Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Influence of addition of butadiene copolymer and modified styrene on the mechanical behavior of a sand

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Technical Note

Keywords
Polymeric sands
Butadiene-styrene polymer
Embankments-soft soils
Slope stabilization method

Abstract

Butadiene-styrene copolymer (SBR) is an elastomer composed of 75% butadiene and 25% styrene and is widely used in the automotive industry in tire production. This elastomer can be produced from two polymerization processes: emulsion or solution polymerization. This paper presents the mechanical behavior of a polymer reinforced sand compared to pure sand. Direct shear tests were performed on pure sand specimens and with the addition of modified styrene butadiene-styrene copolymer (XSBR). The polymeric sand specimens had 10% moisture content, 50% relative density, with water-polymer mass ratios of 1:1, 1:2, and 1:4, with no curing time, or with curing times 48, 72, 96, 576, and 720 h. Improvements were verified in the strength parameters of sand specimens with polymer addition, while comparing with pure sand parameters, showing that the improvement of soils with polymers is satisfactory for application in geotechnical works, such as: embankments in soft soils, soils for shallow foundations and for slope stability.

1. Introduction

Due to the importance of soil to the construction process and the significant variability of properties it can present, soils are subjected to careful analysis, aiming at the characterization and estimation of soil mechanical strength parameters. In geotechnical engineering, there are situations where the soil is not able to withstand increases in stress when compared to its natural state of equilibrium. One of the most common solutions is the partial/total removal of poorly resilient soil layers, followed by their replacement with a soil that meets the minimum geotechnical design requirements. However, this solution may become unfeasible in cases involving large volumes of soil, or even in the absence of nearby borrow/dump areas. As an alternative, soil improvement/stabilization processes have been developed to alter the geotechnical properties of the soil, in situ, for use in geotechnical works. These processes can be performed using several methodologies, varying with project resources and specifications.

As presented in Vendruscolo (1996), soil stabilization is an old technique, developed for paving, which was widely used in other areas, such as: foundations, slope stabilization, retaining works, and dams. On the other hand, Vargas (1977) defines soil stabilization as a process that provides greater stable resistance to loads, wear or erosion. Stabilization can be reached through compaction, grain size correction, and addition of substances that provide cohesion (from cementation or agglutination of grains). Furthermore, the soil's own plasticity can provide some degree of cohesion.

According to Almeida et al. (2016), among the stabilization methods (mechanical, physical and chemical), the chemical stabilization process is the one that presents the largest number of reactions between soil, stabilizing additive and water, to obtain a new material, with better properties than pure soil. As expected, the stabilization characteristics are closely related to the behavior and quality of the soil, as the largest and most heterogeneous component of the mixture. Louzada et al. (2019) suggest that regardless of the soil improvement technique, whether physical or chemical, the improvement of mechanical parameters is attractive according to technical, economic and environmental points.

Studies are being developed to provide more sustainable, less costly and technically efficient solutions to enable the use of new materials in soil stabilization/strengthening processes. These include the use of municipal solid waste (MSW) (Vizcarra et al., 2013), Polyethylene Terephthalate (PET) fibers (Casagrande et al., 2007; Louzada et al., 2019), natural fibers (Sotomayor & Casagrande, 2018) and polymers, aiming to improve the mechanical strength properties of the

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Submitted on August 23, 2021; Final Acceptance on February 4, 2022; Discussion open until August 31, 2022.
https://doi.org/10.28927/SR.2022.074521

soil, as a result, increasing the strength, durability of the soil, as well as reducing compressibility.

The application of polymers and enzymes as materials to improve soil characteristics is not a current technique. Studies by Lambe (1952) and Murray (1952) have already demonstrated the use of these polymeric materials to aggregate particles. However, in recent years, research and use of these products has intensified (Hollaway, 2009).

Khatami & O'Kelley (2013) worked with a biopolymer at different dosages in a sandy soil, they proved that increasing the addition of the polymer increased the mechanical parameters studied. Malko et al. (2016) studied the application of enzymes for soil stabilization in paving and the investigation proved that the use of this material, in the different types of soil horizons studied, led to a mechanical improvement of the soil. Okonta (2019) aiming to improve the strength parameters of a sandy soil in South Africa applied an acrylic polymer at different curing times and temperatures, the study proved that the addition of the polymer solution is effective in generating cementation between grains.

