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SHEAR BEHAVIOR AT THE SOIL–CONCRETE INTERFACE OF AGAROSE-TREATED SAND

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ABSTRACT: Soil–structure interface behavior governs shear transfer mechanisms in many geotechnical systems. This study investigates the soil–concrete interface shear behavior of agarose-treated sand considering the combined effects of fines content and curing time. Direct shear interface tests were conducted under normal stresses of approximately 10.4, 20.8, and 31.2 kPa to evaluate peak shear strength, interface adhesion, interface friction angle (δ), and interface friction ratio (δ/ϕ). The results show that curing time significantly enhances interface shear resistance due to progressive development of biopolymer bonding with substantial strength gain occurring during the first 14 days of curing and the most pronounced increase observed within the first 7 days. Fines content exhibits a non-monotonic influence where moderate fines (5–15%) improve interface strength through enhanced packing and bonding while excessive fines (35%) reduce frictional contribution despite increased adhesion. Increasing agarose content enhances adhesion but may reduce frictional resistance due to particle coating effects. A key finding is the identification of a transition in interface behavior from friction-dominated to adhesion-controlled mechanisms effectively characterized by the interface friction ratio (δ/ϕ). These findings provide practical insight for the design of soil–structure interfaces particularly in foundation systems and support the use of biopolymer stabilization as a sustainable ground improvement method.

Keywords: Agarose; Biopolymer; Interface Shear Strength; Soil–Concrete Interface; Fines Content

1. INTRODUCTION

Soil–structure interface behavior governs shear transfer in many geotechnical systems, including foundations, retaining structures, and reinforced soil systems [1,2]. The mobilized interface shear resistance directly influences sliding stability, load transfer and deformation response. Unlike internal soil strength interface behavior depends not only on soil properties but also on surface conditions and interaction mechanisms at the contact boundary [3,4].

In recent years biopolymer-based soil improvement has attracted increasing attention as a sustainable alternative to conventional chemical stabilizers [5,6]. Biopolymers such as xanthan gum guar gum and agarose-based materials improve soil behavior through the formation of gel networks that enhance interparticle bonding and soil structure [7–10]. Previous studies have demonstrated significant improvements in shear strength stiffness and erosion resistance of treated soils [11–13]. Additional investigations have further confirmed the effectiveness of biopolymer-based treatments under various environmental and loading conditions highlighting their potential for sustainable geotechnical applications [14–18].

The presence of fine particles and environmental factors significantly modifies the soil matrix structure while structural modifications and micro-cracking processes under varying moisture conditions can alter the global shear resistance of stabilized geomaterials [18,19]. Consequently, these microstructural transformations and potential localized failures within the altered soil matrix directly weaken the efficiency of stress propagation across the soil–structure contact boundary.

Previous studies have highlighted the importance of interface conditions and characteristics in controlling shear behavior through changes in interlocking frictional interaction and boundary contact conditions [20,21]. Furthermore, recent studies have demonstrated how structural performance is governed by alternative biopolymer binders geosynthetic-soil interfaces and particle distributions under a wide range of environmental conditions and various mechanical loading scenarios [22,23].

Based on previous studies on biopolymer-treated soils agarose contents of 1% 3% and 5% were selected to represent low, moderate, and relatively high treatment levels in this study. Therefore, this study investigates the soil–concrete interface shear behavior of agarose-treated sand considering the combined effects of fines content and curing time.

The subsequent sections are: Research Significance which explains the importance of the current study and the research gap it aims to address; Materials and Methods which presents the materials used specimen preparation procedures testing methods and experimental program; Results and Discussion which presents the experimental findings and discusses the effects of curing time fines content and agarose content on soil–concrete interface behavior; and Conclusions which summarizes the major findings and their implications for sustainable soil–structure interface design.

2. RESEARCH SIGNIFICANCE

While previous studies have focused on either fines content or biopolymer treatment the combined influence of these factors on soil–structure interface behavior remains insufficiently understood. This study provides a mechanistic interpretation of interface shear behavior by introducing the interface friction ratio (δ/ϕ) as a key parameter to characterize the transition between frictional and adhesive resistance. This contribution offers a practical framework for evaluating shear transfer at soil–concrete interfaces. The findings support improved design of interface-controlled geotechnical systems particularly foundations and pile shafts in sandy soils with varying fines content.

