Chapter-7

Geotechnical Applications of Untreated and Treated MSWF

7.1. Introduction to the Chapter

Building on this comprehensive analysis of municipal solid waste (MSW) in previous chapters, this segment delves into the practical applications of Municipal Solid Waste Fines (MSWF) and biopolymer-treated MSWF in civil engineering. Present focus shifts towards their utility in pavement construction and embankment slope stability, aligning with sustainable waste management practices. In pavement design, the incorporation of MSWF sourced from various depths of dumpsites is explored to assess its impact on (Chandana et al., 2021; Sharma & Jain, 2019)al., 2021; Sharma & Jain, 2019). This approach investigates how MSWF can contribute to more sustainable and cost-effective pavement structures.

Further, the analysis is extended to MSWF treated with biopolymers like Xanthan Gum (XG) and Agar Gum (AG), evaluating their effectiveness under conditions that simulate real-world applications, particularly in wet environments (Latifi et al. 2017; Chang et al. 2020). This part of the study offers insights into the long-term durability and performance of biopolymer-treated MSWF in pavement subgrades.

Simultaneously, embankment slope safety is reassessed using the Finite Element Method (FEM), considering various scenarios involving both natural and biopolymer-treated MSWF. This integrated approach not only assesses the engineering performance of these materials but also their alignment with environmental sustainability (Kjeldsen et al. 2002; Babu et al. 2014).

This chapter aims to bridge the gap between theoretical research and practical application, providing valuable insights for waste management professionals and contributing to the global efforts towards sustainable development and circular economy principles in civil engineering.

7.2. Settlement Analysis of the Foundation Laid over MSWF

7.2.1. Material Characterization

The primary material investigated in this study is Municipal Solid Waste Fines (MSWF), sourced from various depths of a landfill site. The basic physical and chemical properties of the Municipal Solid Waste Fines (MSWF), such as the percentage of fines and detected heavy metals. The MSWF samples were also analyzed for their physio-mechanical properties, including unit weight, saturation unit weight, void ratio, secant modulus, Poisson ratio, internal friction angle, and cohesion. These properties were essential in understanding the behavior of MSWF under load and in different environmental conditions. Table 13 details the properties of MSWF collected from various depths, including unit weight, saturation unit weight, void ratio, secant modulus, Poisson ratio, internal friction angle, and cohesion. These properties varied significantly with depth, impacting the settlement behavior. For instance, at 0 meters depth, the unit weight was 16.06 kN/m³, and the secant modulus was 1150 kN/m², while at 10 meters depth, these values increased to 16.58 kN/m³ and 2900 kN/m², respectively. The secant modulus is calculated using

Equation 7.1. For the stress-strain plot shown in Figure 44 a, the stress corresponding to a 2% strain is manually derived. These plots are generated by analyzing the stress-strain behavior of triaxial samples, which are prepared at the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the material retrieved from various dumpsite depths, as discussed in the paper. The stress-strain plots are based on a confining pressure of 50 kPa.

$$\text{Secant Modulus} = \frac{(\sigma 2 - \sigma 1)}{(\varepsilon 2 - \varepsilon 1)} = \frac{(\text{Stress @ 2\% Strain} - 0)}{(\text{2\% Strain} - 0)}$$

Eq-7.1

Table 13: MSWF properties with varying retrieval depth taken for settlement analysis

Retrieval depth of MSWF (m)	Properties of MSWF taken for settlement analysis						
	Unit weight (γ) (kN/m^2)	Sat. unit wt. (γ_{sat}) (kN/m^2)	Void ratio (e)	Secant modulus (E) (kN/m^2)	Poisson ratio (ν)	The angle of I.F. (φ)	Cohesion (c) (kPa)
0	16.06	18.59	0.35	1150	0.3	22.7	42.3
2	16.27	18.96	0.38	1550	0.3	20.9	48.5
5	16.43	19.09	0.37	2500	0.3	18.2	67.7
10	16.58	19.33	0.39	2900	0.3	17.0	69.9

7.2.2. Finite Element Method (FEM) Analysis

The settlement behavior of MSWF was studied using the finite element analysis-based application 'Plaxis 2D' (Wulandari and Tjandra 2015; Sheth and Raghavani 2021). The analysis involved creating a soil profile extending 12 meters in the 'X' direction and 8 meters in the 'Y' direction, with boundary conditions as follows: lateral boundaries were fixed in the horizontal direction, the bottom boundary was fully restrained, and the top boundary was free to displace vertically. The Mohr-Coulomb material model was adopted, considering Poisson's ratio as 0.3, with the water table lying below the soil profile.