There are some studies conducted in subtropical and tropical climate regions to evaluate the application of polymers in soil improvement found in Qatar (Iyengar et al., 2013), Iran (Naeini et al., 2012) and Australia (Georgees et al., 2015).

Garcia et al. (2015) verified high increments in the cementation, tensile and shear strengths of a sandy soil added with polymer when compared to pure sand and another sand with artificial cementation.

Kolay et al. (2016) evaluated the use of acrylic-based polymer in a clay soil and a silty soil. They used polymer content ranging from 2-5% according to the dry weight of the soil with three curing times (7, 14, and 28 days). They evaluated Atterberg limits, compaction, unconfined compression and ISC (California Support Index). The clay soil with polymer obtained the greatest gain in unconfined strength and improvement in ISC while no significant gains were observed for the silty soil. Few changes in the characterization tests were observed for both soil types.

Given this background, this study consists of evaluating the mechanical behavior and permeability of a pure sandy soil compared to an abundance of different mixtures of sandy soil and liquid polymer: modified butadiene-styrene sand polymer (XSBR). The use of this mixture as an alternative to reinforced soil mixes can be presented as a new solution for geotechnical works such as embankments, shallow foundation soils.

2. Materials and methods

2.1 Materials

In this experimental program, direct shear tests were performed based on the procedures described in ASTM D 3080 (ASTM, 2011). These tests were used to evaluate the effect of adding the XSBR polymer on the strength parameters of the sandy soil. The grain size distribution curve of the soil used in this study is shown in Figure 1. The sandy soil used in this research has a specific gravity (Gs) of 2.65, coefficient of uniformity (Cu) of 3.27, coefficient of curvature of 0.87, average diameter of 0.58 mm and minimum and maximum void ratios of 0.71 and 0.96, respectively. According to the ASTM D 2487 classification, this soil is a medium sand

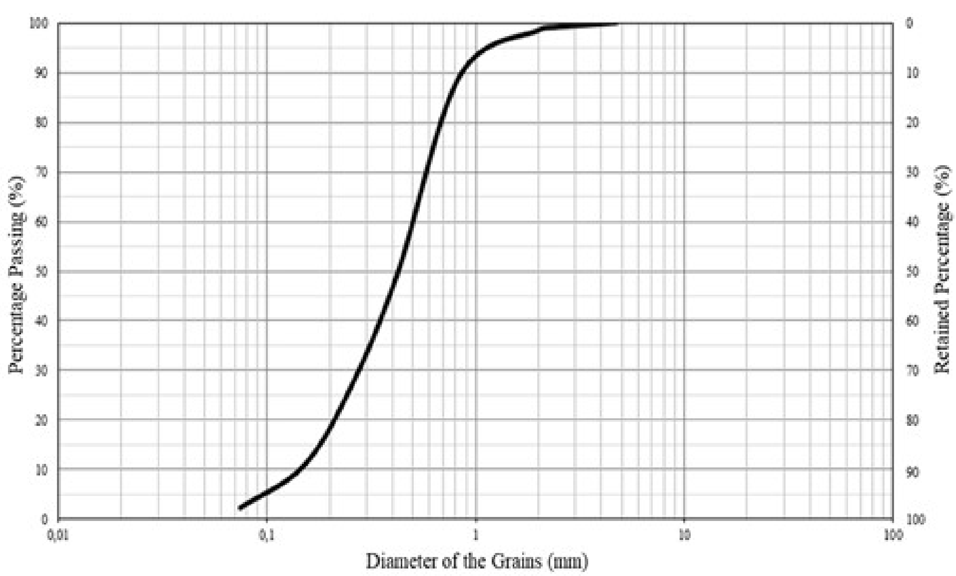

Figure 1. Grain-size distribution.

while the USCS (ASTM, 2000) classifies this material as SP, which corresponds to a poorly graded sand.

In the chemical analysis (Table 1), the soil shows a considerable amount of silica (SiO_2) and alumina (Al_2O_3), as well as small amounts of some oxides, such as potassium (K_2O), titanium (TiO_2) and iron (Fe_2O_3). The soil has a pH value of 4.4, proving that the composite matrix is acidic.