3. MATERIALS AND METHODS

3.1 Materials

The sand used in this study was obtained from a liquefaction-affected area in Jono Oge Village Sigi Regency Central Sulawesi Indonesia which was significantly impacted by the 2018 Palu earthquake. Based on sieve analysis and the Unified Soil Classification System ASTM D2487 [24] the soil was classified as poorly graded sand (SP). The sand has a specific gravity (Gs) of 2.65 and a natural water content of approximately 4.28% and was used throughout all interface shear experiments.

The soil consists predominantly of medium to coarse sand with a fines content (passing sieve No. 200) of approximately 4.93%. The grain size distribution curve of the sand is presented in Fig. 1. The characteristic particle sizes are D10 = 0.11 mm, D30 = 0.42 mm, and D60 = 2.00 mm, yielding a coefficient of uniformity (Cu) of approximately 18.2 and a coefficient of curvature (Cc) of 0.80, reflecting a relatively wide particle size range within the soil.

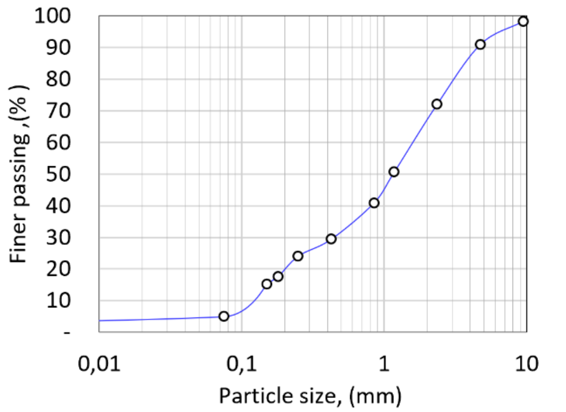

Fig. 1 Particle size distribution of sand used in this study

Non-plastic fine particles passing sieve No. 200 were added to the base sand to produce fines content of 5% 15% and 35% by dry mass. These fines were introduced to simulate a range of soil conditions from clean sand to fines-influenced mixtures.

The physical appearance of the materials used in this study is shown in Fig. 2 including the base sand fines agarose solution and concrete surface.

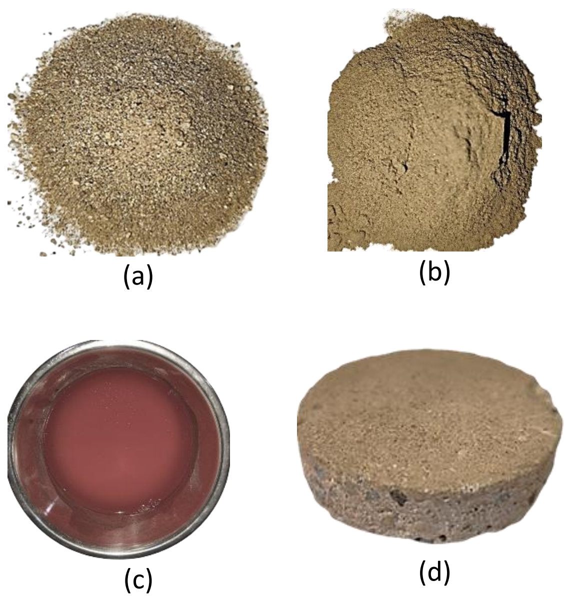

Fig. 2 Photographs of materials used in this study: (a) sand (b) fines passing sieve No. 200 (c) agarose solution and (d) concrete specimen

Agarose biopolymer was used as a stabilizing agent. Agarose powder was dissolved in distilled water and mixed with soil at 1%, 3%, and 5% by dry weight. Upon mixing, agarose forms a hydrogel network that enhances interparticle bonding and modifies soil–concrete interface behavior.

Concrete plates were used as the interface material. The concrete surface was prepared with a uniform finish to ensure consistent roughness conditions throughout the testing program allowing the observed interface behavior to be primarily governed by soil composition and biopolymer treatment.

3.2 Sample Preparation

The soil specimens were prepared by first mixing the dry sand with the required amount of non-plastic fine particles to achieve the target fines contents of 0%, 5% ,15% and 35% by dry mass. The dry materials were thoroughly blended to ensure a homogeneous distribution of particles.

