Evaluating Steel Slag Amended Soil Cover Cover MSW Landfills

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***Abstract*—Municipal solid waste (MSW) landfills pose environmental challenges due to gas emissions and leachate generation. Traditional soil cover systems are becoming inadequate as landfill areas and waste volumes increase, prompting interest in alternative cover materials that improve stability and control pollutant release. This study investigates a steel slag-amended soil cover system as a potential solution to enhance landfill performance. Steel slag, when mixed with soil, can improve shearing resistance and permeability, enabling the construction of steeper and more stable cover slopes. To evaluate this system, an infinite slope stability analysis was performed for four slope configurations (1H:1V, 2H:1V, 3H:1V, and 4H:1V), considering variations in water table height relative to a 1-meter cover layer. Laboratory tests were carried out on soil samples containing 5%, 10%, 15%, and 20% steel slag to determine engineering and index properties. The findings show that steel slag-amended soil covers can safely support steeper slopes while meeting the stability requirements prescribed by the Central Pollution Control Board.**

***Index Terms*—Steel Slag amended soil cover; Slope stability; Cover Slope; MSW Landfill**

I. Introduction (Heading 1)

Landfills are a one of the essential sections of the modern waste management system, and they have become progressively significant in recent years as the world faces the obstacles of solid waste disposal. In most landfill designs, the waste is deposited in number layers, and cover soil is placed over the top of waste to prevent the escape of gases and liquids into the surrounding environment. The stability of landfill covers is one of the crucial factors to be required to their effectiveness and longevity. Slope stability analysis is necessary to ensure the safety of landfills covers.

Guidelines for landfill cover design has been provided by the Central Pollution Control Board (CPCB) and sizing in India. These guidelines are intended to ensure that landfill covers are constructed and maintained in a way that protects human health and surrounding environment. The entire landfill cover comprises the barrier, drainage, final and vegetation layers.

The barrier layer is designed to prevent the mitigation of leachate and other contaminants from the landfill into the surrounding soil and groundwater. The layer of barrier is flexible, for hazardous waste provided barrier is composite barrier and for MSW landfills provided barrier is single barrier so some percent of water goes outside and some will go into the landfill it may be 10 to 15 percent or even less which help for biodegradation so they can be stabilized. Barrier layer uses the materials are clay, Geomembrane underlined by clay and Geomembrane underlined by Geosynthetic clay liner. the thickness of this barrier layer is 600 mm, and it should have a permeability of less than 1x 10-7cm/s. the geosynthetic liners have a minimum thickness of 1.5 mm and a puncture resistance of at least 500 N. the drainage layer allows the collection and removal of leachate and storm water runoff from the landfill cover system. It should have a minimum thickness of 300mm with permeability 1x 10-2cm/s. For drainage layer the material which used is sand, gravel and

Geocomposite with a permeability of at least 1x 10-2cm/s. The final cover system is designed to support the weight of the landfill and to prevent settlement, which may cause failure of the cover system. It should have minimum thickness of 600 mm and devise of compacted soil or other materials with permeability of less than 1x 10-6cm/s. Vegetation layer is also known as Surface layer is made from locally available soil or the soil on which vegetation is grow. The main points to be addressed are that the thickness of the surface layer is dependent on the thickness of the root zone. grass: 15cm or 0.15 m, shrubs: 50cm or 0.5 m, trees: 1m to 2m [1]. the minimum thickness of 300mm provided and be devised with a suitable mix of top soil, organic matter and sand.