According to Ahmed et al. (2013), techniques based on chemical stabilization with the SBR polymer are widely used in the transportation industry, among the main applications are the control of dust generated from the passage of cars on unpaved roads, erosion control, control of fixation and leaching of waste and recycled materials

The XSBR polymer used in this study consists of two monomers, butadiene and styrene, and was obtained commercially as a liquid solution. The use of XSBR polymer, from the environmental point of view, is the replacement of more environmentally aggressive materials such as cement and lime. Both materials, in their procurement and production are highly polluting and, unquestionably, have aggression to the soil and groundwater. SBR is an example of a non-toxic liquid additive, water-soluble, derived from styrene and butadiene monomers. The physicochemical properties of the copolymer are presented in Table 2.

2.2 Specimen preparation

Specimens of sand and polymer-sand mixtures had 10% moisture content, 50% relative density, with different water-polymer mass ratios, with no curing time, or with curing times ranging from 24 to 792 h, as shown in Table 3.

The Water/Polymer Ratio determined in this study (1:1, 1:2 and 1:4) was from higher polymer dosages to lower ones. The value of 1:4 is the recommended value and usually used for this type of polymer. Also, for this reason, longer curing times were observed.

To ensure the relative density of 50%, the mass of mixture required to fill the known volume of the mold was calculated, and after that, manual compaction of the specimen inside the mold was performed. The specimens of the sandy soil and the soil-polymer mixture were molded in square metal molds with dimensions of 100 mm × 100 mm × 20 mm. Figure 2 presents a typical specimen. For each mixture, three specimens were tested for shear strength. All specimens were made using the same methodology, under the same conditions of temperature and relative water content (20 °C and 70%, respectively). To compare the results, the specimens were also made without the addition of the copolymer, i.e. pure sandy specimens. The use of 10% moisture and 50% density, was used for comparison between the sand without addition and in the other dosages, because they are common values in the proportions used.

The curing method used for the composites was air curing (external). After brief observations and tests, such as curing with application at high temperatures and curing with water, it was found that the simplest form and with possible application in real works would be the air curing method. The polymer used, for being similar to glue in its composition, has the effect called "glue effect", in which the catalyst for the activation of the glue is basically oxygen.

Table 1. Chemical composition of the sand soil.

Mixture	Percentage of compounds (%)					
	SiO2	Al2O3	K2O	TiO2	Fe2O3	Others
Sandy matrix	66.02	30.01	3.20	0.50	0.21	0.06

Table 2. Physicochemical properties of XSBR copolymer.

Appearance	Liquid
Odor	Characteristic
pH	8.5-9.5
Melting Point	Not applicable
Boiling Point	100 °C
Evaporation Rate	Similar to water
Density	~ 1.0
Solubility in water	Miscible

Table 3. Mixture ratio and curing time.

Soil	Polymer	Water/Polymer Ratio	Curing Time (h)
Sand	Styrene-butadiene Polymer (XSBR)	1:1	72
		1:2	72
		1:4	72
			96
			120
			576
			720

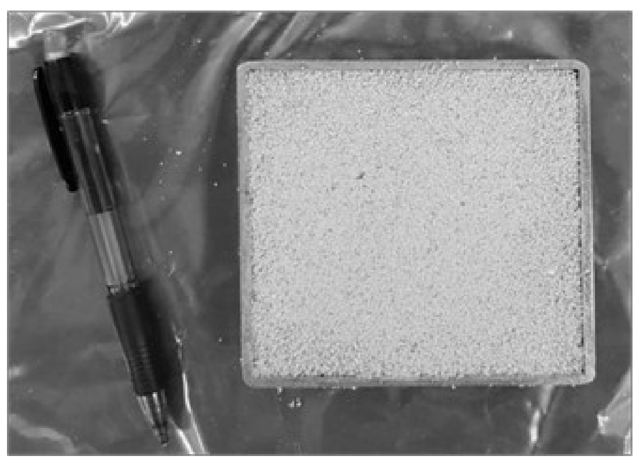

Figure 2. Soil specimen – square shape.

The influence of the addition of the XSBR copolymer on the shear strength parameters of the sand was evaluated using the direct shear test.