The prepared agarose solution was then added to the soil mixture at concentrations of 1%, 3%, and 5% by dry weight of soil. The mixture was continuously stirred until a uniform consistency was achieved ensuring proper distribution of the biopolymer within the soil matrix.

The treated soil was placed into the direct shear box in layers and lightly compacted to achieve a target relative density of approximately 40%. All specimens were prepared with consistent dimensions and compaction procedures to minimize variability between tests.

Two curing conditions were considered: specimens tested immediately after preparation (0 days) and specimens cured for 1, 3, 7, 14, 21, and 28 days. During curing the specimens were stored at room temperature under controlled conditions to allow the development of agarose bonding.

Prior to testing each specimen was carefully assembled with the concrete plate in the lower half of the shear box to form a soil–concrete interface. The preparation procedure was kept consistent for all test conditions to ensure that variations in behavior were primarily influenced by fines content agarose content and curing time.

3.3 Testing Procedure

Direct shear interface tests were conducted using a conventional shear box apparatus to evaluate soil–concrete interaction with a concrete plate placed in the lower half and the prepared soil specimen in the upper half to form the interface. The shear box had an internal diameter of 60 mm and a total specimen height of 30 mm consisting of a 15 mm thick concrete layer and a 15 mm thick agarose-treated sand layer. The resulting soil–concrete interface area was approximately 28.27 cm^2. Normal loads of 3 kg, 6 kg, and 9 kg were applied corresponding to approximately 10.4 kPa, 20.8 kPa, and 31.2 kPa respectively. Shearing was performed at a constant displacement rate of 1.0 mm/min under drained conditions following ASTM D3080/D3080M [25].

During testing shear force and horizontal displacement were continuously recorded. The peak shear stress was identified from the maximum value of the shear stress–displacement response. The interface shear strength parameters including adhesion and interface friction angle were obtained from the relationship between shear stress and normal stress.

3.4 Experimental Program

The experimental program was designed to evaluate the combined effects of agarose content fines content and curing time on soil–concrete interface behavior. Agarose contents of 1% 3% and 5% were applied to sand with fines contents of 0% 5% 15% and 35%.

Curing periods of 0, 1, 3, 7, 14, 21, and 28 days were considered to assess the development of biopolymer bonding over time. Each condition was tested under three normal stress levels of approximately 10.4 kPa, 20.8 kPa, and 31.2 kPa.

For each combination of variables direct shear interface tests were conducted to determine peak shear strength interface adhesion interface friction angle and interface friction ratio. This experimental matrix enables a systematic evaluation of the individual and combined influences of fines content agarose content and curing time on soil–concrete interface shear behavior.

4. RESULTS AND DISCUSSION

The interface shear behavior of agarose-treated sand was evaluated based on peak shear strength adhesion interface friction angle and interface friction ratio. The effects of curing time fines content and agarose content are discussed in the following sections. Particular emphasis is placed on the evolution of interface shear mechanisms and the transition from friction-dominated to adhesion-controlled behavior under different testing conditions.

4.1 Effect of Curing Time on Interface Shear Strength

A rapid increase in interface shear strength is observed during the early curing period (0–7 days) as illustrated in Fig. 3. For example the shear strength increases by approximately 15–25% from 0 to 7 days and continues to increase up to 14 days indicating that the development of biopolymer bonding remains active beyond the initial curing stage. Beyond 14 days the rate of strength gain becomes relatively moderate (about 5–10%) suggesting that the primary bonding mechanism gradually approaches a stable condition with increasing curing time.

Fig. 3 further shows that curing time has a significant influence on the development of interface shear resistance throughout the progressive biopolymer bonding and hardening process. Specimens tested without curing (0 days) exhibit the lowest shear strength while a progressive increase in peak shear strength is observed with increasing curing duration.