I. **Loading Conditions and Simulation:** A three-stage line load of 10 kN/m/m, 20 kN/m/m, and 30 kN/m/m was applied sequentially to simulate real-world conditions, and settlement contours were analyzed accordingly. These values were chosen to reflect typical foundation pressures, assess progressive settlement behavior, and evaluate the material's load-bearing capacity under incremental stress levels. The footing-soil interface was modeled with a perfect contact assumption, ensuring realistic stress transfer and settlement behavior. The response of the MSWF to the applied load was observed by analyzing the deformation and settlement contours (Chauhan 2021; Verma and Mohanty 2021).

II. **Meshing and Analysis:** The soil profile was meshed in medium detail within Plaxis 2D to ensure accurate representation of the MSWF behavior. The meshing process is critical for simulating how the load affects the MSWF and accurately capturing the deformation and settlement patterns. Meshing of the soil and foundation profile is shown in Figure 44 b.

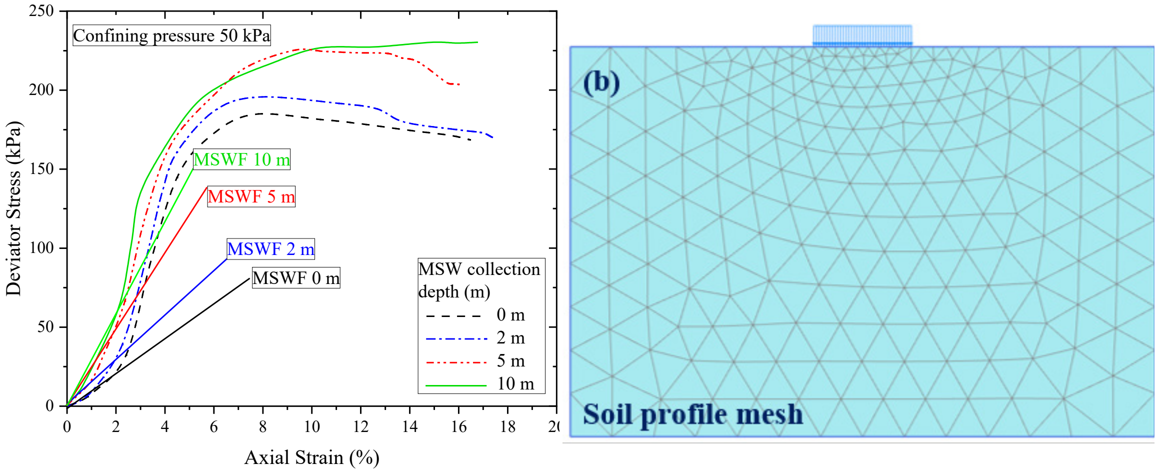

Figure 44: (a) Stress-strain graph to calculate secant modulus (b) Meshing of soil profile (MSWF)

7.2.3. Result and Discussion (Settlement analysis of the Foundation)

The results from the FEM analysis, particularly the settlement contours and deformation patterns, were carefully interpreted to understand how the depth of MSW collection influences the settlement characteristics of MSWF. This involved a comparative analysis of settlement responses at different collection depths, providing insights into the stiffness and stability of MSWF (Schöpke et al. 2017).

