E3S Web of Conferences **730**, 02009 (2026) https://doi.org/10.1051/e3sconf/202673002009
Soft Soils 2026

Residual shear strength of guar gum amended granular bentonite under chemo-mechanical loading

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Abstract. Bentonite clay is widely used as a liner material at the base and along the side slopes of municipal solid waste (MSW) landfills due to its low hydraulic conductivity and high swelling capacity. However, the granular form of bentonite (GB) often fails to seal effectively in the presence of leachate chemicals, compromising its barrier performance. Several recent studies have explored the use of biopolymers to enhance the physicochemical and mechanical behavior of granular bentonite. Among these, guar gum has emerged as a promising stabilizer because it forms a thick, viscous gel in aqueous and saline environments, improving particle bonding. Understanding the residual shear strength behavior of GB and guar gum-amended GB is crucial, as it defines the minimum shear resistance mobilized after large deformations. This study investigates the influence of guar gum inclusion on the residual and peak shear strength of granular bentonite clay using a torsional ring shear test under drained conditions, following ASTM D6467. Samples were compacted to a target density and tested under normal stresses of 300, 500, and 700 kPa, with shearing applied at a constant rate until steady-state conditions were achieved. The shear stress-displacement response was analyzed to determine the residual shear strength at the plateau region. Results revealed a significant improvement in residual shear strength with guar gum addition, attributed to enhanced interparticle bonding and matrix cohesion.

1 Introduction

The leachate from the municipal solid waste (MSW) landfill contains organic material, heavy metals, salts, and other emerging contaminants [1]. Engineered barriers are utilized to prevent the migration of these harmful contaminants to the groundwater [2, 3]. Granular bentonite (GB) is preferred over powdered bentonite in several waste containment applications due to its workability, and it is the primary product in bentonite processing [4, 5]. The GB swells and disperses into individual particles upon hydration, which leads to the sealing of the macro-voids. The municipal solid waste landfill leachate contains high concentrations of salt solutions. The GB loses its sealing ability in the presence of high concentrations of salts due to poorly developed repulsive forces. The presence of macro-voids in the GB can lead to the migration of the various contaminants across the GB [6-8].

The failure of a bentonite-based liner under high-concentration pore fluid can lead to migration of several contaminants to the subsurface environment. Due to compression in diffuse double layers in the presence of salt, the shear strength of clays increases. Further, in the case of GB, the frictional resistance increases in the presence of salt, as granules do not disperse completely and offer frictional resistance during shearing. On the other hand, the shear strength of the liner material reduces significantly due to a reduction in suction upon saturation. The magnitude of reduction in shear strength is higher than the increase due to the presence of salts. In addition to the chemical loading, the GB in landfill is also subjected to the mechanical loading due to the weight of the waste in the landfill. Therefore, the hydraulic and mechanical performance of the liner materials under the chemo-mechanical conditions is essential. The behavior of GB under such conditions is inherently coupled, and its performance cannot be reliably assessed through independent evaluation of hydraulic or shear properties.

To overcome the demerit of sealing in GBs, the amendment of bentonites with polymers and biopolymers has received attention recently. Sodium carboxymethyl cellulose (Na-CMC), propylene carbonate, etc., have been studied to modify the bentonite clays [9,10]. Recent studies also utilized the biopolymers with clays to improve the sealing ability [11, 12]. Several biopolymers like xanthan gum, guar gum, gellan gum, and sodium alginate have been studied previously to modify the soils. These biopolymers are environmentally friendly and have a low carbon footprint as compared to conventional binders [13]. The pore clogging due to gel formation, increase in swelling capacity with polymers, and better chemical compatibility are the main mechanisms for the improved performance of the polymerized clays. The guar gum (GG), a biopolymer, forms a thick and stable gel upon hydration with water. It forms hydrogen bonding due to

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the presence of a large number of hydroxyl groups. The utilization of GG with GB reduces the hydraulic conductivity under high concentrations of KCl and $CaCl_2$ [14]. The inclusion of GG is expected to enhance interparticle bonding through gel formation and polymer bridging, potentially improving shear resistance even under an extreme salt environment.

While improvements in sealing behavior have been demonstrated, the mechanical performance of biopolymer-amended GB, especially under large deformation conditions, remains insufficiently explored. The liner material is also used along the slopes of the landfills, and torsional shear resistance becomes important for stability analysis, as large deformations are expected before failures. Designing the liners corresponding to the peak strength values may lead to the overestimation of the factor of safety against slope failure. The constant shear along the slip plane under large deformations is termed residual shear strength [15]. The residual shear strength governs the long-term stability of the landfill liner system, particularly along the side slopes. There are several studies available on the residual shear strength of the clays, which show that the stability of the slip surface strongly depends on the residual shear strength of the clay [16]. Most of the existing studies on residual shear strength focused on clays and modified clays without considering the role of the biopolymer amendments under harsh chemical environments.

