to be moved about and reoriented into a denser configuration. At a particular water content, sample achieve maximum dry density and corresponding water content is known as optimum moisture content (OMC). If water content is increased beyond OMC, water starts to replace soil particles in the mold and since $\rho w < \rho s$ the drydensity curve starts to fall off (Holtz ad Kovac, 1981), as shown in figure 4.1. No matter how muchwater is added the soil never becomes fully saturated by compaction as during compaction processsome air is always trapped inside sample. The maximum dry unit weight and optimum moisture content of fresh MSW was found to be 12.94 kN/m^3 and 28.5% respectively. Table 4.1 is showing the dry unit weight of waste sample at different moisture contents.

Table 1.1 Dry unit weight of fresh MSW at various moisture contents

Moisture content (%)	Dry unit weight (kN/m^3)
28.5 % (OMC)	12.94
32.5 % (OMC+4%)	11.96
24.5 % (OMC-4%)	11.77

Hettiarachchi (2005) conducted similar experiments on a laboratory produced waste with a maximum particle size of 12.5 mm and determined a maximum dry unit weight of 5.15 kN/m^3 at 62% moisture content using standard compactive effort. The laboratory waste was generated tosimulate the average composition of U.S. municipal solid waste. The composite specific gravity of the waste mixture was determined to be 1.6. Gabr and Valero (1995) determined the compactedunit weight and optimum moisture content through compaction tests. The maximum dry weight density was 9.3 kN/m^3 and optimum moisture content was 31%. The variation of the measured unit weight with increasing moisture content was similar to that observed in soil. Full saturation was achieved at approximately 70% water content with a unit weight of 8 kN/m^3. A unit weight of 12 kN/m^3 was estimated from the zero air void curves at moisture content of 31%.

Reddy et al (2009) reported the maximum dry unit weight and optimum moisture content of fresh waste for Orchard hills landfill as 4.12 kN/m^3 and 70% respectively with maximum allowable particle size 40 mm. The optimum moisture contents for wastes are significantly higherthan for most soils, ranging from 31% to 70% (Gabr and Valero 1995, Hettiarachchi et al. 2005, Itoh 2005, Reddy et al. 2008a). The differences in maximum dry unit weight and moisture contentbetween the observed and reported could be due to differences in maximum waste component size, nature of waste as well as component size distribution. Punia (2014) performed same study on MSW residue obtained from Bharwara landfill Lucknow. The response of unit weight with water content for fresh as well as for MSW residue wasfound to follow same pattern. Maximum dry unit weight obtained for MSW residue was 13 kN/m^{3}and corresponding OMC value was 24 %. For fresh MSW maximum dry density (γd) was found 12.94 kN/m^3 at OMC 28.5%. Considering MSW residue which had decomposed waste with high specific gravity its maximum dry density was found higher than fresh MSW. Similarly, γd value obtained at 4% dry and wet side of optimum moisture content was 12.65 kN/m^3 and 12.85 kN/m^{3}for MSW residue and this value for fresh MSW was 11.77 kN/m^3 and 11.96 kN/m^3. Since the fresh MSW is initial outcome from the complete integrated solid waste management, the percentage organic content and the particle sizes are found to be large and specific gravity was found to be low when compared to the MSW residue reported in various literatures, hence, comparison of test results, obtained for the MSW residue with the results of fresh waste reported in various literatures can therefore be done with caution.

Field compaction of MSW is critical for control of waste and also has important environmental and economic implications. Control of the moisture content of wastes during compaction may have potential to change both the compacted dry unit weight and subsequent engineering properties of the waste. The unit weight of compacted waste will depend upon the waste components, thickness of layer, weight and type of compaction plant and the number of times equipment passes over the waste (Wong 2009). Remaining tests for compression, hydraulic conductivity, and shear strength were performed in sets of three: one below/dry of optimum moisture content, one at the optimum moisture content, and one above/wet of optimum moisture content. Target dry unit weights as calculated from the trend line for the tests are presented in Table 1.1.

