Chapter: 5

Stabilization of Municipal Solid Waste Fines by Xanthan Gum & Agar Gum

5.1. Introduction to the Chapter

Building upon the foundational characterization of Municipal Solid Waste Fines (MSWF) with depth from previous chapters, this chapter introduces a novel approach to stabilizing MSWF using biopolymers, specifically Xanthan Gum (XG) and Agar Gum (AG). Previous work established the geotechnical properties of MSWF and identified the need for sustainable stabilization methods to enhance its usability in civil engineering applications. This chapter aims to improve the mechanical and chemical characteristics of MSWF by incorporating XG and AG. These biopolymers, derived from natural sources, offer environmentally friendly alternatives to traditional stabilization methods (Anandha Kumar et al. 2021). The chapter focus on optimizing the concentrations of these biopolymers to maximize efficacy. The experiments include a series of tests to evaluate the impact of XG and AG on the geotechnical properties of MSWF, such as consistency limits, Maximum Dry Density (MDD), and Unconfined Compressive Strength (UCS) (Adabi et al. 2022).

The statistical analysis is also conducted using ANOVA to determine the significance of present findings and to optimize the biopolymer concentrations for the best stabilization results.

Additionally, dry curing in open air is also applied to demonstrate the effect of biopolymer bonding in MSWF under open conditions, simulating surface treatment scenarios. This method helps us understand how biopolymer-stabilized MSWF performs in real-world applications where exposure to air and environmental factors is common.

This chapter primarily addresses the stabilization of MSWF for below-surface treatment and evaluates its immediate mechanical improvements. The assessment of long-term durability and the effectiveness of these biopolymers for prolonged applications will be thoroughly examined in the next chapter.

5.2. Materials & Method

In this chapter, Municipal Solid Waste Fines (MSWF) (MSW sieved through a No. 4 ASTM (4.75 mm) sieve and oven dried), which were collected from different depths (as discussed in the previous chapter) of a legacy waste site in Varanasi, India, were combined in equal amounts to reflect the overall homogenized behaviour of the collected material (Ref. Table 10). Xanthan Gum (XG) and Agar Gum (AG) were used as biopolymers, mixed in water according to their Optimum Moisture Content (OMC) with biopolymer-to-water ratios (Wb/Ww) of 0.25, 0.5, 1, and 1.5%. The mixed samples were compacted to achieve Maximum Dry Density (MDD) following ASTM standards and underwent open-air curing for 5 hours, 24 hours, 3 days, and 7 days to simulate surface treatment conditions.

Various experiments were conducted, including Unconfined Compressive Strength (UCS) tests, Unconsolidated Undrained (UU) Triaxial tests, California Bearing Ratio (CBR), Scanning Electron Microscopy (SEM) for microstructural analysis, Energy Dispersive Xray (EDX) for elemental characterization, and Atomic Energy Spectroscopy to analyze heavy metal concentration in leachates. The results are compared and reported. Statistical analysis using ANOVA was performed to identify the influence of parameters such as biopolymer dose, curing time, and biopolymer type on UCS. The experiments were conducted with three replicates for accuracy, aiming to improve the mechanical and chemical properties of MSWF for sustainable civil engineering applications. For a clear understanding flowchart of the methodology is given below (Ref Figure 25).

Table 10: Average engineering properties of MSWF after mixing all depth sample

Properties	Values
Maximum Dry Density (MDD) (Mg/m3)	1.71
Optimum Moisture Content (OMC) (%)	17.0
Organic Content (%)	3.4
pH	6.3
Specific Gravity	2.23
Clay and Silt Size Particles (%)	60.8
Sand Size Particles (%)	39.2
Unified soil classification system (USCS)	CL
Liquid Limit (LL) (%)	34.7
Plastic limit (PL) (%)	23.6
Plasticity Index (PI)	11.09