2.3 Direct shear test

Direct shear tests were performed with the sand soil and the sand-XSBR mixtures, attempting to determine the shear strength of these mixtures. The direct shear test was performed in a split metal box, where the upper half slides relative to the lower half. Prismatic square section soil specimens were used in this process. At first, the specimen was compressed by a normal force and then the application at a constant rate of a shear force. This shear force imposes a horizontal displacement on the specimen until failure of the specimen (in this test, the failure plane is horizontal). The tests were performed on similar specimens for each soil and mixture. The normal stress values applied were those of 50, 100, and 150 kPa.

2.4 Permeability test

The permeability test used in this research was the variable head permeability test. It was performed to analyze the permeability of the soil specimen with polymer. The permeability test was performed according to the Standard Test Method for Leaching Solid Material in a Column Apparatus (ASTM, 1995). It was decided to adapt the existing permeameter in the Geotechnical and Environmental Laboratory at PUC-Rio (Pontifical Catholic University of Rio de Janeiro), where it was possible to apply the same type of pressure and percolate water through the specimen. For each stress increment the pore pressure value in the specimen was measured. Increments were applied until specimen saturation was reached, when Skempton's parameter B approaches 1 ($B = \Delta u / \Delta \sigma c$).

2.5 SEM analysis

The methods and procedures adopted for specimen preparation for SEM analysis were the same as those used for specimen preparation for direct shear testing, as were the environmental conditions, such as temperature and water content. The standard specimen used in the analysis is cylindrical, 20 mm high and 5 mm in diameter, as shown in Figure 3.

The analyses were performed on specimens with 1:4 water/polymer ratio and for two different curing times, 576 and 720 h.

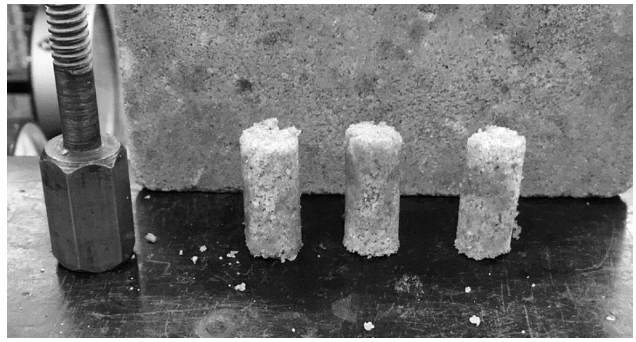

Figure 3. Standard specimens for SEM analysis.

3. Results and analysis

The results of the direct shear tests of both mixtures (pure sand and sand -XSBR) can be expressed in terms of shear strength behavior and horizontal displacement. As the mixtures were subjected to many curing times, it is important to evaluate the influence of the water-polymer ratio on the specimens for each of these curing times.

Figure 4 shows the shear test results for the pure sand specimen and all the results at 72 h of curing, but with water-to-polymer ratio of 1:1, 1:2 and 1:4, respectively. Figure 5 shows the stress *versus* displacement plot and the Mohr-Coulomb failure envelope of the results presented in Figure 4.

Figure 6 shows the shear test results for the pure sand specimen and all results with 1:4 water/polymer ratio, but at 72, 96, 120, 576, 720 h of curing, respectively.

In Figure 7, show the stress x displacement plot and the Mohr-Coulomb failure results envelope from Figure 6. In Table 4 all the results of the strength values (angle of friction and cohesion) have been compiled.

The results of mixtures with high water-polymer ratio, such as 1:4, revealed a substantial increase in shear strength when compared to the pure sand specimen and lower water-polymer ratios (1:1 and 1:2).

Analyzing the data presented, it can be seen that increasing the curing time is critical to improving the strength. As for the dosages with (1:4), there are higher values in the cohesive interception when compared to (1:2 or 1:1). The variation of the friction angle is not significant, which shows that the action of the polymer takes place at the grain bonding.

Because it is a new use of this type of stabilization in soils (with polymer), often when applying the studies already consolidated for saturated soils the interpretation of the results becomes more complex. In the observed, throughout the research, one should consider ideal values of water-polymer ratio, in addition to the type of soil to be used, and the influence of curing and time. When these factors are evaluated, it is observed that there is not an exactly proportional growth between the values of the angle of friction and cohesion over time.