Compressibility

Consolidation test was performed on fresh MSW to determine compressibility behaviour. The totalamount of compression of a soil is the sum of three mechanisms: elastic compression, consolidation, and secondary compression or creep. Elastic compression of soil occurs as a resultof the application of load to the soil, resulting in compression of the voids within the soil matrix and rearrangement of the soil particles into a tighter packing structure. Elastic compression of soil is a function of initial void ratio, applied stress, and stress history of the soil. The application of load to soils is generally considered to result in an elastic response. Although the portion of settlement described as elastic settlement is not truly elastic, it is often approximated with the use of elastic theory. Elastic settlement occurs in an undrained state, prior to dissipation of excess pore pressures due to loading (Lambe and Whitman 1969). Consolidation occurs as the water within the soil pore space is expelled by continued loading and is time-dependent. Continued settlement due to consolidation is generally more pronounced in fine grained soils as the hydraulic conductivity is lower and the rate of pore water drainage is orders of magnitude lower than that of coarse-grained soils. Consolidation of soils is often approximated using Terzaghi’s one-dimensional consolidation theory (Terzaghi and Peck 1948). With the passing of time, as the pore water dissipate the rate of flow decrease and eventually, the flow ceases altogether, leading to a condition of constant effective stress. After that soils exhibit time dependent settlement at constant effective stress due to plastic readjustment of soil fabric, known as secondary compression settlement.

Secondary compression of soils occurs after excess pore water pressure has dissipated and at constant vertical pressure. The secondary compression of soils is time dependent and is particularly problematic in organic soils such as peats (Holtz and Kovacs 1981). The similar concept used here in case of fresh MSW. It can be assumed that the total settlement, (excluding any contribution from the subgrade) is made up from two main components; primary compression and secondary compression. Primary compression includes physical compression of particles (distortion, bending, and crushing and particle orientation) and consolidation which is significantfor saturated waste bodies.

Primary compression

Consolidation test was performed on fresh MSW to determine compressibility behaviour. Test was performed at three compaction levels i.e. optimum moisture content and 4% of dry and wet side of optimums. Quantifying compressibility characteristics in MSW is more complex than doing so in soils due to its heterogeneity and the interaction of a variety of non-uniform particles.Figure 4.2 shows the variation of void ratio of fresh MSW with vertical pressure in logarithmic scale for loading-reloading cycle.

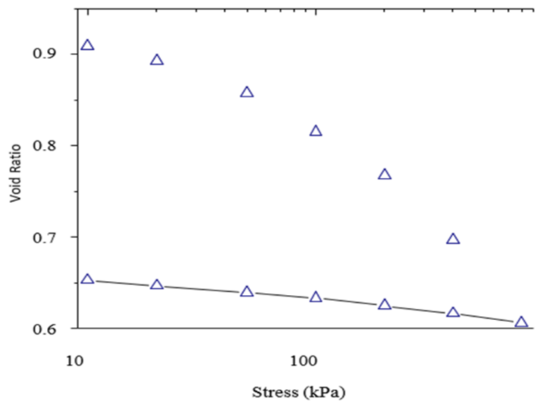

Figure 1.2 Variation of void ratio of fresh MSW with vertical pressure (e-log p - plot) for OMC +4%

A considerable decrease in the void ratio can be noticed after loading the fresh MSW sample. The compression curve plotted using a logarithmic plot exhibit nearly a straight shape indicating normally consolidated behaviour of fresh MSW. The inclination of the curve during loading period is defined as the primary compression index Cc, while slope of curve in unloading zone is defined as coefficient of recompression Cr. From the unloading curve shown in figure 1.2 it is clear that in fresh MSW recompression is quite less.

Figure 4.3 shows the variation of void ratio with vertical pressure at normal scale for sample compacted at OMC+4%, while other curves for sample compacted at OMC and OMC-4%are provided in appendix A. As soon as load is applied, void ratio decreases rapidly in early stage while for larger vertical pressure level flatter curve is obtained. Recompression is also more significant for smaller vertical pressures. Slope of void ratio vs stress curve in loading zone can beobtained and it gives coefficient of compressibility value (av). The primary compression index Ccis commonly used in engineering practice to characterize the compressibility of a porous medium.The inclination of the unloading curve is assumed to represent the recompression index, Cr. It should be noted that compression ratio (Ccε) is used commonly in MSW settlement calculations and it is related to compression index (Cc), which is used commonly for soils, by:

$$C_{c\varepsilon} = \frac{C_c}{(1 + e_o)} \quad 4.1$$

The values of Ccε, Cc and Cr for fresh MSW compacted at OMC and 4% of dry and wet side of OMC is shown in table 1.2.Compression ratio Cc is found maximum when compaction is done at wet side of optimum, relatively lesser at dry side of optimum and lowest when compaction is done at OMC. This phenomenon can be explained from initial void ratio value, e0 is minimum at OMC which is 0.784,while at wet and dry side of optimum its value is 0.930 and 0.962 and because compression is a function of initial void ratio obtained Cc values are justified.