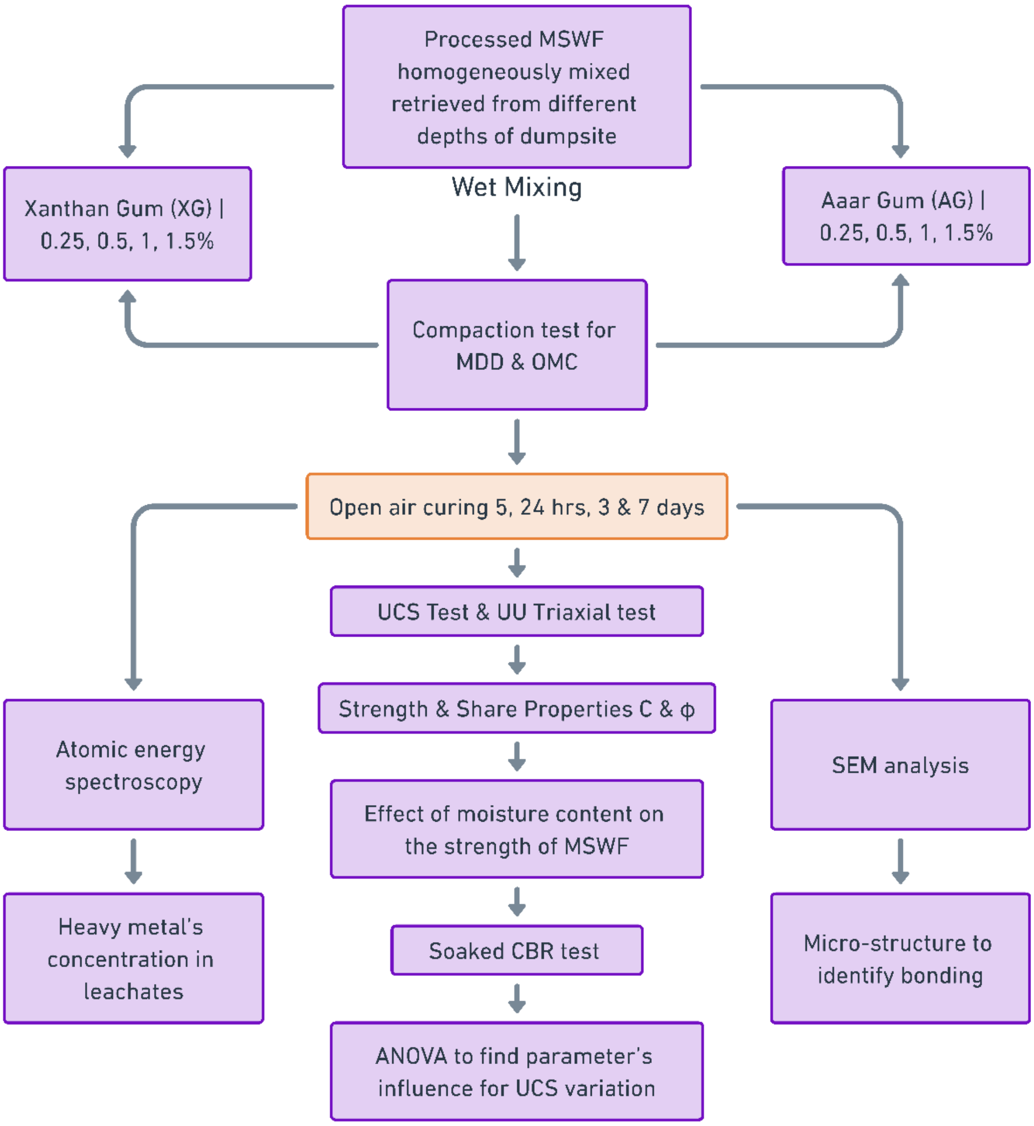


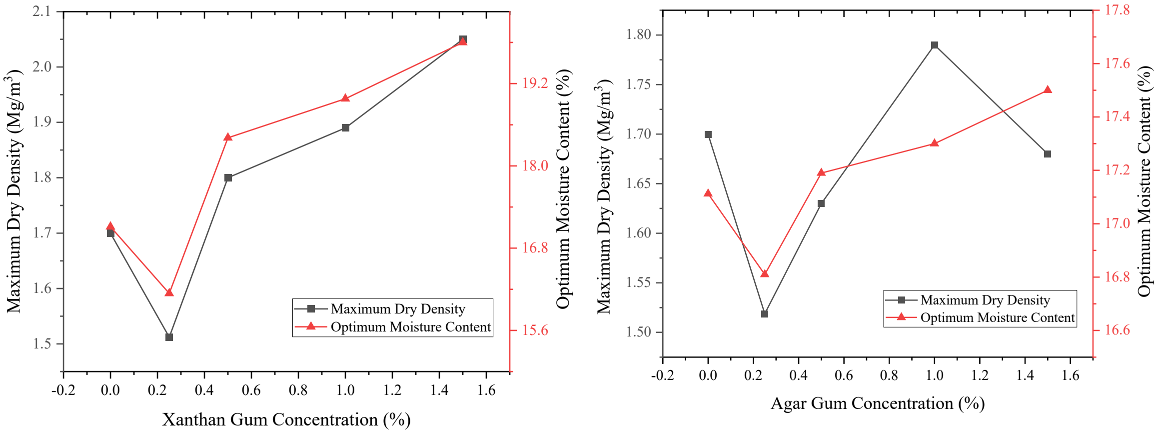
Figure 25: Typical Flow chart of the experimental program

5.3. Results and Discussion

All experiments were executed carefully following respective ASTM standards. The findings of the experiments are as follows:

5.3.1. Effect of Biopolymers on Compaction Characteristics of MSWF

The soil fraction of municipal solid waste is a heterogeneous material. Its compaction characteristics are shown in Figure 26 . It can be observed that the maximum dry density in both cases of XG and AG initially decreases and then increases with an increase in biopolymer content. A similar trend is observed in the case of optimum moisture content as well. The MDDs are 2.05 Mg/m3 and 1.79 Mg/m3 in the case of 1.5% XG and 1% AG, respectively. The corresponding optimum moisture contents are 19.80 and 17.5%. Normally, an increase in optimum moisture content reflects a decrease in the maximum dry density of soil. When some admixture is added to the soil in varying percentages while keeping the compactive effort constant, the particles of external material adjust themselves into the soil voids, replacing water voids and creating a denser soil profile even under low moisture conditions. Unlike this, biopolymers, when mixed in water, create a water-based gel that increases interparticle lubrication in soil. In the present case, when 0.25% (Wb/Ww) XG is added to MSWF, a decrease in the MDD and OMC of MSWF is observed. The formation of a viscous biopolymeric gel influences the density of the mixture in two ways. Initially, it acts as a lubricant, promoting better particle rearrangement and densification, which increases the MDD. However, at higher concentrations, the gel may begin to occupy space between particles, leading to a more porous structure and potentially reducing the overall density. In the case of agar gum, the maximum denseness is achieved with 1% of AG (Wb/Ww). As biopolymers have a water-retaining property and make polysaccharides with water, which is responsible for increasing the viscosity of the gel. When the biopolymer content increases from 0 to 1.5%, after a specific viscosity, it becomes tougher to mix it in the soil. Hence, more gel is required to coat soil particles to achieve maximum density and reduce air voids. This is a possible reason for higher OMC with increased biopolymer content. A similar trend of MDD and OMC was observed in the case of red mud when it was stabilized with Xanthan Gum, Guar Gum, and their composite (Bonal et al. 2021). While studying the effect of xanthan gum on expansive soil, Singh and Das (2020) found an increasing trend of OMC and MDD when increased it from 0-1% in soil (Singh & Das, 2020). Chang and Cho (2014) conducted an experimental study to find the effect of mixing beta-1,3/1,6-glucan biopolymer in residual soil and found that OMC increased slightly from 25% to 28%. MDD also increased from 13.6 to 14.1 kN/m3 while treating the soil with up to 0.23% biopolymer 33. Ayeldeen et al. (2016) conducted a study on two different types of soil by treating them separately with xanthan gum, guar gum, and modified starch by varying their quantity from 0.25% to 2% and found that both OMC and MDD increased when the percentage of all three biopolymers in the soil was increased (Ayeldeen et al. 2016).



(a) **(b)**

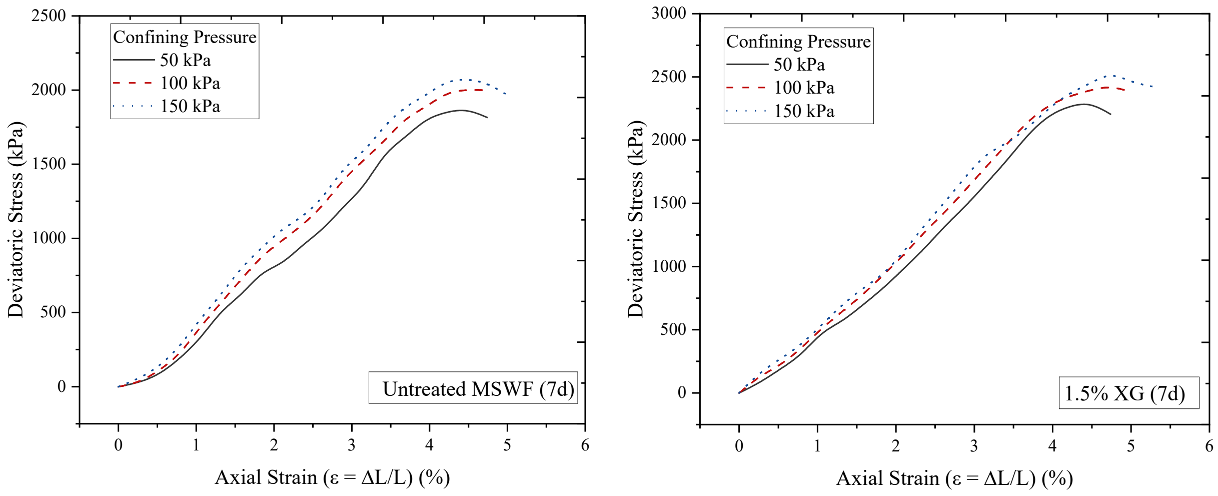
Figure 26: Compaction Characteristics (MDD and OMC) with varying percentages of Biopolymers: a Xanthan Gum, and b Agar Gum

5.3.2. Effect of Biopolymers on Shear Strength Parameters

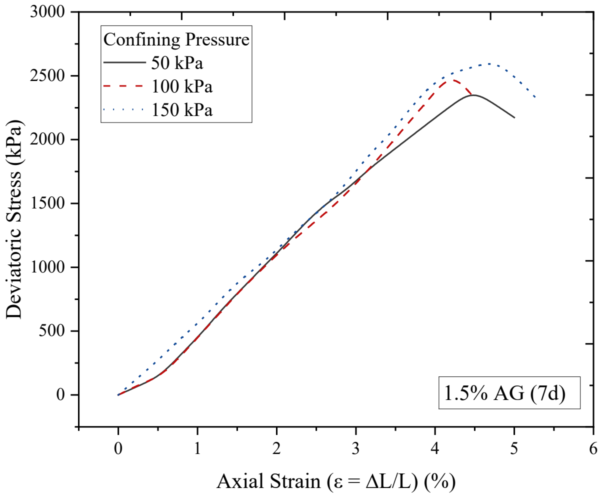
In this study, the stabilization of MSWF was done using biopolymers XG and AG at concentrations of 0%, 0.25%, 0.5%, 1%, and 1.5%. Triaxial tests (UU) were conducted on samples of 36 mm diameter and 72 mm height, as per ASTM D2850. These samples were cured at room temperature and open air for different periods, including 5 hours, 24 hours, 3 days, and 7 days, and then tested at confining pressures of 50, 100, and 150 kPa.