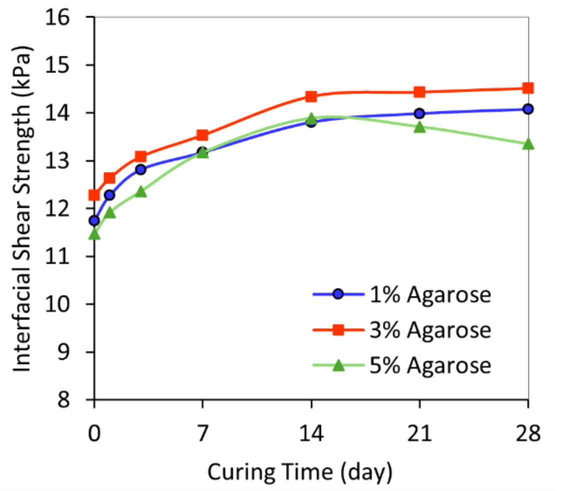

Fig. 3 Effect of curing time on soil–concrete interface shear strength at different agarose contents

The influence of agarose content is also evident. Specimens with 3% agarose generally exhibited higher shear strength compared to 1% and 5% suggesting the existence of an optimum biopolymer content for maximizing interface strength and bonding efficiency. At lower agarose content (1%) the bonding between particles is limited resulting in lower interface resistance. In contrast, excessive agarose content (5%) tends to form thicker gel layers at the interface which may reduce particle interlocking and limit the contribution of frictional resistance.

The observed behavior can be attributed to agarose-induced bonding at the soil–concrete interface. During curing, the agarose gel undergoes dehydration and forms a stiffer network structure, enhancing adhesion between soil particles and the concrete surface. As a result, increased adhesion contributes directly to peak shear strength. However, as curing progresses, the rate of strength gain decreases, indicating that the bonding mechanism approaches a stable condition.

The results indicate that curing time influences interface behavior primarily through the development of biopolymer bonding. In addition, the interaction between curing time and agarose content affects the balance between adhesion and frictional resistance.

4.2 Effect of Fines Content

The effect of fines content on soil–concrete interface shear strength is presented in Fig. 4. In contrast to curing time, which primarily influences bonding development fines content directly modifies the mechanical interaction at the interface. The results consistently show that fines content plays a critical role in governing interface shear behavior under varying curing conditions and agarose contents.

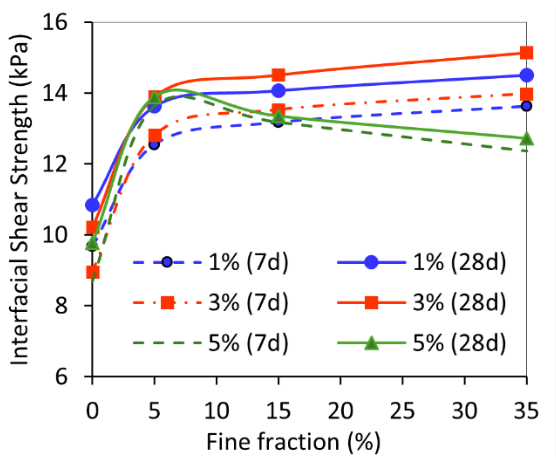

Fig. 4 Effect of fines content on soil–concrete interface shear strength at different agarose contents and curing times

Compared to clean sand (0% fines) the inclusion of fines at 5% and 15% results in a clear increase in peak shear strength. The improvement is on the order of approximately 10–25% depending on curing duration and agarose content. This increase is attributed to enhanced particle packing and a greater effective contact area at the interface which promotes more efficient stress transfer between soil particles and the concrete surface.

At a fines content of around 15%, the interface shear strength reaches an optimum level. Under this condition, the soil structure benefits from improved packing density and sufficient particle interlocking, while agarose-induced bonding further strengthens interparticle connections. This synergy between mechanical interlocking and adhesive bonding leads to maximum interface resistance.

However, when the fines content increases to 35% the trend deviates from proportional improvement. Although the measured shear strength remains relatively high the rate of increase diminishes and may even slightly decline under certain conditions. This behavior indicates that excessive fines begin to alter the dominant shear mechanism at the interface.

At high fines content the fine particles tend to fill voids and coat the surfaces of sand grains forming a smoother and more continuous interface layer. While this condition enhances adhesion due to increased surface area and bonding potential it simultaneously reduces particle interlocking and frictional resistance. As a result the interface behavior shifts from a friction-dominated mechanism to one increasingly governed by adhesion.

This transition highlights a critical balance between fines content and interface performance. Moderate fines (5–15%) enhance both frictional and adhesive contributions whereas excessive fines (35%) reduce friction efficiency despite increasing adhesion. Therefore, the results emphasize the importance of optimizing fines content to achieve a balanced interaction between interparticle friction and biopolymer bonding in soil–concrete interfaces.