There is no study available on the residual shear strength of biopolymer-amended granular bentonite under high chemo-mechanical loadings. Addressing this gap is essential for elevating the suitability of such materials in geoenvironmental engineering applications. The present study systematically evaluated the influence of GG inclusion on the peak and residual shear strength behavior under higher chemo-mechanical loading using the torsional ring shear apparatus. This gap is particularly critical for predicting the long-term stability of liner systems exposed to saline leachates.

2 Materials and methodology

2.1 Materials

The granular bentonite (GB) exhumed from commercially available GCL was utilized in the present study. The index and surface properties of the studied GB were reported from the earlier work of the authors [5, 17] and presented in Table 1.

The guar gum (GG), a biopolymer, was procured from Urban Platter. The GG, also known as *Cyamopsis tetragonoloba*, is a polysaccharide extracted from guar beans. It forms a thick, viscous gel with water. GG forms hydrogen bonds with water molecules upon hydration due to the abundance of hydroxyl groups in its structure. The required amount of GG was mixed with air-dried GB. In this work, the 10 % GG by weight was considered. The GBGG sample indicated a mixture of 10 % of GG along with GB.

The potassium chloride salt was procured from Spectrochem (India) with 99 % purity. The required amount of KCl was weighed and mixed in distilled water to make a 0.5M KCl solution.

Table 1. Index and surface properties of the studied GB.

Property	Values
Specific gravity	2.78
Liquid limit (%)	658
Plastic limit (%)	48
Specific surface area (m^2/g)	648
Cation exchange capacity (meq/100g)	153

2.2 Methodology

The influence of normal stresses on shear and volume change behavior of GB and GBGG samples was studied using Tortional shear tests. The Bromhead ring shear apparatus test, manufactured by CONTROLS, Italy, has been utilized in the work as shown in Fig. 1. The torsional shear test has a very short drainage path and hence is quite effective in determining the effective shear parameters. The GB or GBGG sample was placed in an annular ring with an inner diameter of 70 mm and an outer diameter of 100 mm, and an initial sample thickness of 5 mm. An annular porous stone was placed on either side of the sample, as shown in Fig. 1. A filter paper was placed between the porous stone and the clay sample to avoid the clogging of the porous stone. The air-dried GB sample has a moisture content of around 10 %. The samples were compacted at a placement density of 1.2 Mg/m^3, which also corresponds to the dry density of 1.1 Mg/m^3, and a degree of saturation of 18 %.

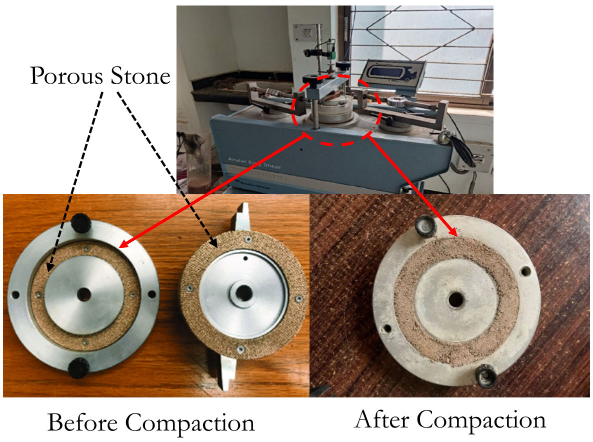

Fig. 1. Torsional ring shear apparatus and specimen configuration used in the study.

The experiment was conducted in two phases, following the ASTM standards [18]. In the first phase, the sample is subjected to the chemo-mechanical loading, which means the application of the required mechanical load through a lever arm and inundation of the sample with 0.5 M KCl salt solution as pore fluid. In the second phase, the drained shearing was performed on a consolidated saturated sample at a slow rate (0.05°/min) to avoid the generation of excess pore water pressures. The saturation of the samples was ensured by checking the volume change readings. The volume change measured with changes in sample thickness did not change upon equilibrium. The samples took 24 hours to 48 hours to achieve the equilibrium from the application of chemo-mechanical loadings.