The cover system is purposed to mitigate the deserter (fugitive) emission generated through the anaerobic digestion of MSW. As per this report in India almost 3 to 5 landfills fail each and every year due to various reasons like Overload Capacity, Due to heavy Rainfall, Methane gas blasting and poor management. The several recent fire explosions in several years, the Deonar dumping ground, one of India's oldest and largest open dumpsites, holds 12 million tonnes of waste and has experienced frequent fires. A significant fire in February 2015 lasted for 10 days before being extinguished. Since then, numerous fire incidents have been reported each year, including 11 fires during the January-February period of 2016 (Hindustan Times, Mar 26, 2018). On May 9, 2024, the Bhagtanwala garbage dump in Amritsar experienced a significant fire. Methane gas released from the decaying waste fuelled the fire, This incident highlights ongoing waste management issues at the site (The Tribune, May 10, 2024). In April 2024, a large fire broke out at the Bandhwari landfill near the Gurugram-Faridabad border. High concentrations of methane, a byproduct of decomposing waste, intensified the fire. This incident marked the fourth occurrence of its kind at the location that month. The dump site has long suffered from poor waste processing and management (Hindustan Times, Apr 23, 2024) [2].

The use of steel slag as an alternative cover material has beneficial properties such as good strength, durability and latent pozzolanic (cementations) properties that make them attractive and potentially suitable for in engineering applications, such as soil stabilization, as filler or binder in concrete or as drainage or low-permeability barrier layers [3]. In addition, the performance of a cover liner constructed using Steel slag was studied in a 2-year field trial on a landfill for municipal solid waste, in which the average amount of leachate collected from ten lysimeters was only 27 L m—2 year—1, easily meeting Swedish criteria for the permeability of covers on non-hazardous waste landfills (≤50 L m—2 year—1). Thus, the material seems to have promising potential for use in barrier constructions [4].

II. Methodology

A. Sample Collection

Soil samples were collected from the vilholi site in district Nashik, Maharashtra, India. Soil samples were obtained from pre-excavated soil that was stored for the Vilholi landfill's cover. The soil samples were oven-dried at 1050 C to reduce excess moisture and sieved through a 4.75 mm IS sieve. The steel slag used in the investigation was obtained from Vilholi, Nashik, Maharashtra, India's Geeta Metal Casting. The Geeta Metal Casting Industry is a manufacturer and supplier of aluminum casting, iron die casting, pressure die casting, etc. 50 kg of steel slag blocks were collected in plastic bags and stored in the laboratory.

B. Testing Program

The effect of steel slag on the geotechnical properties of landfill soil sample was investigated using a variety of laboratory testing programs. Index Properties (Specific gravity, grain size analysis, Atterberg limit test, pH test) and Engineering properties (Direct shear, Hydraulic conductivity and standard compaction tests) were among the tests carried out. These tests were conducted with 5%, 10%, 15% and 20% to the soil percentages of steel slag at optimum water content and maximum dry density, as determined.

C. Index Properties

a. Specific Gravity

As per IS 2720-1987(Part III) [8] the specific gravity test is conducted. Specific gravity of Fined Grained soil Solids (Gs) is the property which is required in the computation of other quantitates such as void ratio, degree of saturation, soil densities in the sedimentation analysis. Conventionally, specific gravity of soil solids is determined in the laboratory by pycnometer method (ASTM Designation D 854-06, 2007) [7].

b. Grain Size Distribution

Particle size distribution also known as gradation, refers to the proportions by dry mass of a soil distributed over specified particle-size ranges. Gradation is used to classify soils for engineering and agricultural purposes as per IS 2720-1985 (Part IV) [9] the Sample taken for this test is having total weight 1000 gm this sieve sizes which are used and found D60, D30 and D10.

c. Consistency Limit of soil

The Atterberg limit refers to the liquid limit and plastic limit of soil. These two limits are used internationally for soil identification, classification, and strength correlations. The code for the liquid limit of soil is IS 2720(Part 5):1985[10], the soil sample is taken 120gm and passing it through the is sieve 425µ and taking 4 number of samples. Plastic Limit is the moisture content at which the soil transition from a plastic state to a semi solid state.in plastic limit no longer soil can be easily moulded; it is one of the key parameters used in the classification of fine grain soil. The IS Code used is IS 2720 – 1985 (Part V) [10]. Shrinkage limit of soil is the moisture content at which the soil changes from a semi-solid to a solid state and further reduction in moisture content does not result in decrease in volume. The shrinkage limit is an important property because it indicates the water content at which soil reaches its minimum volume.IS code which is used in this test is IS 2720- 1972 (Part VI) [11].