Figure 27 displays the deviatoric stress-strain plot for untreated MSWF, MSWF + 1.5% XG, and MSWF + 1.5% AG at 7 days of curing. The results showed that for nearly the same amount of strain, the deviator stress increased from 2.0 MPa to 2.5 MPa for XG and 2.6

MPa for AG. This increase in deviator stress can be attributed to enhanced intermolecular bonding and the agglomerative property of biopolymers that led to increased mechanical strength. Figure 28 shows the variation in shear strength parameters (cohesion and angle of internal friction) for XG and AG stabilized MSWF. The results indicate that both cohesion and angle of internal friction increased with increasing biopolymer content. However, for the 5-hour curing period, the cohesion (c) in both XG and AG cases showed an increase up to 0.5% biopolymer and then decreased. The varying pattern of cohesion is possibly due to two significant reasons. The first is that biopolymer particle hydration is still in its early stages of curing, and the second reason is that MSWF contains several random tiny textile fibers and metal scraps, which form connections with soil particles and are possibly a significant factor in the inconsistent trend of cohesion in both biopolymers, XG, and AG. For the rest of the curing periods, 24 hours, 3 days, and 7 days, both XG and AG were hydrated enough to create interparticle bonds and induce a substantial increase in strength in MSWF.



(a) **(b)**

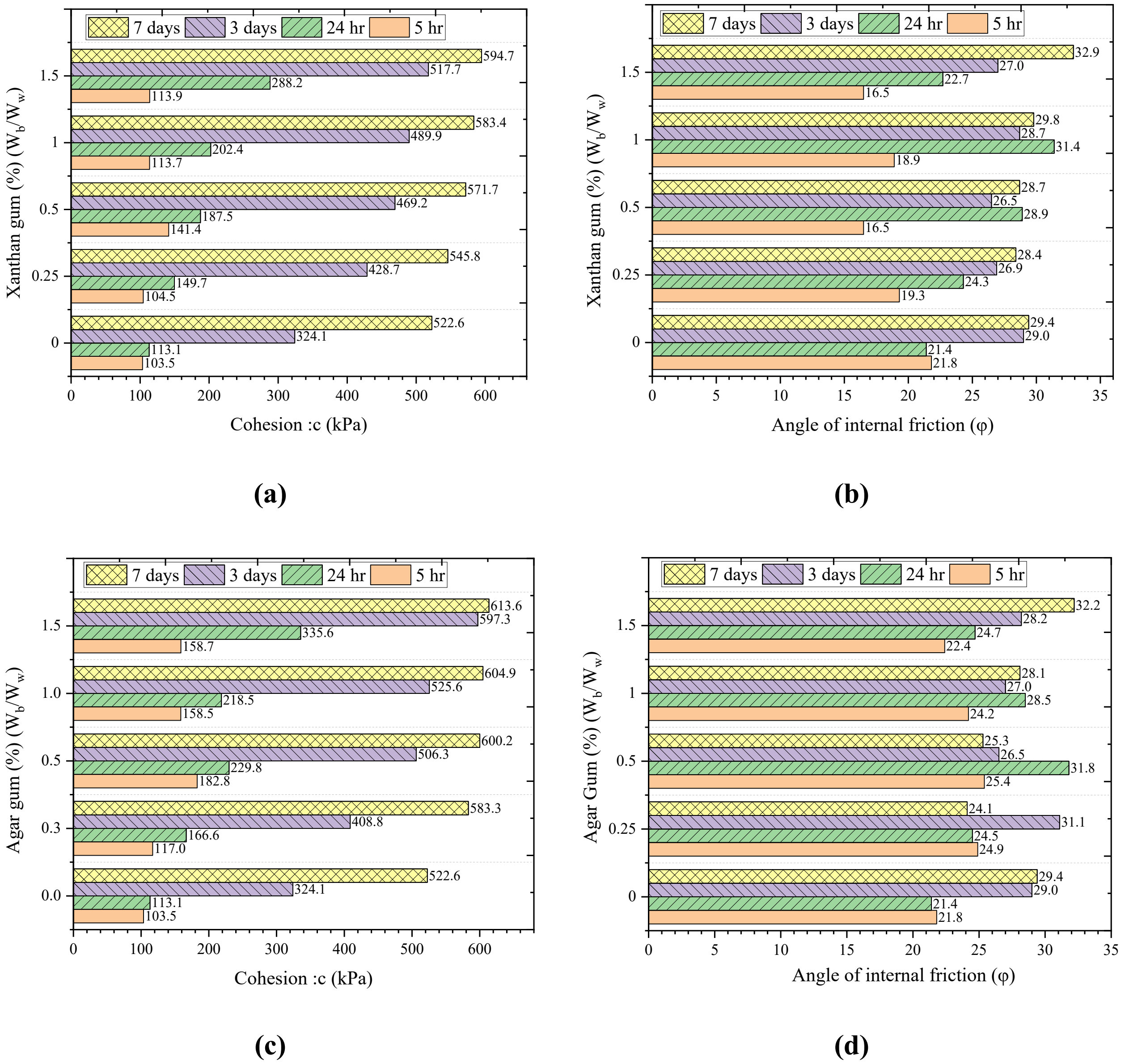


(c)

Figure 27: Plot between deviatoric stress and axial strain for a Untreated MSWF, b 1.5% XG Mix and c 1.5% AG Mix MSWF with 7 days of open-air curing

In the present study, cohesion increased significantly from 103.5 kPa (untreated MSWF, 5-hour curing) to 594.7 kPa (MSWF + XG) and 613.6 kPa (MSWF + AG) after 7 days of curing (Ref. Figure 28 a,c). The angle of internal friction also showed a notable rise from 16.5° to 32.8° (Ref. Figure 28 b,d). The initial reduction in the angle of internal friction (φ) may be attributed to the lubricating effect of water, which temporarily weakens interparticle contacts. However, as the curing period progresses, the biopolymer bonds strengthen and enhance cohesion, leading to an improvement in overall shear strength.