After meshing, the line load is applied in 3 stages of 10 kN/m/m, 20 kN/m/m, and 30 kN/m/m consecutively. After the load is applied, the soil profile is deformed, and the typical deformed soil profile/settlement is given in the Figure 45 a while Figure 45 b show the maximum settlement observed below the load, Table 14 shows the value of settlement. It can be seen that the settlement is reducing with the depth of MSW collection as the collected MSWF from the greater depth has high stiffness. The minimum and the maximum settlement in MSWF are observed as 1 cm and 7.56 cm. The Figure 46 settlement contours show displacement distribution across the MSWF profile. The negative values in the legend indicate vertical displacement (Uy), where larger negative values correspond to greater settlement closer to the load application, and smaller negative values indicate minimal settlement as the distance from the load increases. This variation is due to the depth-dependent stiffness of MSWF, as reflected in the numerical simulation. (Figure 46).

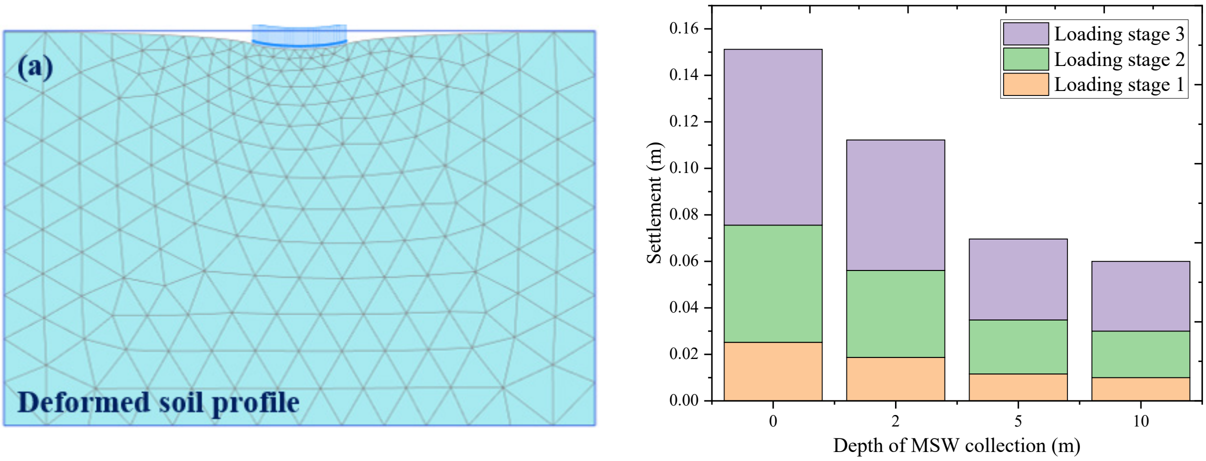

Figure 45: (a) Typical deformed mesh of MSWF (b) Final settlement of MSWF of varying depth

Table 14: Settlements of MSWF profile at different loading phases and depths

	Settlement (m)		
Retrieval depth of MSWF (m)	Loading phase 1 (10 kN/m/m)	Loading phase 2 (20 kN/m/m)	Loading phase 3 (30 kN/m/m)
0	0.0252	0.0504	0.0756
2	0.0187	0.0374	0.0561
5	0.0116	0.0232	0.0348
10	0.0100	0.0200	0.0300