The observed behavior is generally consistent with previous findings reported by Hamdi and Lemaire [20] and Lings and Dietz [21] who showed that increasing fines content reduces interface friction due to particle coating and reduced surface roughness. However, the present results provide a more refined interpretation by identifying a non-monotonic response of interface shear strength.

Unlike previous studies that primarily emphasized the reduction in frictional resistance this study demonstrates that moderate fines content (5–15%) can enhance interface shear strength through improved particle packing and increased contact area particularly when combined with biopolymer-induced bonding. This indicates that the influence of fines is not purely detrimental but depends on the balance between mechanical interlocking and bonding mechanisms.

At higher fines content (35%), the results align with the classical interpretation where excessive fines reduce frictional efficiency due to smoothing and coating effects. However, in the presence of agarose, this reduction in friction is partially compensated by increased adhesion, leading to a shift in the governing interface mechanism rather than a simple reduction in shear strength. This difference is attributed to agarose, which introduces an additional bonding mechanism not considered in conventional sand–fines interface studies.

4.3 Effect of Interface Adhesion and Friction Angle

The effect of agarose content on interface adhesion and friction angle is presented in Fig. 5 and Fig. 6. The results indicate that agarose content plays a critical role in controlling the balance between adhesive bonding and frictional resistance at the soil–concrete interface.

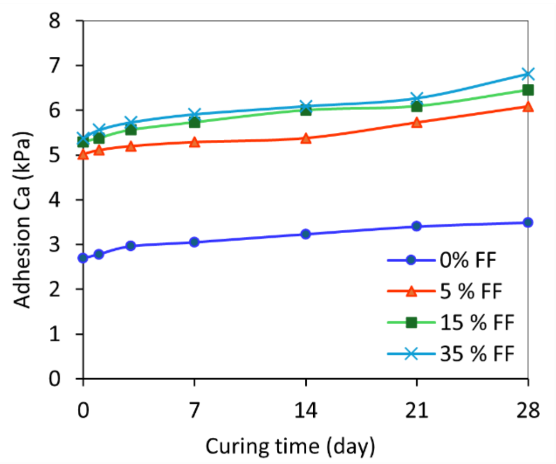

Fig. 5 Effect of curing time on soil–concrete interface adhesion at different fines contents

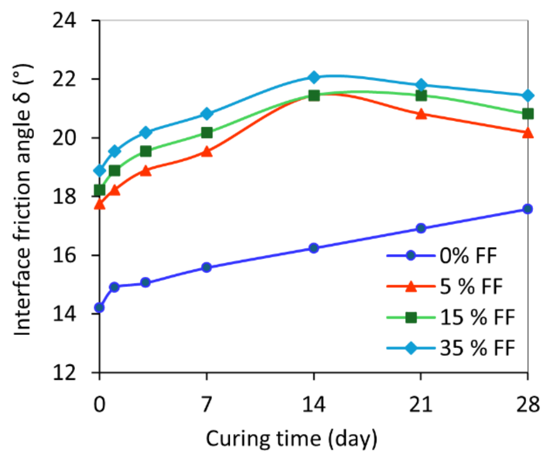

Fig. 6 Effect of curing time on soil–concrete interface friction angle (δ) at different fines contents

As shown in Fig. 5 interface adhesion increases consistently with curing time and becomes more pronounced with increasing agarose content. The increase in adhesion is attributed to the formation of a gel network that enhances bonding between soil particles and the concrete surface. Specimens with higher agarose content exhibit greater adhesive strength due to the increased availability of bonding material.

In contrast, the interface friction angle (δ) presented in Fig. 6 shows a different trend. While a slight increase in friction angle may be observed at moderate agarose content (3%) further increase to 5% does not result in proportional improvement and may even lead to a reduction under certain conditions. This behavior suggests that excessive agarose content begins to interfere with particle interlocking at the interface.

At low agarose content (1%) interface behavior is dominated by friction due to direct particle contact. At moderate content (3%) adhesion and friction act synergistically producing optimal shear resistance. At higher content (5%) thicker gel layers smooth the interface reducing particle contact and limiting frictional mobilization.

This contrasting behavior between adhesion and friction angle indicates a shift in the governing interface mechanism. Increasing agarose content enhances adhesion but may simultaneously reduce frictional resistance. As a result the overall interface shear strength is controlled by the combined contribution of these two mechanisms. The increase in adhesion is attributed to the formation of a gel network that enhances bonding between soil particles and the concrete surface [8,12,13].