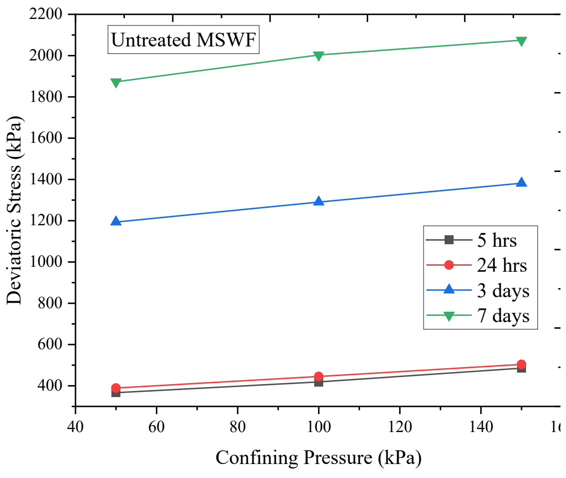
Figure 29 shows typical plots between confining pressure and deviatoric stress. XG and AG are carbohydrate polymers that form a hydrogel in soil. The hydrogel coats soil particles and increases their cohesion while the gel matrix around the particle thickens as the curing period increases, raising cohesiveness. Previous findings suggested that the friction angle increased from 21.8 to 22.3° with blending up to 0.16% chitosan in clay-type soil while curing at a constant relative humidity and temperature. The cohesion was observed to increase by 10.3 kPa to 30.3 kPa for the same case (Hataf et al. 2018) . A study on sand showed that the angle of internal friction and cohesion increased from 36.66° and 0.17 kPa to 45° and 145 kPa, respectively while mixing casein and sodium caseinate (Fatehi et al. 2018).



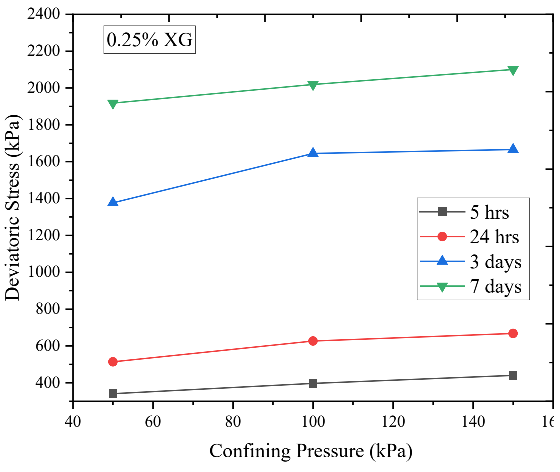
(a) **(b)**

(c) **(d)**

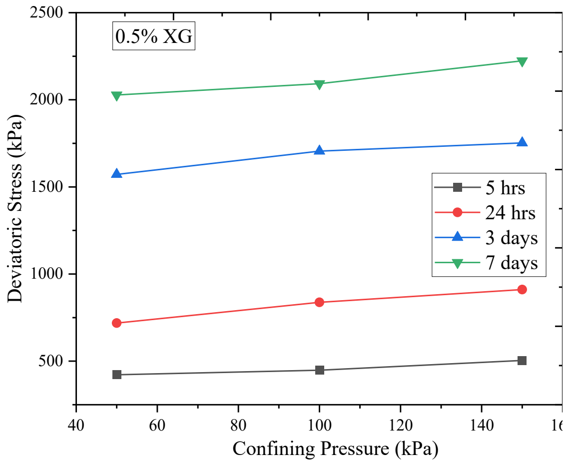
Figure 28: Angle of internal friction (φ) and cohesion (c) with varying percentages of XG and AG in MSWF.


Untreated MSWF
Deviatoric Stress (kPa)
2200
2000
1800
1600
1400
1200
1000
800
600
400
Confining Pressure (kPa)
40
60
80
100
120
140
16
5 hrs
24 hrs
3 days
7 days

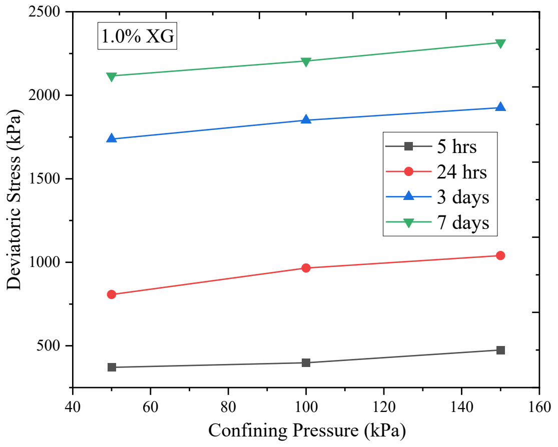
(a)


0.25% XG
Deviatoric Stress (kPa)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
Confining Pressure (kPa)
40
60
80
100
120
140
16
5 hrs
24 hrs
3 days
7 days

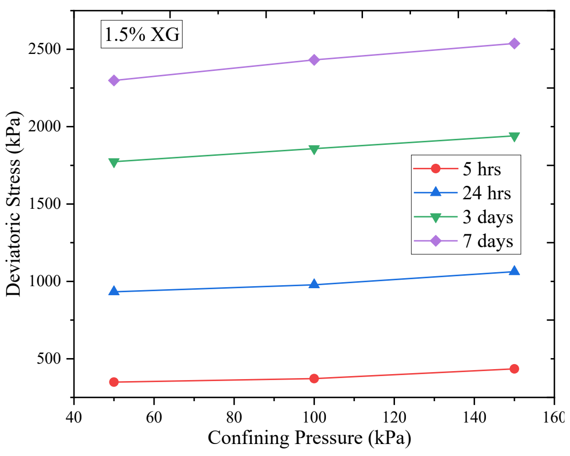
(b)


0.5% XG
Deviatoric Stress (kPa)
2500
2000
1500
1000
500
Confining Pressure (kPa)
40
60
80
100
120
140
16
5 hrs
24 hrs
3 days
7 days

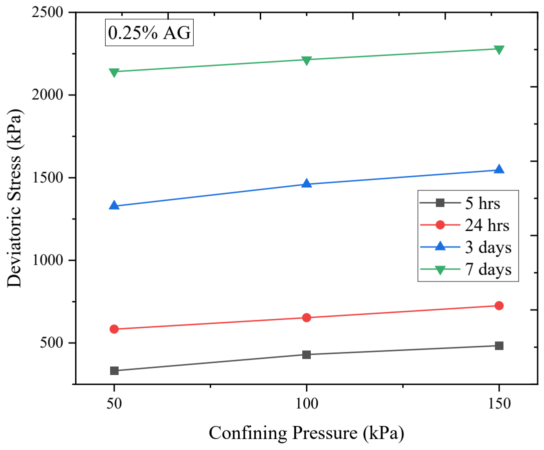
(c)


1.0% XG
Deviatoric Stress (kPa)
2500
2000
1500
1000
500
Confining Pressure (kPa)
40
60
80
100
120
140
160
5 hrs
24 hrs
3 days
7 days