3 Results and discussion

The results for the torsional shear test of GB samples under chemo-mechanical loadings were presented in Fig. 2a. The torsional shear tests were performed under different normal stresses under normally consolidated drained conditions. The samples were sheared until the residual condition was achieved. All samples showed a rapid development in stress and achieved the peak stress value at very low shear horizontal displacement. The peak value is due to the mobilization of the interparticle resistance present in GB granules. The magnitude of peak stress increases with an increase in the normal stress.

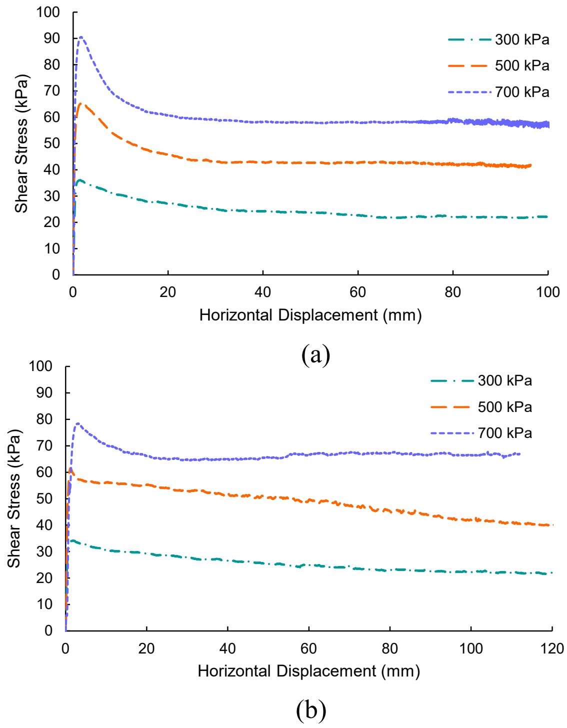

Fig. 2. The shear stress profiles under different normal stresses with a 0.5M KCl environment for (a) GB, and (b) GBGG.

The samples showed a reduction in the shear stress after the peak, indicating the strain softening behavior. This stress reduction is attributed to the breakdown of GB granules and particle reorientations. The strain softening is found to be more pronounced in the case of higher stress (i.e., 700 kPa), suggesting more breakdown of GB granules and enhanced particle rearrangement. The increased breakdown of GB at higher normal stresses is consistent with the established behavior of crushable granular materials. At low stresses, deformation is primarily governed by particle rearrangement, whereas at higher stresses, particle crushing becomes dominant. Granular bentonite, being composed of relatively weak agglomerates, is particularly susceptible to stress-induced disintegration under high confinement, which explains the observed increase in particle breakdown. The improved sealing at higher normal stresses is attributed to stress-induced breakdown of GB granules, leading to the generation of finer particles that fill intergranular voids. This process reduces pore connectivity and permeability, resulting in enhanced sealing capacity [6].

The shear stress approaches a constant value subsequently at higher horizontal displacement, representing the residual shear strength. This steady-state condition indicates that the GB sample has reached a fully remolded state, where shear resistance is governed primarily by frictional sliding between aligned particles rather than interparticle bonding or structure.
The residual strength also increases with normal stress; however, the rate of increase is lower compared to peak strength, which implies a reduction in the effective friction angle from peak to residual conditions. This behavior is characteristic of materials exhibiting significant particle reorientation and loss of dilatancy at large strains.

The shear stress – horizontal displacement response from the tortional shear test of the GBGG sample under chemo-mechanical loadings was presented in Fig. 2b. These samples also exhibited a strain-softening behavior followed by stabilization at large horizontal displacements. Samples showed a quick mobilization of the shear stress during the initial stage of the shearing, and samples achieved the peak stresses at very small values of shear displacement. The peak shear stress values increase with an increase in the normal stresses. The samples showed a strain softening behaviour; however, the magnitude of reduction in stresses was lower than in the case of GB. This resulted in higher residual stresses in GBGG samples as compared to GB, which is attributed to the gel formation from GG. The residual shear strength increases with normal stress, but the difference between peak and residual strength is not very large, indicating a relatively stable post-peak behavior. This suggests that the GBGG sample maintains a significant portion of its shear resistance even after large deformations, which is advantageous for applications requiring long-term stability.