Sand-XSBR (1:4) had a change in the friction angle, however, the values are close to each other, with an average of 39°. Despite the stabilization applied the base substrate is a sand, and the angle of friction is a fundamental part of the strength in sands.

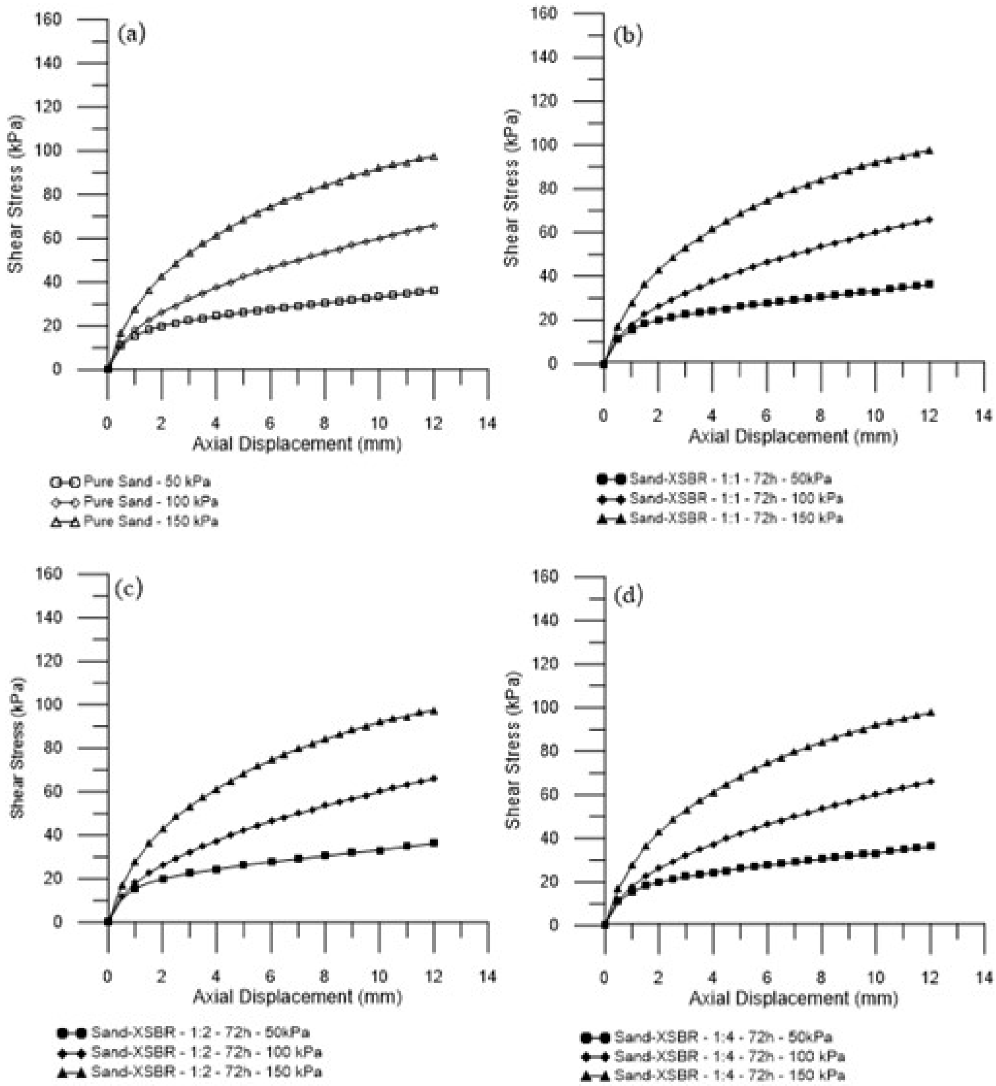

Figure 4. Shear stress *versus* horizontal displacement: (a) pure sand; (b) sand-XSBR – 1:1 – 72 h; (c) sand-XSBR – 1:2 – 72 h; (d) sand-XSBR – 1:4 – 72 h.