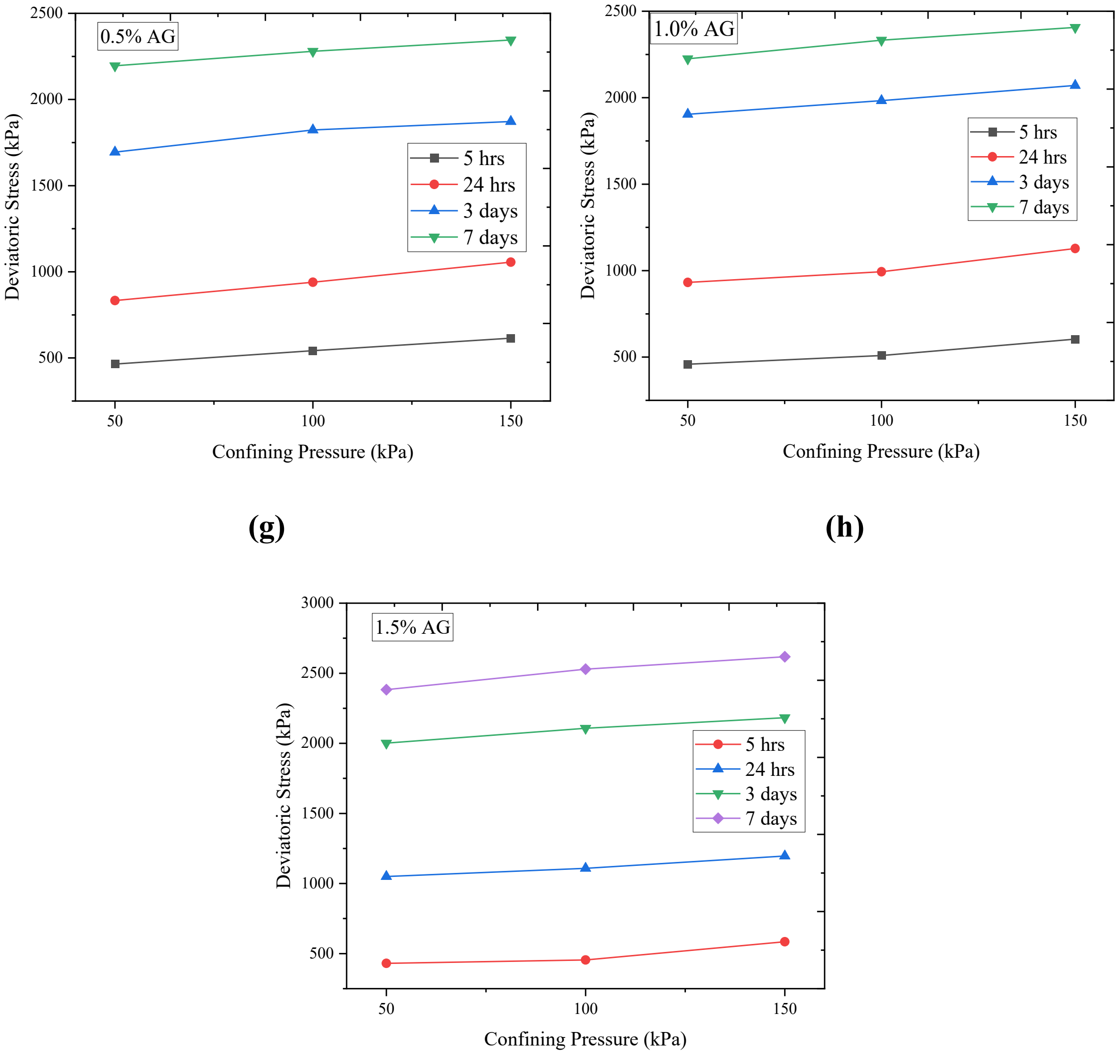
(d)


1.5% XG
Deviatoric Stress (kPa)
2500
2000
1500
1000
500
Confining Pressure (kPa)
40
60
80
100
120
140
160
5 hrs
24 hrs
3 days
7 days

(e)


0.25% AG
Deviatoric Stress (kPa)
2500
2000
1500
1000
500
Confining Pressure (kPa)
50
100
150
5 hrs
24 hrs
3 days
7 days

(f)



(g) **(h)**

(i)

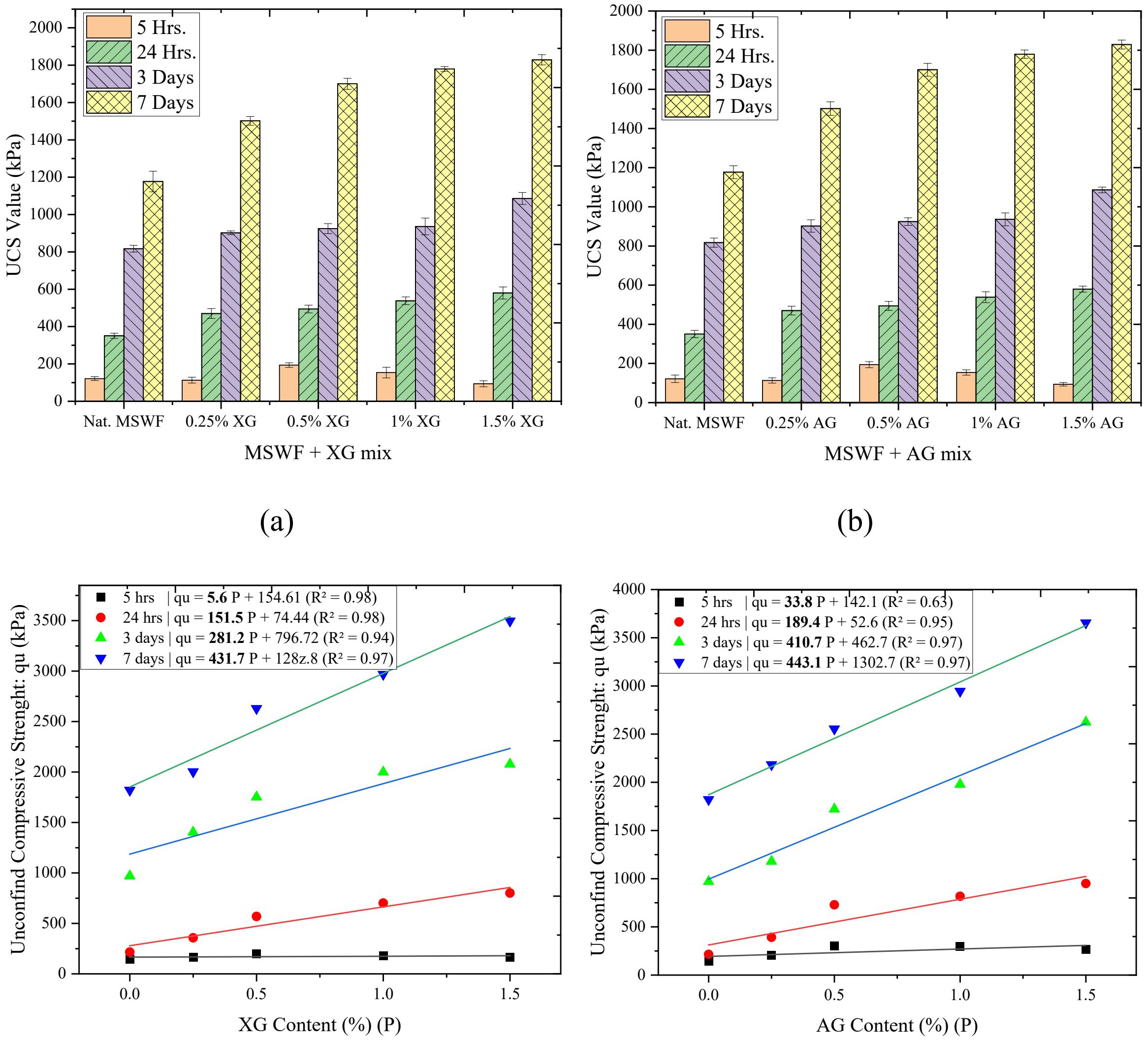
Figure 29: Plot between deviatoric stress and confining pressure for varying percentages of XG and AG mixed MSWF

5.3.3. Unconfined Compressive Strength of Bio-Stabilized MSWF

Unconfined compressive strength (UCS) tests were performed following the procedure mentioned in ASTM D2166 to investigate the compressive strength behavior of MSW samples with varied biopolymer content and curing duration. XG and AG are hydrocolloid gums that form an adhesive gel that bridges soil particles. The UCS test results are presented in Figure 30. For samples with 5 hours of curing, it can be observed that there is a decrease in the UCS value. This might be because at this stage, the biopolymers in the sample are not making interparticle bonds properly, while providing relative lubrication between particles. As a result, the sample's UCS decreases. A similar trend is observed in both cases of biopolymers (XG and AG).