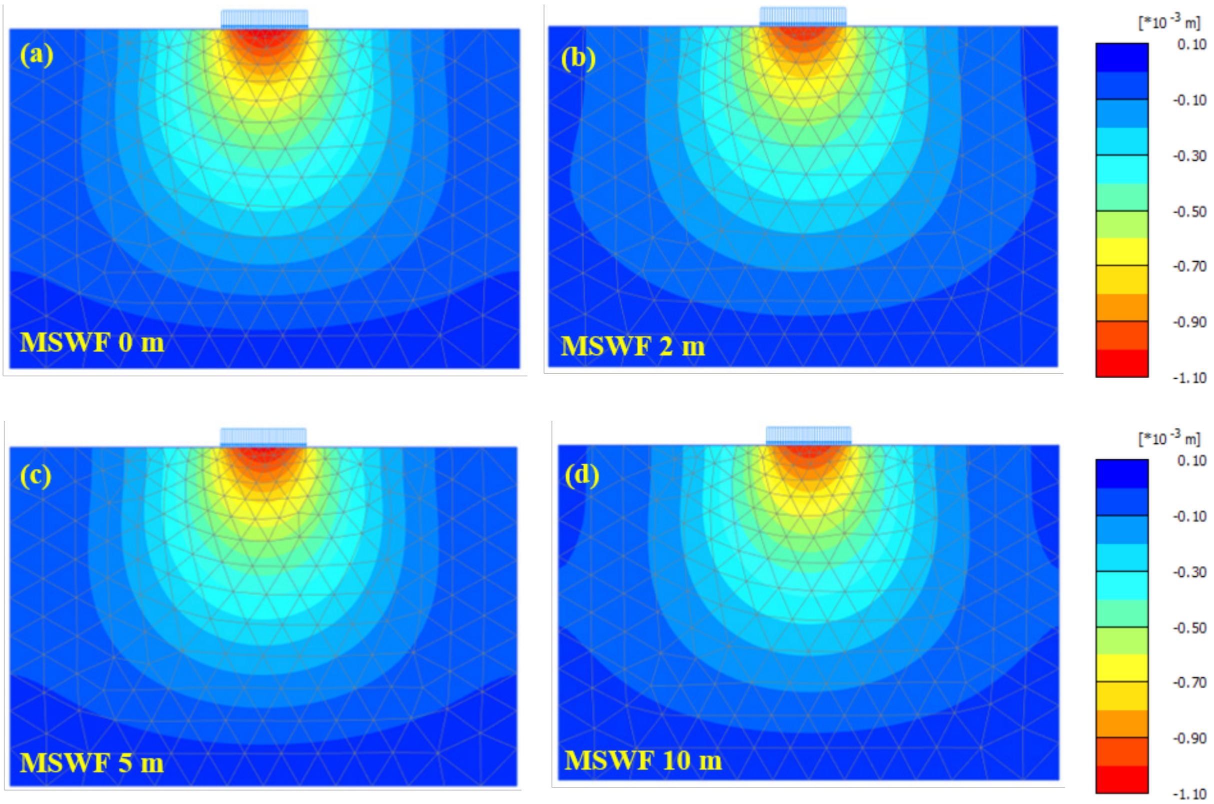

Figure 46: Settlement contours of the MSWF profile at varying depths. Negative values indicate downward displacement (Uy), with red showing maximum settlement near the load and blue showing minimal settlement farther away.

The results from the FEM analysis in paper show a clear correlation between the depth of MSWF retrieval from the dumpsite and its settlement behavior under various load conditions. Notably, MSWF from a depth of 0 meters exhibited higher settlement values (0.0252, 0.0504, and 0.0756 meters for loading phases 10, 20, and 30 kN/m/m, respectively) compared to MSWF from a depth of 10 meters (0.0100, 0.0200, and 0.0300 meters under the same loading phases).

This trend in settlement behavior can be attributed to the physical properties of MSWF that vary with depth. The data indicates that with increasing depth, there is a decrease in the friction angle and an increase in cohesion. For instance, at a depth of 0 meters, the consequently friction angle and cohesion are observed to be lower & higher compared to those at 10 meters. These variations in properties suggest that MSWF becomes more stable and less prone to settlement as depth increases, likely due to the natural compaction and consolidation processes occurring in the dumpsite over time.

The analysis offers crucial insights into the suitability of MSWF retrieved from different depths for use in construction projects, particularly for foundations. It indicates that MSWF from deeper layers, with higher cohesion and lower friction angles, is potentially more stable and less susceptible to settlement, making it a viable material for foundation engineering.

7.3. Pavement Thickness Analysis while using MSWF in Subgrade

For designing pavement, two cases were considered:

1. Pavement subgrade made from borrowed MSWF retrieved from varying depths of the dumpsite.

2. Pavement subgrade made from MSWF treated with varying percentages of Xanthan Gum (XG) and Agar Gum (AG).

For the first case, the values of soaked CBR are taken from Chapter 4. For the treated samples with XG and AG, the CBR values are determined in this chapter and represented in the coming section.