d. pH test

The pH scale is logarithmic and inversely indicates the activity of hydrogen ions in the solution. The pH range is commonly given as zero to 14, but a pH value can be less than 0 for very concentrated strong acids or greater than 14 for very concentrated strong bases. The IS Code refer for this PH of Soil is 2720-1987(Part 26) [12].

Table 1: Index Properties (Specific gravity, pH test, Atterberg limit test grain size analysis)

Material	Specific Gravity	pH	Consistency Limit				Grain Size Distribution		
			Liquid Limit	Plastic Limit	Shrinkage limit	Plasticity Index	D60	D30	D10
Soil	2.648	6.3	62.20	30	14.05	32.20	3.474	1.56	0.686
Steel Slag	3.597	10.2	33.703	21.65	7.59	12.053	5.21	1.21	0.29
Soil 95% + 5% steel slag amended	2.82	6.46	58.13	29.22	13.86	28.91	3.619	1.498	0.511

Soil 90% + 10% steel slag amended	2.951	6.7	56.11	28.14	12.75	27.97	3.697	1.42	0.49
Soil 85% + 15% steel slag amended	3.001	7.2	54.24	27.34	12.15	26.9	3.773	1.343	0.462
Soil 80% + 20% steel slag amended	3.07	7.62	51.67	25.59	11.28	26.08	3.823	1.305	0.417

D. Engineering properties

a. **Direct shear test**
The test involves applying horizontal shear force to soil specimens contained within the shear box until failure occurs. The results yield a failure envelope, which can be used to derive the effective cohesion and internal friction angle of soil. The IS code used is IS 2720 (part 10)-1991[13].

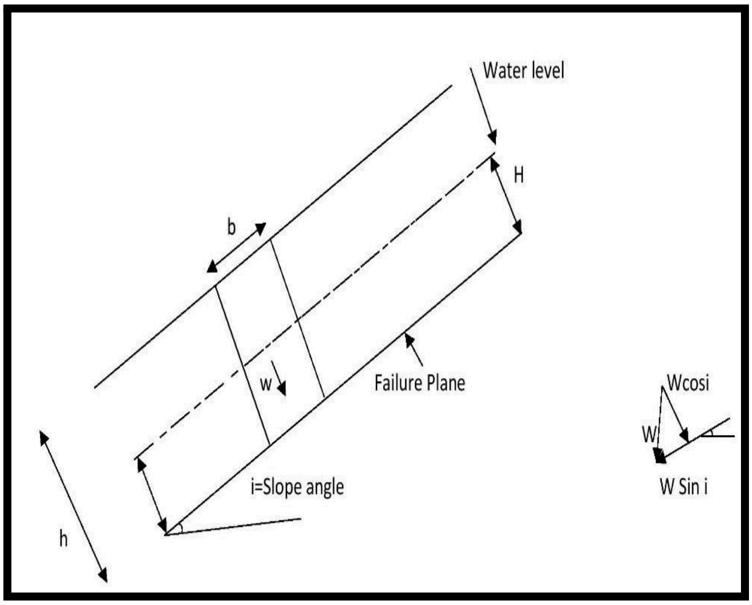
b. **Standard proctor compaction test**
The standard Proctor test employs a 105 mm diameter mould and 25 blows from a 2.5 kg hammer with a compaction energy of 593.7 kJ/m3 to compact three separate layers of soil. The American Society for Testing and Materials (ASTM) standard manual was used for the test methods.

c. **Hydraulic conductivity**
For determining hydraulic conductivity of fine-grained soil falling head test is used, constant head method not yield accurate results due to low permeability. The falling head test is performed under the IS 2720(Part 5)1987 [10]. the falling head method involves measuring the time taken for water to flow through a soil sample under a decreasing water head, hydraulic conductivity based on the rate of flow.