However, as soon as the biopolymeric gel dried out, it developed interparticle bridging in the sample. The minimum compressive strength is 145.12 kPa for 5 hr curing at 0% biopolymer content, while the maximum strength is 3654.88 kPa for 7 days curing at 1.5% AG mix. Further, UCS values of more than 3000 and 1300 kPa on wet curing were reported in clay minerals such as montmorillonite, and kaolinite, respectively, using 2.5% XG presented by a researcher (Latifi et al. 2017). Other research on soil using xanthan gum, guar gum, and starch reported enhanced UCS value and other improved mechanical properties (Ayeldeen et al., 2016; Dehghan et al., 2019).

Figure 30 c,d shows the linearly fitted plot and equations for UCS of MSW stabilized with XG and AG. It is observed that the rate of strength gain with increasing biopolymer content is minimum for 5 hr curing (m= 5.6 and 33.8), and it gradually increases for an extended curing period. It is observed to be the maximum for a curing period of 7 days (m= 431.7 and 443.1). The thickening of the gel is relatively less for 5 hr curing. The thickening of the gel is more for a higher curing period and higher biopolymer content. This may be why the rate of strength gain is the highest for seven days of curing. Also, the water content at this stage, specifically at the seven-day curing period, is close to zero, resulting in the maximum strength with higher biopolymer content.



(a) (b)

(c) (d)

Figure 30: (a-b) Error plot of UCS (c-d) Trendline plot of UCS of biopolymer treated MSWF.

5.3.4. Effect of Moisture Content on the Strength of MSWF

Carbohydrate polymers have substantial emulsifying properties. Because of their emulsifying nature, both biopolymers XG and AG exert considerable strength on moisture dehydration. Naturally, soil, when dried, induces strength due to inherent cohesion. Soil particles combine due to cohesion, and lubrication between particles is reduced as soon as the water evaporates. The biopolymer gel fills up the voids in the soil matrix and forms a coating around the particles. This might be the reason for developing additional cohesion in the soil matrix. Similar observations were also made elsewhere (Fatehi et al. 2021). Figure

30 a, b shows the average UCS value for the given curing period. The average compressive strength of MSWF samples decreases when the moisture content of the samples is high. It can also be observed that the moisture content was reduced to a meager value, which is about 2%. The hydration of biopolymer particles below this water content will be either nil or very minimal. Hence, the curing is done for up to a maximum of 7 days in the present study. On the minimum water content observed on the 7th day of open-air curing of MSWF samples, the maximum compressive strength is 3496.78 kPa with 1.5% XG, and 3654.88 kPa with 1.5% AG.

The water content of every sample is checked after the UCS test to determine the level of dehydration of samples. Figure 31 shows the variation in dehydration with UCS values for different curing periods for XG and AG. These graphs show that higher UCS values are recorded, corresponding to a higher level of dehydration. In past studies, agar gum was reported to improve soil properties on dehydration 120,121. Several researchers also observed similar findings on strength gain on dehydration of Xanthan Gum (Chang et al. 2015a; Latifi et al. 2017).

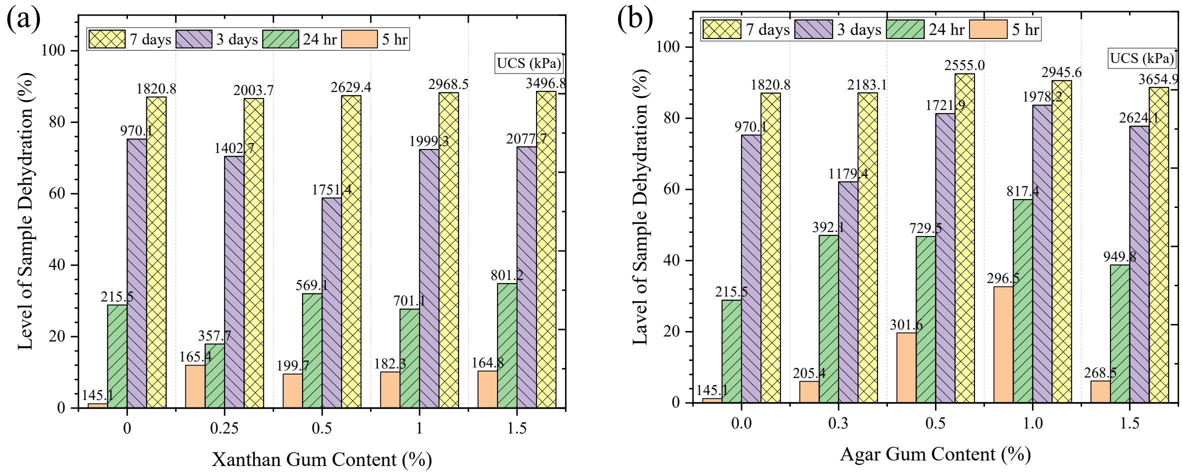


Figure 31: Variation in Biopolymer Content vs. Level of sample-dehydration and corresponding UCS value of MSWF at different curing periods

5.3.5. Analysis of Soaked CBR of treated MSWF

In the California Bearing Ratio (CBR)- Soaked experiment, varying percentages of Xanthan Gum (XG) and Agar Gum (AG) were mixed with Municipal Solid Waste Fines (MSWF) to evaluate their impact on the load-bearing capacity of the subgrade under soaked conditions (variation of soaked CBR shown in Figure 32. The initial CBR value for untreated MSWF was recorded at 6.1%. With the addition of 0.25% Xanthan Gum, the CBR value increased to 7.5%, and further increments in Xanthan Gum content to 0.5% and 1.0% resulted in CBR values of 9.4% and 11.2%, respectively. However, at 1.5% Xanthan Gum, the CBR value decreased to 10.4%. This decline is attributed to the formation of hydrogels by Xanthan Gum when it interacts with water, which imparts a lubricating effect, making the compacted MSWF easier to penetrate and thus reducing the CBR value.

In contrast, the addition of Agar Gum to the MSWF consistently increased the CBR value across all tested percentages. Starting from the base CBR value of 6.1% for untreated MSWF, the introduction of 0.25% Agar Gum raised the CBR value to 8.6%. Further increments in Agar Gum to 0.5%, 1.0%, and 1.5% led to CBR values of 10.5%, 11.6%, and 13.1%, respectively. Agar Gum's ability to solidify at temperatures between 30-40ºC and remain semi-solid even when submerged in water contributes to the formation of strong interparticle bonds, enhancing the mechanical strength of the MSWF mix.