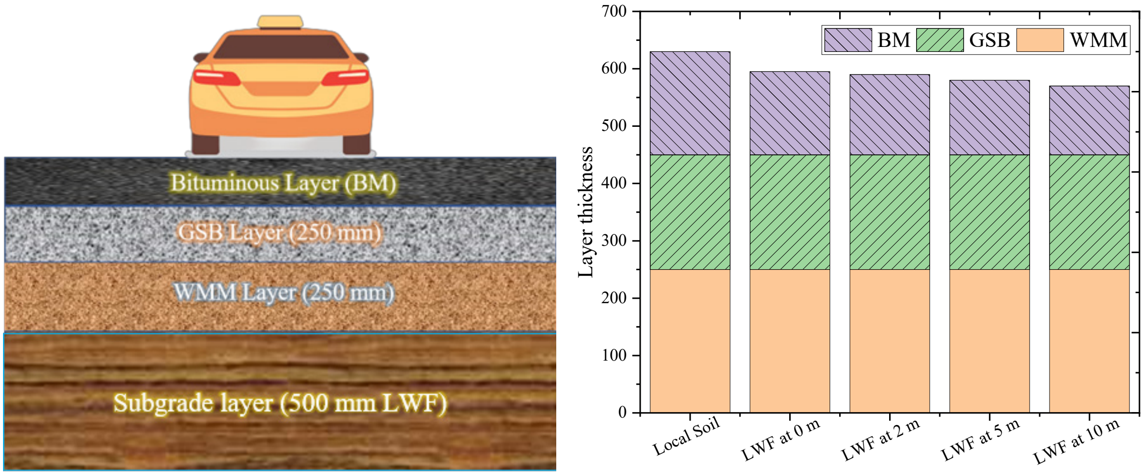

Figure 47: Pavement Structure Overview (a) Schematic Representation of Pavement Layering (b) Comparative Layer Thickness for Pavements with Local Soil and MSWF Subgrades

7.3.1. Pavement Design for MSWF Retrieved from Varying Depths

The properties of MSWF from different depths are described in the previous chapter and are used in the current section where the foundation is designed using Plaxis. For pavement design, the design traffic is taken as 50 MSA. The pavement consists of a subgrade, sub-base, and bituminous layer. The subgrade is made of 500 mm borrowed MSWF (recommended thickness of borrowed material by IRC) over local clay soil having CBR 4.5%.

Table 15: Detail of CBR and Resilient modulus of different pavement layers.

Soil Type	Soaked CBR Value	MR subgrade	MR of Sub-base	MR of Bituminous Mix VG-40 at 35º C
Local Soil	4.5 %	45 Mpa	141.00 MPa	3000 MPa
MSWF at 0 m	7.5 %	64 Mpa	201.00 MPa	3000 MPa
MSWF at 2 m	7.9 %	67 Mpa	210.00 MPa	3000 MPa
MSWF at 5 m	9 %	72 Mpa	226.00 Mpa	3000 MPa
MSWF at 10 m	9.8 %	76 Mpa	238.00 Mpa	3000 MPa

The sub-base layer consists of two layers: a granular sub-base (GSB) with a thickness of 200 mm, and the wet mix macadam layer (WMM) thickness of 250 mm. The bituminous layer BM (Bituminous macadam) is made of VG-40 grade bitumen with MR value 3000 MPa at 35º C temperature. A typical pavement layers illustration is shown in Figure 47 a. The main objective of this pavement design is to optimise the thickness of the bituminous layer. The design calculation is carried out on a 90% reliability condition, which means there is only a 10% chance that the actual strains (rutting and cracking) will be higher than that of allowable strains calculated through eq. 3-6.

The pavement is tested for two criteria: rutting over the subgrade layer and fatigue below the bituminous layer. As mentioned in IRC-37, the resilient modulus of the subgrade and sub-base are calculated by equations (1) and (2) using the subgrade CBR, and their values are given in Table 15. The elastic modulus based on recoverable strain under repeated loads is called the resilient modulus (MR). It is a fundamental factor while designing flexible pavement and depends on the subgrade CBR.