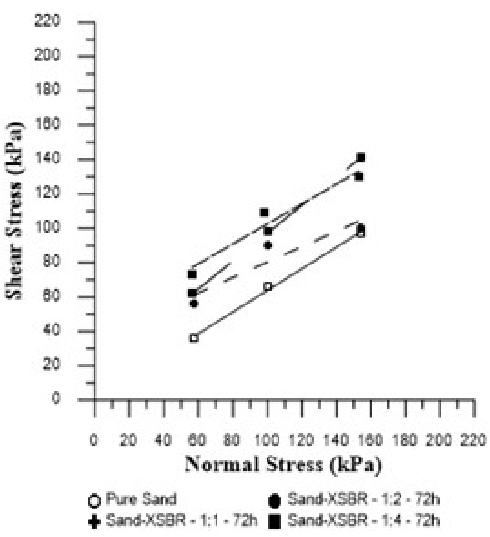

Figure 5. Mohr-Coulomb failure envelope with 72 h of curing.

Table 4. Final strength parameters.

Mixtures			Strength parameters	
Specimen	Water/ Polymer Ratio	Curing time (h)	φ' (º)	*c*' (kPa)
Pure sand	-	-	33	0
Sand-XSBR	1:1	72	25	36
Sand-XSBR	1:2	72	39	16
Sand-XSBR	1:4	72	30	47
Sand-XSBR	1:4	96	40	44
Sand-XSBR	1:4	120	37	43
Sand-XSBR	1:4	576	41	51
Sand-XSBR	1:4	720	38	84

Evaluating only the cohesive intercept at 72 h, 96 h, and 120 h there is a variation, although considered insignificant, such changes are attributed to the polymer settling/curing