d. **Slope Stability Analysis by limit equilibrium method**
The limit equilibrium method used for the slope stability analysis is one of the most effective methods among the methods available for analysis of slope [14]. the consequence of this method represents a factor of safety (FOS). The factor of is the ratio of the summation of resisting forces to the summation of driving forces.

$$FOS = \frac{\sum \text{resisting forces}}{\sum \text{driving forces}} \quad (1)$$

The limit equilibrium method presumes the factor of safety should be constant along the entire length of the slip surface. If this equal to 1, it shows failure, and the factor safety less than 1 it indicates unstable condition. Therefore, the slope is speculatively stable if the factor of safety is greater than 1. The three main types of limit equilibrium analysis are used are the method of slices, wedge method and infinite slope method [14].The shear parameter (C and Φ) quantified from direct shear test results were used to perform infinite slope stability analysis to examine and compare the stability of landfill cover material of soil and steel slag amended soil. Infinite slope stability analysis was carried based on the slope geometry, water levels and formulations. the cover slope's factor of safety (FS) was computed by assuming four different slopes (1H:1V, 2H:1V, 3H:1V and 4H: 1V).at various ratios of the height of the water table(H) to the total height of landfill cover(h) ranging from 0 to 0.54. The thickness of landfill cover is assumed to be 0.45 m, unit weight of soil and steel slag amended soils are calculated by measured values of maximum dry density.



i = Cover Slope angle

H=Height of water table

h=soil thickness

c and Φ = Shear apparatus

Fig 1: Infinite Slope Stability Analysis

III. Result and Discussion

A. Effect of steel slag on the specific gravity

Figure 1 depicts the variation in specific gravity test results for both steel slag amended soil and soil samples. With an increase in steel slag content from 0–20%, the average specific gravity of the expansive soil increases from 2.648 to3.07. The presence of a high amount of iron in slag, as well as a higher specific gravity than the soil, accounts for the increase in specific gravity for the treated soil. The result of this study can be supported by [15], in which the steel slag improves the specific gravity of soil.

B. Effect of steel slag on Consistency limit

Figure 2 depicts the variation of Atterberg limits and linear shrinkage with the addition of steel slag. From the results, it can be observed that there is a significant reduction in Atterberg limits and linear shrinkage. This reduction is due to the fact that the addition of steel slag causes a reduction in the ability of water absorption. The decrease in the thick-ness of the double layer of clay particles resulted in lower Atterberg limits and linear shrinkage values. The reduction in the Atterberg limits of the soil is due to the non-plastic behavior of the steel slag particles and to the cat ion exchange reaction, which causes the particles to flocculate by increasing the attraction force. The particle size of the mixed sample increases when steel slag is combined with soil. As the particle size has increased, the surface area of the particles has decreased. Furthermore, as the amount of steel slag in the soil mixture increases, the amount of clay minerals in the soil decreases. As a result, the soil mixture’s water-carrying capacity decreased, lowering the linear shrinkage and Atterberg limits.

Similar results have been found in other studies. (Aldeekyand Al Hattamleh 2017) discovered that with the addition of 25% steel slag, the LL and PI were reduced by 30% and21%, respectively. The results of the study by (Abdalqadir and Salih 2020) show that adding steel slag to the soil sample from 0 to 20% reduced the value of LL by 26%, the plasticity index by 12.64%, and the LS by

53.6%. Other studies, including (Abdalqadir et al. 2020; Zumrawi and Babikir, 2017; Shalabi et al. 2017; Patel and Patel 2016), also support these findings.