$\mathbf{M_{RS}} = 10.0 \times CBR$ for $CBR \leq 5.00\ \%$ (Eq.7.2)

$\mathbf{M_{RS}} = 17.6 \times (CBR)^{0.64}$ for $CBR > 5.00\ \%$ (Eq.7.3)

Where,

M_{RS} = Resilient modulus of subgrade soil (in MPa).

CBR = California bearing ratio of subgrade soil (%)

Sub-grade rutting criteria

$\mathbf{N_R} = 1.41656 \times 10^{-08} [1/\varepsilon_v]^{4.5337}$ For 80% Reliability (Eq.7.4)

$\mathbf{N_R} = 1.4100 \times 10^{-08} [1/\varepsilon_v]^{4.5337}$ For 90% Reliability (Eq.7.5)

Where

N_R = Subgrade rutting life

ε_v = Vertical compressive strain (rutting) at the top of the subgrade

Fatigue cracking criteria for bituminous layer

$\mathbf{N_f} = 1.6064 \times C \times 10^{-04} \times [1/\varepsilon_t]^{3.89} \times [1/M_{Rm}]^{0.854}$ For 80% Reliability (Eq.7.5)

$\mathbf{N_f} = 0.5161 \times C \times 10^{-04} \times [1/\varepsilon_t]^{3.89} \times [1/M_{Rm}]^{0.854}$ For 90% Reliability (Eq.7.6)

Where

N_f = Fatigue life of bituminous layer

C = Factor based on the % bitumen and % air voids in the bitumen layer

ε_t = maximum horizontal tensile strain (cracking) at the bottom of the bottom bituminous layer (BM)

M_{Rm} = Resilient modulus (MPa) of the bituminous mix used in the bottom bituminous layer

Allowable strain from the equation (4) & (6) for 90% reliability

ε_v (for rutting) = 0.0003716 ε_t (for cracking) = 0.0001781

Table 16: Optimized Bituminous Layer Thickness and Strain Iterations for MSWF at Various Depths Versus Local Soil

Subgrade layer Type	**The thickness of BM (mm)**	**Actual Iterated rutting strain ε_v**	**Actual Iterated cracking strain ε_t**	**Design remark**
Local Soil	180	0.0003263	0.0001739	Actual stains are less than allowable strains (ε_v =0.0003716 ε_t = 0.0001781); hence the design is safe
MSWF at 0 m	145	0.0002979	0.0001747	
MSWF at 2 m	140	0.0002917	0.0001743	
MSWF at 5 m	130	0.0002832	0.0001749	
MSWF at 10 m	120	0.0002784	0.0001778	

b shows the optimized bituminous layer thickness, revealing that the bituminous layer's thickness is reduced from 180 mm to 120 mm compared to the local soil. The BM thickness is reduced by 25 mm due to the higher CBR value of MSWF at a lower landfill depth, resulting in a saving of 25 m3 of bituminous layer material per kilometer run and unit width of the pavement. The given pavement thickness design can be adopted for using MSWF in the subgrade with similar geotechnical characteristics. The rutting and cracking strains are determined using IIT-Pave software, and the thickness of the bituminous layer is optimized through iteration. The calculated rutting and cracking strains are presented in Table 16, and the design is considered safe if these strains are lower than the allowable rutting and cracking strains calculated using Eq. 3-6. Table 17, Table 18 and **Error! Reference source not found.**.

7.3.2. Pavement Design from Treated MSWF with XG and AG

CBR Observations & Design: The MSWF is mixed with biopolymer in varying percentages and compacted in a CBR mold. The soaked CBR values are measured for each mix, and the results are shown in Figure 48 a-b; the particular is also discussed in Chapter 5.