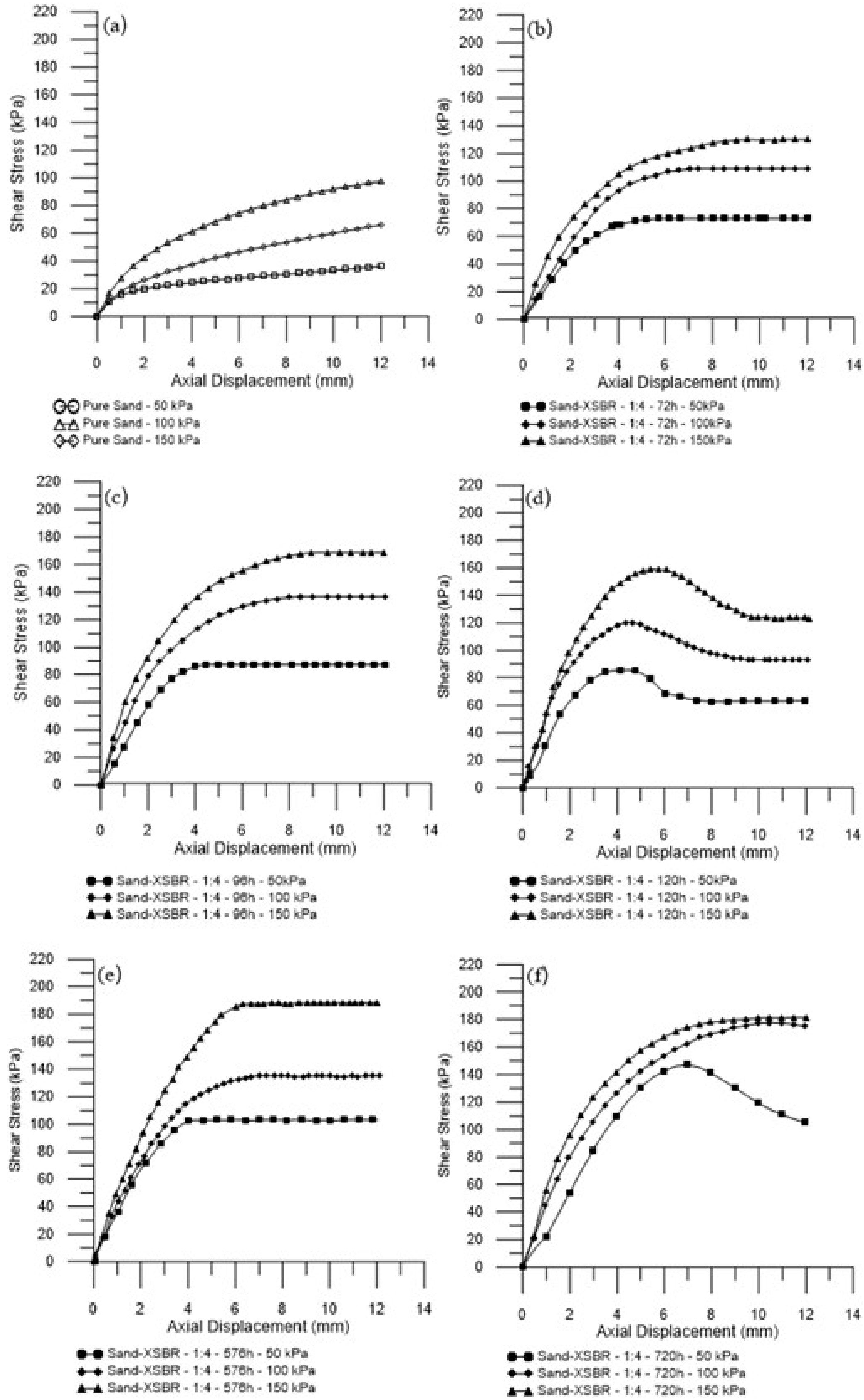

Figure 6. Shear stress *versus* horizontal displacement: (a) pure sand; (b) sand-XSBR – 1:4 – 72 h (c) sand-XSBR – 1:4 – 96 h; (d) sand-XSBR – 1:4 – 120 h; (e) sand-XSBR – 1:4 – 576 h; (f) sand-XSBR – 1:4 – 720 h.

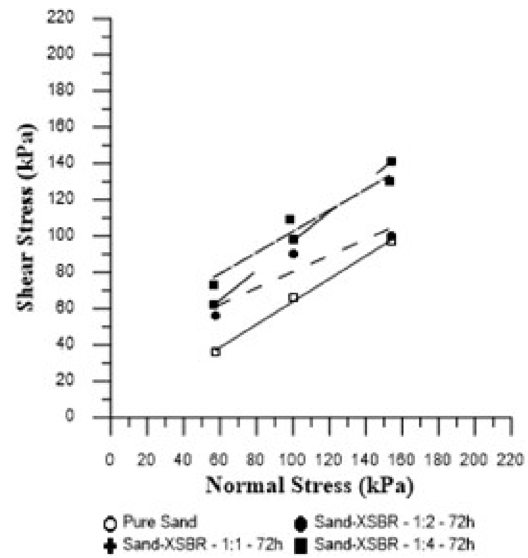

Figure 7. Mohr-Coulomb failure envelope – sand-XSBR – 1:4.

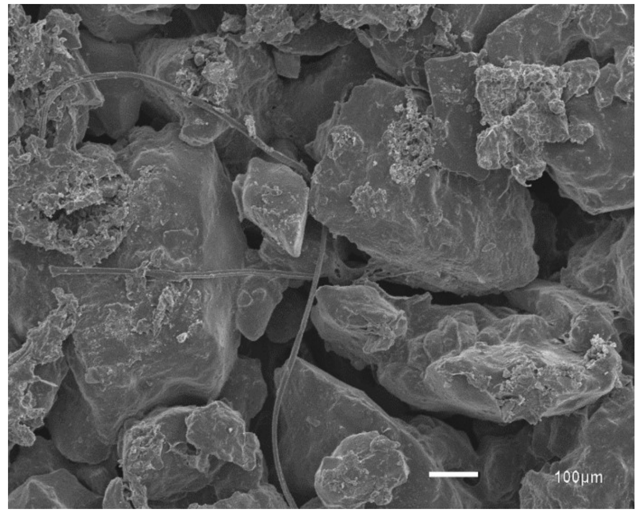

Figure 9. SEM analysis – Soil/water/polymer – 576 h (100 µm)