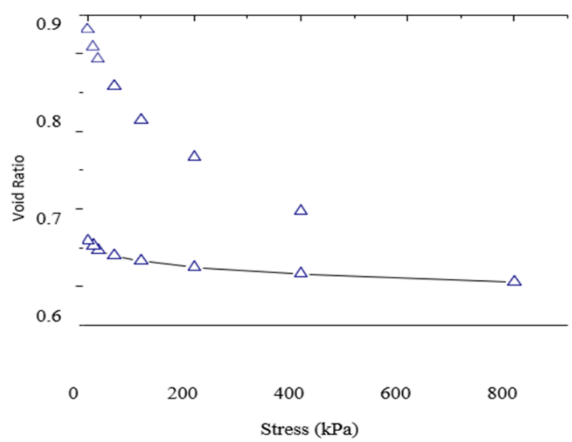

Figure 1.3 Variation of void ratio of fresh MSW with vertical pressure (e- p plot) for OMC +4%

Table 1.2 Calculated values e0, Ccε, Cc and Cr for fresh MSW

	OMC-4% (24.5%)	OMC (28.5%)	OMC +4 (32.5%)
γ_d (kN/m^3)	11.77	12.94	11.96
e_o	0.962	0.784	0.930
Ccε	0.090	0.0673	0.0979
Cc	0.177	0.120	0.189
Cr	0.0220	.0198	.0240

Figure 1.4 shows the variation of cumulative settlement of fresh MSW sample with square root time for various vertical pressures for OMC+4%. Same type of response has been observed for samples prepared at OMC and OMC-4% and given in appendix A.

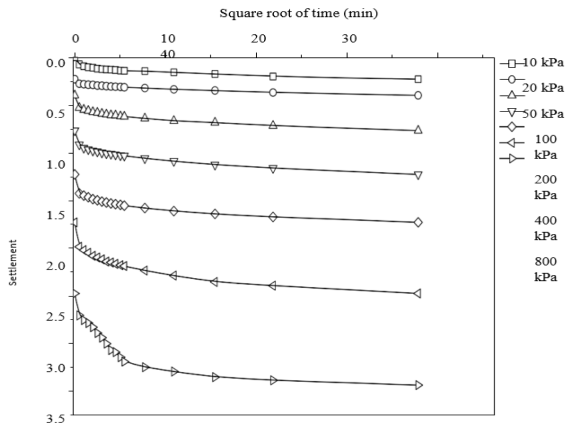

Figure 1.4 Variation of cumulative settlement with square root time at OMC+4%

The pattern of variation of settlement with time was found to be almost similar for various pressures. It can be noticed that with the increase in the vertical pressure, settlement was found toincrease. From curve it is clear that maximum amount of settlement is occurring within few minutes after application of load. This phenomenon can also be explained by obtained value of T90. For fresh MSW T90 value varies from 2-5 hours and from curve also it can be seen that maximum compression is occurring in this period. Settlement value was increasing as vertical pressure was increasing and for larger vertical pressures compression is quite large compared to smaller vertical pressure.

Based upon obtained dial gauge reading with time, coefficient of consolidation Cv was determined using Taylor's square root of time fitting method; as the 90% degree of consolidationis sufficient enough to predict the time taken for primary consolidation settlement. The exact demarcation of time taken for primary and secondary compression for MSW is still debatable. Hence, it is more logical to adopt this approach. Even though the 90% degree of consolidation happens well before 24 hours, next incremental loading on fresh MSW sample was applied only after 24 hours to get a holistic response.

Cv values were found for each vertical pressure and given in table 4.3. The variation of Cvfor OMC + 4% at various vertical pressure is shown in Figure 4.5. While Cv variation for OMC and OMC -4% is given in appendix A. It can be noticed that with the increase in the pressure, coefficient of consolidation was found to decrease. This pattern of Cv with vertical pressure is found same for all three compaction levels (OMC, OMC-4% and OMC+4%).