The results clearly demonstrate that an optimum agarose content exists where the enhancement of bonding does not excessively compromise frictional resistance. This balance is essential for achieving maximum interface performance in biopolymer-treated soil systems.

4.4 Interface Friction Ratio Behavior

The interface friction ratio (δ/ϕ) was used to evaluate the efficiency of shear resistance mobilization at the soil–concrete interface. The variation of δ/ϕ with curing time and fines content is presented in Fig. 7. The results show a consistent decreasing trend in δ/ϕ with increasing fines content and agarose content. At low fines (0–10%) and low agarose content (1%) δ/ϕ ranges between approximately 0.90 and 1.00 indicating that shear resistance is primarily governed by frictional interaction and particle interlocking at the interface.

With increasing fines content to 20–30% δ/ϕ decreases to approximately 0.75–0.85 reflecting a reduction in the relative contribution of frictional resistance. This behavior is associated with the filling of voids and smoothing of the interface by fine particles which reduces surface roughness and limits the mobilization of interparticle friction even though the overall shear strength may still increase due to enhanced adhesion.

A similar trend is observed with increasing agarose content. At higher agarose contents particularly 5% δ/ϕ further decreases to approximately 0.60–0.75. Higher agarose concentrations promote the formation of a thicker gel layer at the interface which enhances bonding but reduces direct particle-to-particle contact. Consequently, the interface becomes smoother and more cohesive leading to a reduction in the frictional component relative to the internal soil friction angle.

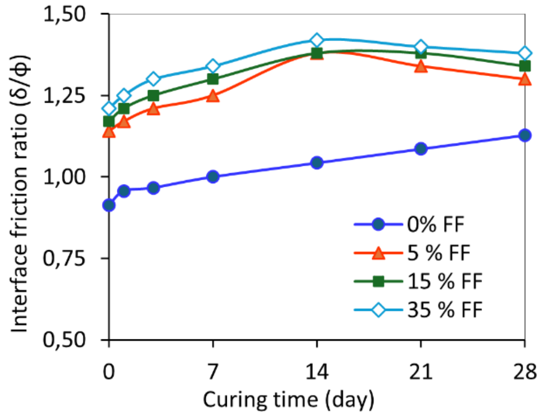

Fig. 7 Effect of curing time on soil–concrete interface friction ratio (δ/ϕ) at different fines contents

These results clearly demonstrate a progressive transition in the governing interface mechanism. At low fines and low agarose content the interface behavior is friction-dominated (δ/ϕ ≈ 0.90–1.00). At intermediate levels (δ/ϕ ≈ 0.75–0.85) both friction and adhesion contribute significantly representing a transitional regime. At high fines and agarose content (δ/ϕ ≈ 0.60–0.75) the behavior becomes increasingly adhesion-controlled.

The interface friction ratio therefore provides a robust parameter for characterizing the shift in shear mechanism from friction-controlled to adhesion-controlled behavior. A similar transition in interface behavior has been reported in soil–structure interaction studies where changes in contact conditions significantly alter the relative contribution of friction and adhesion [20-23].

This finding extends previous interface studies by demonstrating that the transition from friction-dominated to adhesion-controlled behavior can be quantitatively captured using the interface friction ratio (δ/ϕ). While earlier studies [20,21] primarily focused on frictional degradation with increasing fines content the present results highlight the coupled role of fines and biopolymer bonding in governing interface behavior.

4.5 Mechanism Interpretation

The observed trends in interface shear strength adhesion friction angle and interface friction ratio can be comprehensively interpreted through the physical condition of the tested specimens. As shown in Fig. 8 clear differences in surface texture compactness and coating behavior are evident with variations in agarose content and fines.