The variations of the GB sample thicknesses with shearing under chemo-mechanical loading were presented in Fig. 3a. The initial drop in the sample thickness is attributed to the inundation of the samples with 0.5 M KCl and application of respective mechanical loadings. The application of chemo-mechanical loadings leads to the breakage of GB granules. The resistance of GB granules to breakage is governed primarily by their internal bonding and fabric rather than their size. The granules consist of weakly bound clay platelet aggregates, which are susceptible to disintegration under combined chemo-mechanical loading. The inundation with high-concentration salt (0.5 M KCl) led to poorly developed repulsive pressures, and hence, it could not overcome the effect of applied mechanical loads. The magnitude of initial collapse increased with an increase in the applied normal stresses, and a lower sample thickness was observed for the sample with 700 kPa as compared to 300 and 500 kPa. The samples showed further reduction in the sample thickness upon shearing; however, this reduction in sample thickness was observed to be gradual. It is attributed to the particle rearrangements. At the residual state, the sample thicknesses were found to be consistent with minimal changes. The GB samples showed a contractive response, a higher magnitude of collapse with higher normal stresses, and leading to lower equilibrium thickness at large strains.

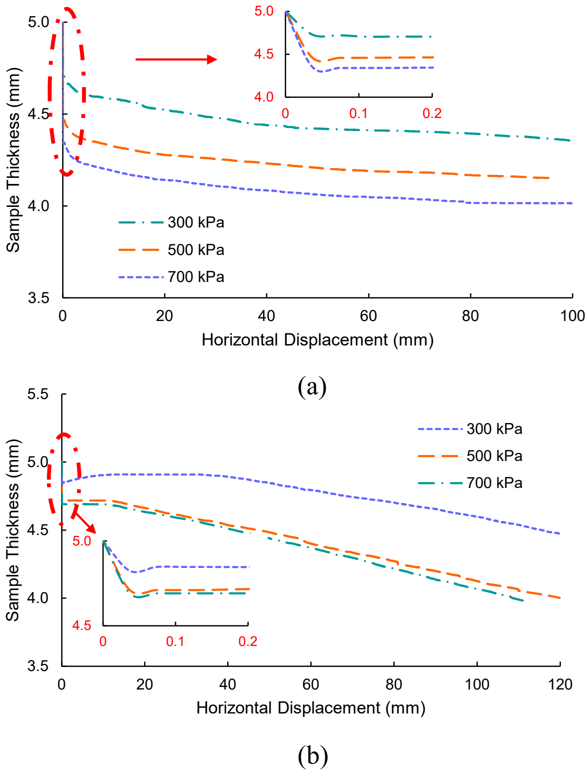

Fig. 3. The sample thicknesses under different normal stresses with a 0.5M KCl environment for (a) GB, and (b) GBGG.

The variations of the sample thicknesses with shear under chemo-mechanical loadings for the GBGG sample were presented in Fig. 3b. The samples showed an initial collapse due to the inundation of 0.5 M KCl as pore fluid and the application of mechanical loads. The GBGG samples showed relatively lower collapse than the respective GB samples. Such behaviour of GBGG samples is attributed to the gel formation due to the hydration of guar gum. Upon shearing, a gradual and continuous decrease in the sample thickness was observed for all normal stresses. The sample with the highest mechanical loading (i.e., 700 kPa) showed higher collapse as compared to lower mechanical loads. The GBGG sample showed gradual contractive behaviour and an enhanced matrix that controls the magnitude of collapse.

The shear strengths for GB and GBGG samples were plotted against normal stresses as shown in Fig 4a and 4b, respectively. A linear Mohr–Coulomb fit yielded an R^2 value close to unity, with a negligible intercept relative to the measured shear stresses. This indicates that cohesion is minimal within the tested stress range; therefore, a zero-intercept assumption was adopted.

The cohesion refers to the interparticle attractive forces among the soil particles contributing to shear strength. Both peak and residual shear strength of GB and GBGG samples exhibited a linear increase with the normal stress, indicating friction-controlled behavior. The slopes of the peak envelope for both samples showed a greater frictional angle compared to the respective residual condition, as presented in Table 2. Higher internal angle of friction at peak is due to stronger interparticle resistance prior to mobilization. The reduction from peak to residual state is attributed to the particle rearrangements and breakdown of GB granules during shearing, which resulted in reduced interlocking among the particles.