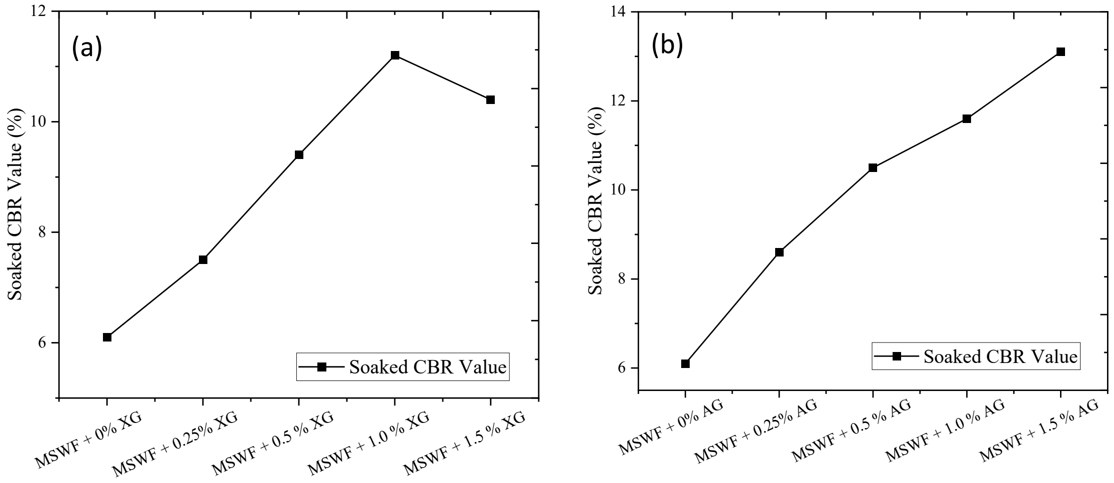

Figure 48: Variation of soaked CBR values (a) For Xanthan Gum and (b) For Agar Gum

Viability of the MSWF mixed with biopolymer in pavement subgrade: The CBR of the subgrade has a vital role in deciding the thickness of the upper layers of pavement. The CBR of the subgrade can be enhanced to optimize the sub-base thickness, and the bituminous layer since the pavement rests over it. As recommended by IRC-37, the pavement subgrade can be strengthened by replacing the upper 500 mm of the weak soil with the borrowed high-strength soil in the subgrade. In the present study, the pavement will be designed over the subgrade modified with borrowed MSWF-Biopolymer mix. The bituminous layer's thickness is optimized to lower the cost of the pavement. The typical pavement layers are shown in Figure 47 a.

By following the procedure of designing pavement as described in the previous section the resilient modulus of the treated subgrade with XG and AG, sub-base, and Bituminous layer is determined as given in the Table 18 below:

Table 17: Details of pavement for the MSWF subgrade stabilized with Xanthan gum (XG)

MSWF & Biopolymer mix	Soaked CBR Value (%)	MSWF & Biopolymer mix	Soaked CBR Value (%)	Bituminous layer thickness (mm)
MSWF + 0% XG	6.1	MSWF + 0% AG	6.1	175
MSWF + 0.25% XG	7.5	MSWF + 0.25% AG	8.6	158
MSWF + 0.5 % XG	9.4	MSWF + 0.5 % AG	10.5	150
MSWF + 1.0 % XG	11.2	MSWF + 1.0 % AG	11.6	138
MSWF + 1.5 % XG	10.4	MSWF + 1.5 % AG	13.1	145
MSWF + 1.5 % XG				

Table 18: Details of pavement for the MSWF subgrade stabilized with Agar gum (AG)

MSWF & Biopolymer mix	Soaked CBR Value (%)	MR subgrade (MPa)	MR of Sub-base (MPa)	Bituminous layer thickness (mm)
MSWF + 0% AG	6.1	56.0	175.0	175
MSWF + 0.25% AG	8.6	69.8	218.1	155
MSWF + 0.5 % AG	10.5	79.3	247.8	145
MSWF + 1.0 % AG	11.6	84.5	264.1	140
MSWF + 1.5 % AG	13.1	91.3	285.5	130

In the present analysis, the total sub-base thickness is taken as 450 mm, in which the granular sub-base and granular base are taken as 200 and 250 mm consecutively for all cases. The bituminous layer optimized thickness is given in Table 17, Table 18 and Figure 49. The bituminous layer consists two sub layer one is dense bituminous macadam (DBM) and bituminous macadam (BM), which is the surface course. The minimum thickness of BM is taken 40 mm. It can be seen that the bituminous layer thickness decreased for both cases of XG and AG, while for XG, the thickness reduced by up to 1% of XG. The maximum and minimum thickness of the bituminous layer is calculated at 175 mm, and 130 mm (for 1.5% W_b/W_w AG) for XG minimum thickness is analyzed as 138 mm.