C. Effect of Steel Slag on Compaction

The variations in water content with dry density for soil samples containing various percentages of steel slag are shown in Fig 4. Soil has been found to have an MDD of 1.504 g/m3 and an OMC of 16%. As shown in Fig.5, the value of MDD was increased to 1.719 g/m3 and the value of OMC fell to 12.5% as 20% steel slag was added to the soil. Steel slag particles, which are heavy materials with a high specific gravity when compared to soil samples; cause an increase in maximum dry density as the steel slag content increases. Steel slag reduces the diffused double-layer thickness and the particles are brought closer together due to its lower water adsorption, resulting in a higher MDD value. As a result, the particles pack together and the MDD rises with the same amount of compaction effort. The OMC values decreased as the particles became closer together and their water-holding capac- ity decreased. Similar results have been obtained from the study (Aldeeky and Al Hattamleh 2017). They propose using fine steel slag to stabilize the weak subgrade soil, and adding up to 25% of steel slag increases the dry density by a significant amount. Another study (Abdalqadir et al. 2020) found that adding steel slag up to 20% to the soil increased dry unit weight from 18.34 kN/m3 to 19.32 kN/m3, while decreasing OMC from 15 to 11.28%. Other studies by (Hirapure and Dalvi 2018; Abdalqadir and Salih 2020; Patel and Patel 2016).

D. Slope Stability

As per the guidelines by the regulatory authorities CPCB 2002, for the landfill constructed on loose/soft soil, the base is checked for stability against bearing failure or excessive settlement. The stability of the side slope of the landfill cover system in landfill is 4H:1V. The acceptable minimum factor of safety is 1.5.(without considering seismic or imposed loading) for permanent slopes. Thus, a factor of safety value remains at 1.5 throughout the design life of the final system [16].

The infinite slope stability analysis is finding the stability of a homogenous single layer landfill cover system of steel slag amended soil. For this study, the slope stability and factor of safety of soil, steel slag and 5%,10%,15% and 20% steel slag amended soil were studied. All factors of safety values for these amendments at different slopes and water levels as shown in figure.

The factor of safety for different water levels in the final cover system was calculated for typical topsoil 5%,10%,15% and 20% steel slag amended soil for four slopes conditions (1H:1V, 2H:1V, 3H:1V and 4H:1V). The H/h (H= height of water level, h= landfill soil thickness) was considered from 0 to 0.54 (Figures 6 to 9). The unit weight of the steel slag amended soil and soil was computed from the maximum dry density 16.09 KN/m3.

For all six samples considering slope inclination, the soil possessed the factor safety values ranging from 1.48 to 0.92 (4H: 1V to 1H: 1V) for slope inclination conditions at H/h =0, which slightly less than 1.5 standard value for permanent slopes given by CPCB.

For 5% steel slag, amended soil had a factor of safety for slope inclination 1H:1V as 1.12, which was the lowest value at condition H/h =0. Therefore, as the slope inclination increased 2H: 1V, 3H: 1Vand 4H: 1V, the factor of safety values increased 1.30, 1.43, and 1.77 respectively. Though the factor of safety values is less than 1.5, it is still greater than 1.2, which is sufficient to meet slope stability criteria based on the assumption that the complete cover system is a short loading condition, and the cover system will soon be restored to the expected long term loading condition.

10% steel slag amended soil shows the factor of safety values less than 1.5 for two slope inclinations, but the safety values are still greater than 1.2 for short term conditions, which is sufficient to meet criteria. As the H/h ratio increases the factor of safety decreases. The factor of safety for 3H: 1V and 4H: 1V slope is 1.55 and 1.98, which is greater than 1.5, which meets the stability criteria.

15% steel slag amended soil possessed a factor of safety for 3H:1V and 4H:1V slope is 1.7 and 2.22, which is greater than 1.5, which meets the stability criteria.

20% steel slag amended soil shows the factor of safety is 1.59 to 2.52, which is greater than 1.5, which meets the stability criteria.

Therefore, it was observed that the factor of safety values of soil, steel slag and steel slag amended soil increased at decreasing slope angles irrespective of the water table level within the cover system.