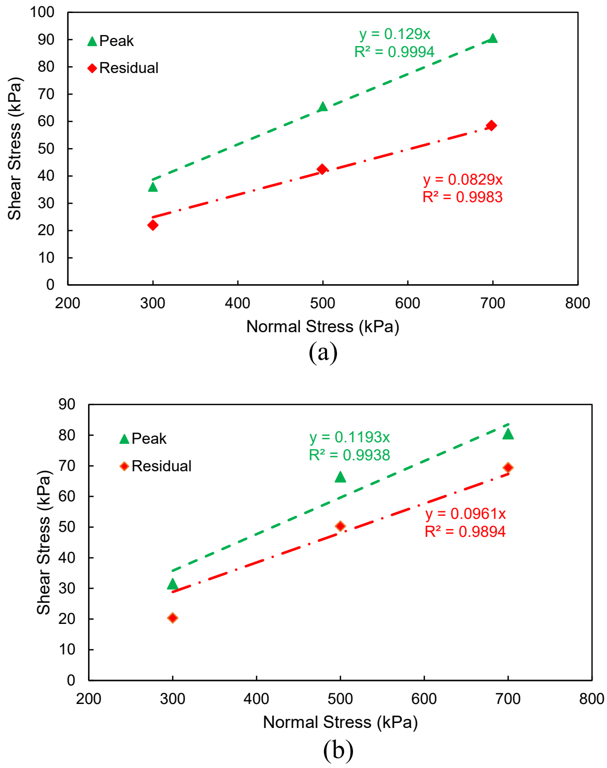

Fig. 4. Measured shear strength data under different normal stresses fitted with the Mohr-Coulomb envelope for peak and residual state for (a) GB and (b) GBGG.

Table 2. Values of effective angle of internal friction.

Sample	Φ'_{peak}	$\Phi'_{residual}$
GB	7.35°	4.74°
GBGG	6.80°	5.49°

The peak strength envelope of GBGG exhibits a slightly lower slope compared to GB, indicating a marginal reduction in peak frictional resistance due to better interparticle resistance in GB. However, the residual strength of GBGG is higher than that of the GB sample due to the resistance provided by the guar gum gel formation. This suggests that the modification enhances the stability of the material during large shear deformations. Furthermore, the reduction in strength from peak to residual state is less pronounced in GBGG, indicating improved structural integrity and reduced particle rearrangement as presented in Fig. 5. This behavior can be attributed to gel formation from the hydration of guar gum that maintains interparticle bonding and resists degradation under shear. From an engineering perspective, the enhanced residual strength of GBGG makes it more suitable for applications where long-term shear resistance is critical.

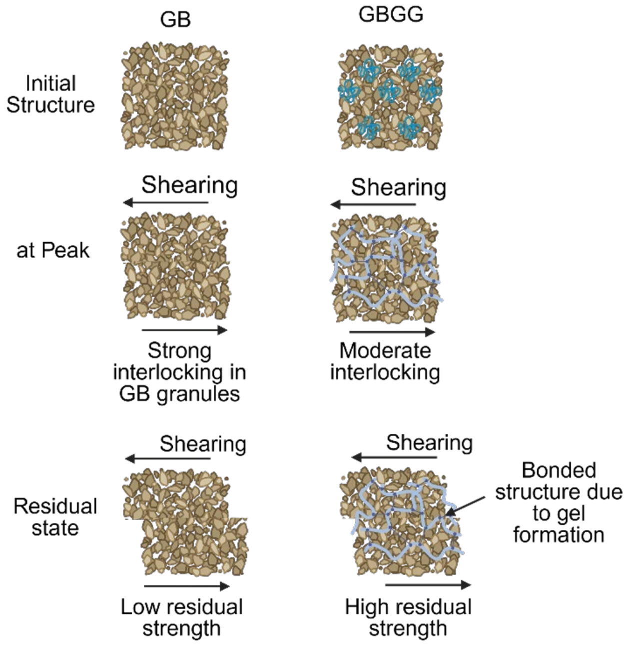

Fig. 5. Conceptual illustration of shear behavior in GB and GBGG.

4 Conclusions

The work was conducted to investigate the rshear strength behavior of granular bentonite (GB) and modified granular bentonite (GBGG) under high concentration KCl and varying normal stresses. The following conclusions were derived from the study :

- Both GB and GBGG exhibit a linear Mohr–Coulomb behavior with negligible cohesion, indicating friction-dominated shear strength.
- The peak friction angles are higher for GB (~7.35°) compared to GBGG (~6.80°), indicating stronger interparticle resistance in GB at initial loading.
- The residual friction angle of GBGG (~5.49°) is higher than that of GB (~4.74°), demonstrating improved post-peak strength retention.
- GB shows a significant reduction from peak to residual strength, suggesting pronounced particle rearrangement and structural breakdown during shearing.
- GBGG exhibits a smaller strength reduction, indicating enhanced structural stability and resistance to degradation under large shear displacement.
- The improved performance of GBGG can be attributed to modification-induced interparticle bonding, which limits particle reorientation and maintains shear resistance.
- The findings highlight that GBGG is more suitable for long-term applications, where residual strength governs performance (e.g., side slope liners in landfills).

Overall, modification of GB to GBGG enhances mechanical stability, making it a promising material for geoenvironmental engineering applications.

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