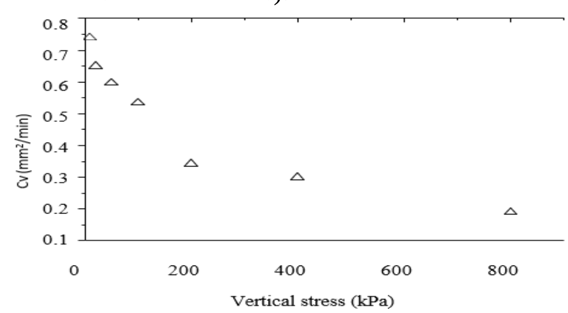

Figure 4.5 Variation of coefficient of consolidation of fresh MSW with pressure for OMC+4%

Table 1.3 Cv value (mm^2/min) for fresh MSW at various vertical pressure

Vertical pressure (kPa)	OMC-4% (24.5%)	OMC (28.5%)	OMC +4 (32.5%)
10	0.701464	0.715	0.736854
20	0.554262	0.618	0.649209
50	0.53024	0.579	0.597234
100	0.380479	0.408	0.534047
200	0.328637	0.352	0.340846
400	0.249331	0.306	0.299434
800	0.17813	0.192372	0.190499

Punia (2014) in his experiments on MSW residue has also obtained same type of reduction in Cvvalues as vertical pressure is increasing. This phenomenon indirectly suggests that time taken for any chosen degree of consolidation was found to increase with an increase in the vertical pressure.Cv value obtained by Punia (2014) for MSW residue varies between 1 – 8 mm^2/min indicating high rate of consolidation compared to fresh MSW for which Cv value is varying between 0.19 –0.74 mm^2/min. Compressibility of MSW residue as studied by Punia (2014) is also obtained higherthan fresh MSW. Full comparison of Cc value for current research work is summarized in table 4.2. The compression ratio values of current research were compared with many researchers as shown in table 4.4. Landva and Clark (1990) reported Cc value 0.35 for 470 mm diameter consolidometer, fresh shredded MSW samples. Punia (2014) conducted consolidation test on MSW residue with maximum particle size 4.75 mm and found Cc value lies between 0.30 – 0.35.Reddy et al (2009) reported compression ratio 0.28 at gravimetric moisture content 44% with fresh shredded MSW, having maximum particle size approximately 40 mm. The range of Cr, Cc and Ccε was found to be within the range reported in other research literatures.

Table 1.4 Compressibility of solid MSW based on laboratory experiments (Adapted from Reddyet al., 2011)

Source	Compression ratio
Current research 60 mm diameter oedometer test, fresh MSW, maximum allowable particlesize 10mm. Considering only immediate settlement	0.12 – 0.19
Punia (2013) 60 mm diameter oedometer test, MSW residue waste, maximum allowableparticle size 4.75mm	0.30 – 0.35
Reddy et al.(2009d) 63 mm diameter oedometer test, fresh synthetic MSW particles were ofaverage size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm	0.16-0.31
Dixon et al. (2008) Large scale test of size 500× 500 ×750 mm, fresh synthetic MSW, maximumparticle size 120–500 mm.	0.30
Hettiarachchi (2005) 63 mm Teflon cell, fresh synthetic MSW, maximum particle size 5 mm	0.18-0.21
Langer (2005) 0.5 ×0.5× 0.75 m compression box, shredded fresh synthetic MSW controlsamples, maximum particle size 10 mm ×40 mm	0.30
Durmusoglu et al. (2006) 63 mm oedometer, 10 years old degraded MSW 711 mm diameter oedometer, 10 years old degraded MSW	0.13–0.23
Hossain (2002) 63.5 mm diameter oedometer tests, shredded relatively fresh MSW in controlsamples, maximum particle size 120–500 mm, majority was 40–120 mm	0.16-0.25
Reddy et al. (2009b) 63 mm diameter oedometer test, shredded fresh MSW, maximum particle size40 mm	0.24-0.33
Gabr and Valero (1995) 63 mm diameter oedometer test, 15–30 years old degraded MSW, maximumparticle size 6.3 mm	0.15-0.22

CONCLUSION

A representative sample of fresh MSW was collected form Bharwara landfill site and used for the test program. To obtain the moisture content effect on fresh MSW, all tests have been performed at samples compacted at optimum moisture content and 4% of dry and wet side of optimums. Tests were performed in conventional geotechnical testing apparatus with maximum allowable particle size 10 mm. Specific gravity, index properties gradation analysis, and consolidation tests were performed for fresh MSW and results were obtained.

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