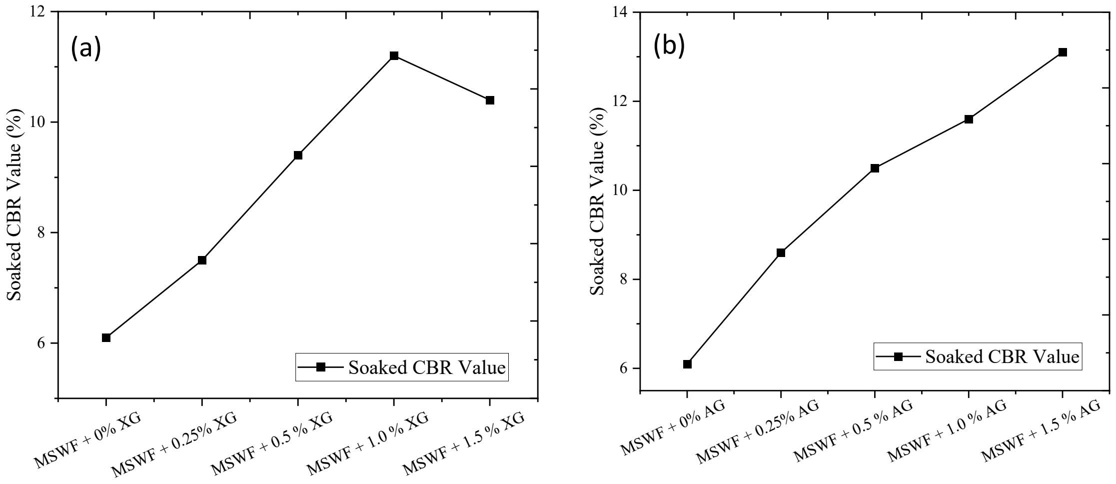


Figure 32: Variation of soaked CBR values (a) For Xanthan Gum (b) For Agar Gum

Overall, the maximum improvement in CBR value for Xanthan Gum was observed at 1.0% XG, where the value increased from 6.1% to 11.2%. In comparison, Agar Gum provided a more consistent enhancement, with the highest CBR value of 13.1% recorded at 1.5% AG. These findings suggest that while both biopolymers effectively improve the load-bearing capacity of MSWF, Agar Gum demonstrates a more robust and reliable performance, particularly at higher concentrations, making it a preferable choice for stabilizing MSWF under soaked conditions.

5.3.6. Analysis of Leachates of Bio-Treated MSWF

Leachate analysis was carried out to determine the heavy metal content released when water flows through stabilized and non-stabilized municipal solid waste (MSW). Atomic absorption spectroscopy was used to analyze the heavy metals in the leachate. For the preparation of the MSW leachate, 1 g of MSW sample was taken and digested with 15 mL of HNO3 and 25 mL of $HClO_4$. The sample was heated, and the extract was separated using filter paper. After separation, the leachate was analyzed for heavy metals using the Atomic Absorption Spectrometer, and the results are described in Table 10.

It can be seen in Table 11 that hazardous elements such as Cd, As, and Pb are present in minimal quantities or below detectable levels in the MSW leachate. Moreover, mixing 1.5% of xanthan gum (XG) and agar gum (AG) shows that the secretion of heavy metals and other elements is substantially reduced in the leachate. The observed values suggest that XG has a better metal encapsulation capacity than AG. This can be attributed to the fact that biopolymers form a protective barrier around the waste particles, preventing the release of heavy metals. Several researchers have previously demonstrated the effectiveness of biopolymeric substances in the remediation of contaminated soil 123. Chitosan biopolymer is commonly used to remove heavy metals (Kanmani et al. 2017; Shariatmadari et al. 2020). Other biopolymers such as cellulose, guar gum, glucan, xanthan, and polycaprolactone-coated hydroxyapatite-foam have also shown their ability to absorb and remediate heavy metals (Palanisamy et al. 2019).

In addition to biopolymers, microorganisms also play a crucial role in the biotreatment process and can contribute to the reduction of heavy metal concentrations in leachates. Microorganisms can degrade organic matter in the waste and convert it into harmless byproducts, reducing the toxicity of the waste. Additionally, some microorganisms have the ability to accumulate heavy metals within their cells, removing them from the environment. The combination of biopolymers and microorganisms in the biotreatment of MSW can therefore be an effective method for reducing the release of heavy metals into the environment.

Table 11: Leachates analysis for heavy metals in MSWF (all quantities are in PPM)

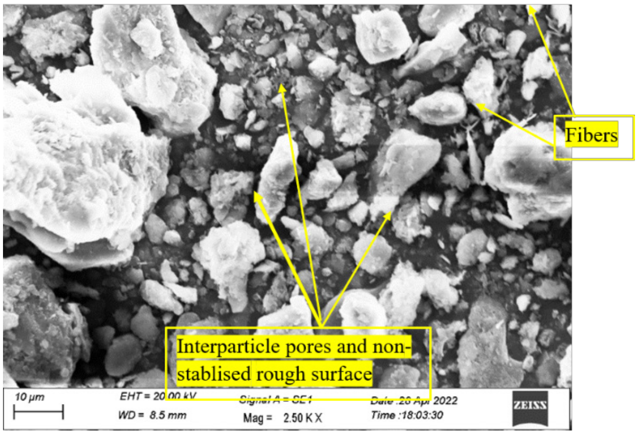
Elements	Cd	As	Mg	Al	Pb	K	Ca	Ti	Fe	Nb	Ta
MSWF	0.003	0.0004	0.351	1.41	BDL	0.792	0.031	1.175	2.311	0.124	1.073
MSWF + 1.5% XG	BDL	BDL	0.078	0.798	BDL	0.821	0.009	0.564	0.076	BDL	0.894