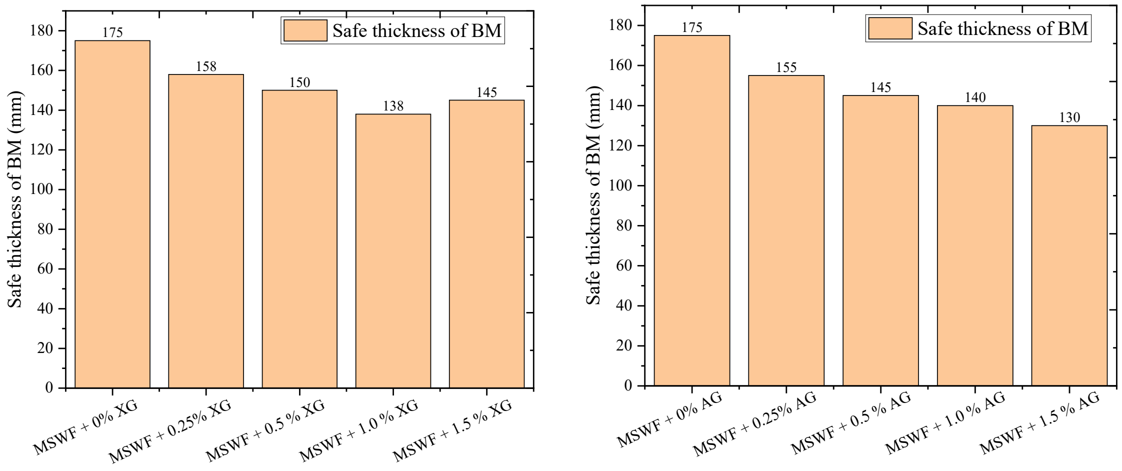

Figure 49: Bituminous layer thickness of pavement having biopolymer stabilized subgrade (a) Xanthan Gum (b) Agar Gum

7.4. Potential Risks and Mitigation Strategies

The use of Municipal Solid Waste Fines (MSWF) in geotechnical applications can poses potential risks, including leachability of contaminants, structural instability, microbial activity, and public perception challenges. MSWF may contain heavy metals and organic pollutants, which could leach into groundwater, while variations in moisture content and biological decomposition can impact long-term stability. To mitigate these risks, biopolymer stabilization (using Xanthan Gum and Agar Gum) can enhance mechanical strength and reduce contaminant mobility. Encapsulation techniques, such as geosynthetic liners and engineered compaction, can help prevent leachate migration, while controlled moisture management through drainage layers can improve durability. Additionally, ensuring regulatory compliance and increasing public awareness through pilot projects can facilitate the safe and sustainable use of MSWF, supporting circular economy principles and sustainable waste management.

7.5. Key Takeaways and Way forward

- MSWF from 10 meters depth exhibited settlement values significantly lower (0.0100 to 0.0300 meters) compared to the surface (0.0252 to 0.0756 meters)
- Pavement using MSWF reduced bituminous layer thickness from 180 mm to 120 mm, saving 25 m³ of material per kilometer.
- Soaked CBR tests showed significant resistance to penetration with XG and AG. Optimized pavement design reduced bituminous layer thickness by up to 25.7%.
- Xanthan Gum (XG): Maximum soaked CBR increased up to 11.2% with 1.0% XG, reducing bituminous layer thickness to 138 mm. Agar Gum (AG): Maximum soaked CBR increased up to 13.1% with 1.5% AG, reducing bituminous layer thickness to 130 mm.
- In coming chapter through sustainability analysis is carried out to understand the various sustainability aspects of biopolymer stabilization compared to conventional binders.