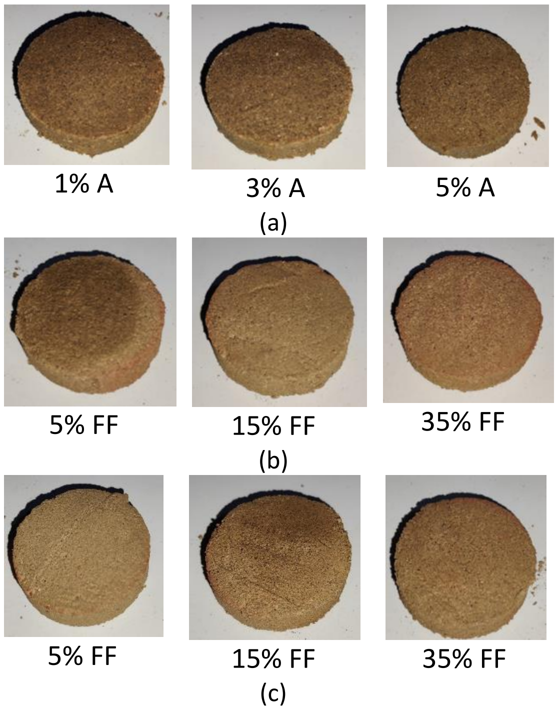

Fig. 8 Photographs of agarose-treated sand specimens: (a) variation in agarose content without fines (b) fines at 1% agarose and (c) fines at 3% agarose

At low agarose content (1%) the specimens exhibit a loose and granular structure with limited bonding indicating that the interface behavior is primarily governed by frictional resistance arising from direct particle contact and interlocking. As the agarose content increases to 3% a more continuous gel network develops resulting in improved particle bonding and a more cohesive and uniform interface. This condition represents an optimum state in which both adhesion and frictional resistance are effectively mobilized.

At higher agarose content (5%) the gel layer becomes thicker and more dominant progressively coating the particle surfaces. This condition reduces direct particle contact and weakens interparticle interlocking leading to a decrease in frictional contribution despite increased adhesion. Consequently, the interface response shifts toward an adhesion-controlled mechanism.

The influence of fines further modifies this behavior. At low fines content the interface remains coarse and friction-dominated. Increasing the fines content to moderate levels (≈15%) enhances particle packing and reduces voids resulting in a denser interface where both mechanical interlocking and biopolymer bonding contribute synergistically. However, at high fines content (≈35%) fine particles fill the voids and form a smoother and more continuous interface layer which increases adhesion but reduces surface roughness and limits frictional mobilization.

These observations support a unified interpretation of the interface behavior as a progressive transition from friction-dominated to adhesion-controlled mechanisms. At low fines and low agarose content shear resistance is governed primarily by particle interlocking. At intermediate levels both friction and adhesion contribute forming a transitional regime. At high fines and high agarose content the interface becomes increasingly smooth and cohesive with shear resistance controlled predominantly by bonding.

This mechanism is consistent with the reduction in interface friction ratio (δ/ϕ) and the increase in adhesion observed in previous sections. Overall the interface behavior of agarose-treated sand is governed by the balance between mechanical interlocking and biopolymer-induced bonding and an optimum combination of fines content and agarose content is required to maximize interface performance. This interpretation is consistent with micro-mechanical observations reported in previous studies where interface behavior is governed by evolving contact conditions and bonding mechanisms [20–23].

5. CONCLUSIONS

Based on the experimental investigation of soil–concrete interface behavior of agarose-treated sand the following conclusions are drawn:

1. Curing time significantly increases interface shear strength with the most pronounced gain of approximately 15–25% occurring within the first 7 days. The strength continues to increase up to 14 days indicating ongoing biopolymer bonding development before approaching a more stable condition with additional gains of about 5–10% up to 28 days.
2. Fines content exhibits a non-monotonic effect. The inclusion of 5–15% fines increases peak shear strength by approximately 10–25% compared to clean sand while higher fines content (35%) reduces frictional efficiency due to particle coating and diminished interlocking.
3. Agarose content controls the balance between adhesion and frictional resistance. Increasing

agarose content enhances adhesion; however, excessive agarose (5%) reduces frictional contribution due to the formation of thicker gel layers that limit particle contact.

4. The interface friction ratio (δ/ϕ) decreases from approximately 0.90–1.00 (low fines and agarose) to 0.60–0.75 (high fines and agarose) indicating a clear transition from friction-dominated to adhesion-controlled interface behavior.
5. Optimum interface performance is achieved at moderate fines content (5–15%) and intermediate agarose content (≈3%) where both mechanical interlocking and biopolymer bonding are effectively mobilized.
6. The results demonstrate that agarose-treated sand can improve interface performance under low confining stress conditions (10–30 kPa) providing a practical basis for the design of soil–structure interfaces in sustainable geotechnical applications.

6. ACKNOWLEDGEMENTS

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