MSWF + 1.5% AG	0.001	0.0012	0.34	1.091	BDL	0.697	0.028	1.006	1.295	BDL	1.102

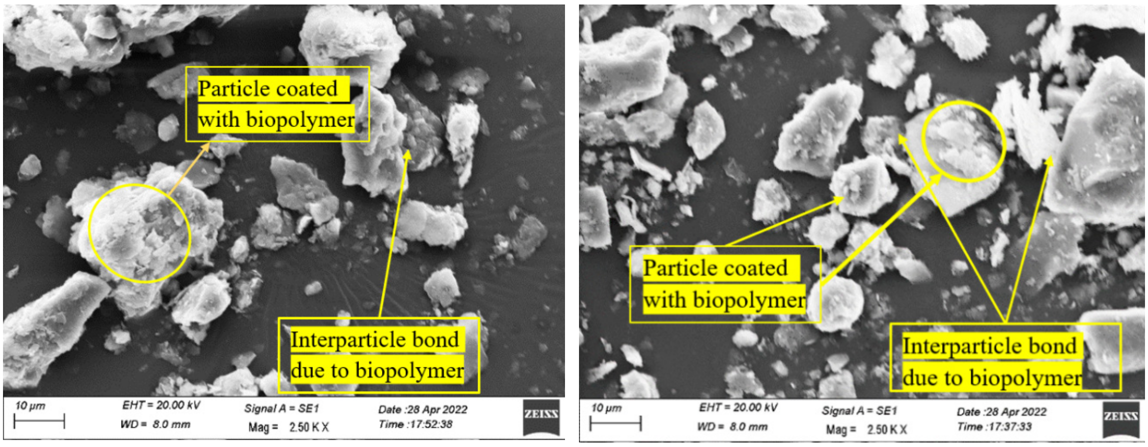
BDL: Below detectable level

5.3.7. SEM Analysis

SEM imaging was carried out using ZEISS EVO 18 SEM from ZEISS Microscopy at a magnification of 2500x to observe the bonding among the particles. The powder sample was used for the analysis. The results of the SEM analysis are shown in Figure 33 a, b & c. The MSWF particles can be observed coated with biopolymers in the SEM images. Figure 33 a shows the SEM analysis of an untreated sample, where the soil surface morphology is rough, and the particles are mutually discrete. Pores are also visible on the MSWF surface. In contrast, in Figure 33 b & c , the particles of MSWF are coated with biopolymers, and the hydrated MSWF-biopolymer matrix fills the maximum pores (Al-Mazrouei et al. 2023). These biopolymer bondings strengthen the soil matrix by increasing cohesion and the angle of internal friction. The hydrated biopolymers XG and AG also fill pores in MSWF, making the MSWF matrix stiff and responsible for increased mechanical strength. Previous studies have also reported a similar trend in biopolymer-stabilized soil morphology (Fatehi et al. 2018; Arab et al. 2019; Ghasemzadeh and Modiri 2020). The bondings of biopolymers between soil particles have been shown by several authors(Chang and Cho 2019; Ramachandran et al. 2021).



(a)



(b) **(c)**

Figure 33: SEM images of (a) Natural MSWF, (b) XG stabilized MSWF, and (c) AG-stabilized MSWF

5.4. Statistical Evaluation of UCS

ANOVA is a tool used to study the influence of independent variables on dependent variables in regression analysis, indicating the significance of a particular variable on the final experimental outcome. In the present study, ANOVA analysis is carried out to determine the significance of variables like biopolymer type, biopolymer content, and curing period on the UCS of treated MSWF. Three-way ANOVA is used in this analysis, implying three ways to indicate the number of independent variables. ANOVA works on the principle of comparison based on the mean of samples. The significance of the mentioned parameters is verified for a significance level (α) of 0.05. If the P value (Table 12) is less than 0.05, it indicates that the particular parameter is significant. In this case, the P value is zero for all parameters, indicating that all selected parameters are relevant for deciding the UCS of treated MSWF. The F-Value also indicates the significance of the parameter, with a higher value indicating higher significance.

The main-effect graph in Figure 34 shows the plot between mean UCS and parameters like biopolymer type, biopolymer content, and curing period. The graph shows that the curing period is the most dominant parameter, while the biopolymer type is the least dominant for deciding the UCS of MSWF. Although the biopolymer type (XG or AG) shows its minimum effect on UCS, the influence of AG is indeed on a higher side than XG. Biopolymer content is also significant, but the dry air-curing period is more significant in the present case. Therefore, regardless of the biopolymer utilized, a higher proportion of biopolymer can be used for a more extended curing period to reach the desired strength, especially for surficial or crust applications where dry curing is achievable.

The statistical analysis also suggests that the strength gain is maximum at 1.5% of both biopolymers. However, as discussed earlier, beyond 1.5% XG mixed in water, the biopolymer-water mix becomes too viscous to be mixed in MSWF. Although this is not the case for AG, the solution remains workable while mixing more than 1.5% of AG in water. The present study compares the physical and mechanical properties of AG and XG stabilized MSWF when mixed in equal quantities in MSWF. The fact is that better mechanical properties of soil after treatment can be obtained in the case of AG when both AG and XG are used separately in equal amounts. However, to obtain the maximum reported UCS, the dosage of 1.5% of AG (Wb/Ww) with seven days of open-air curing is recommended for materials like MSWF.

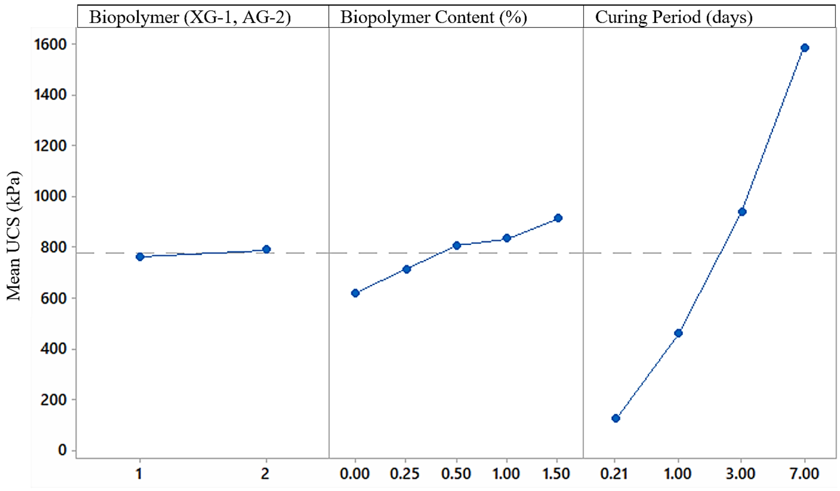


Figure 34: Plot showing the relative importance of parameters defining UCS

Table 12: A statistical representation of influencing parameters for UCS

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Biopolymer (XG,AG)	1	13937	13937	890.09	0.000
Biopolymer content (%)	4	821986	205496	13124.37	0.000
Curing period (days)	3	24204132	8068044	515278.69	0.000
Biopolymer *Biopolymer (%)	4	23687	5922	378.20	0.000
Biopolymer*Curing period	3	10456	3485	222.60	0.000
Biopolymer %*Curing period	12	745554	62129	3968.00	0.000
Biopolymer*Biopolymer (%) *Curing period	12	17186	1432	91.47	0.000
Error	40	626	16		
Total	79	25837564			

Note: Adj SS Adjusted sums of squares, Adj MS, Adjusted mean squares, DF Degrees of freedom

5.5. Key Takeaways and Way forward

- Xanthan Gum (XG) and Agar Gum (AG) offer sustainable alternatives for stabilizing Municipal Solid Waste Fines (MSWF), addressing environmental concerns of traditional methods.

- The highest Maximum Dry Density (MDD) observed was 2.05 Mg/m^3 for 1.5% XG (12.2% increase) and 1.79 Mg/m^3 for 1% AG (7.8% increase) .

- Cohesion increased from 103.5 kPa (untreated) to 594.7 kPa (1.5% XG) and 613.6 kPa (1.5% AG), reflecting an increase of up to 492.7%.

- Maximum UCS was 3654.88 kPa for 1.5% AG after seven days of curing, a 2419% increase from the base value of 145.12 kPa.

- UCS increased to 3496.78 kPa with 1.5% XG after seven days, demonstrating the effectiveness of biopolymer gels in enhancing cohesion and reducing voids.

- Agar Gum consistently outperformed Xanthan Gum in enhancing the CBR of MSWF, with a peak value of 13.1% at 1.5% AG, making it a more effective stabilizer for improving the load-bearing capacity under soaked conditions.

- Biopolymer treatment significantly reduced heavy metals in leachates, with hazardous elements like Cd, As, and Pb below detectable levels after treatment.

- SEM analysis showed enhanced particle bonding and reduced porosity in biopolymer-treated MSWF, contributing to improved mechanical strength.

- ANOVA confirmed significant impacts of biopolymer type, content, and curing period on UCS, with curing period being the most influential factor.

These findings underscore the potential of XG and AG for sustainable stabilization of MSWF, offering a viable alternative to conventional methods while enhancing the mechanical and chemical properties of the material. The next chapter will explore long-term durability and strength retention of biopolymers under constant moisture and closed conditions, simulating below-earth crust stabilization.