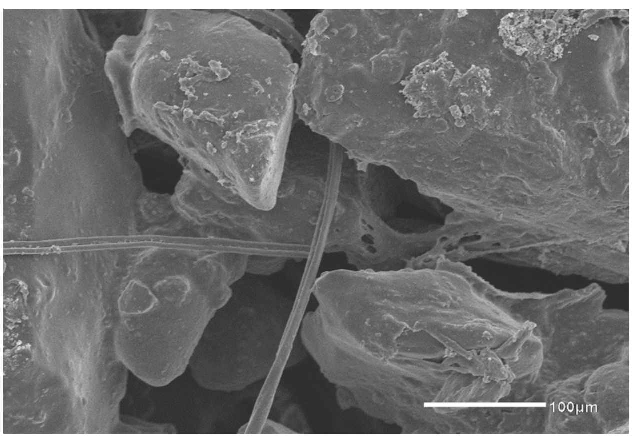

Figure 8. SEM analysis – Soil/water/polymer – 576 h (100 µm)

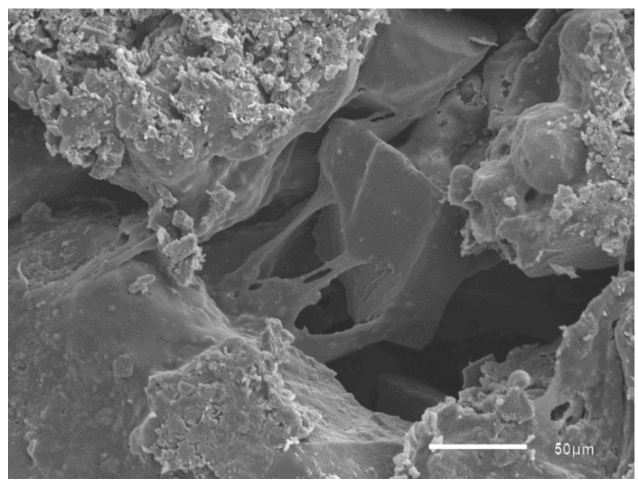

Figure 10. SEM analysis – Soil/water/polymer – 720 h (50 µm).

time, the specimens used, and the mathematical model itself. Observing the time of 576 h, there is a considerable and more stable increase. When completing the study, at 720 h you really see the considerable gain in the cohesive intercept and the stabilization of the friction angle value.

The permeability test was performed on all specimens at 576 h. The values found were extremely close, with minimal variations between specimens (not significant in the order of magnitude of the test). This value was used for having the proportion considered ideal and with the longest curing time, so the value of sand-XSBR was 1.16E-03.

Finally, the SEM analysis images (Figures 8 to 11) show an elastic structure that connects the soil grains. The polymer vice creates “bridges” to the soil matrix. In the Figures it is possible to observe that the sand grains become more tightly bound together. Between the grains it is possible to

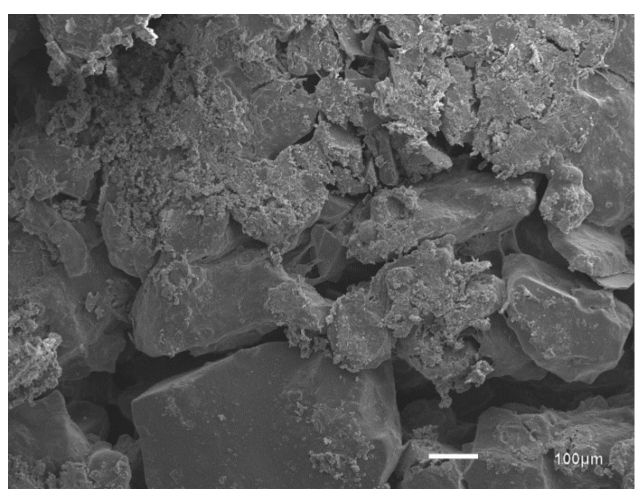

Figure 11. SEM analysis – Soil/water/polymer – 720 h (100 µm).

see something that binds these grains together, like a glue, which is possibly the polymer. With increasing curing time, this bonding is more intense.

4. Conclusions

This paper presented a study of the influence of the addition of Modified Butadiene-Styrene Copolymer on the mechanical behavior of a sand. Direct shear tests were performed on soil specimens of pure sand and sand/polymer mixtures with 10% moisture content, 50% relative density and different water-polymer mass ratios, without curing time or with curing times ranging from 24 to 792 h.

The results show an improvement in the strength parameters of the sand/polymer specimens. It is possible to verify especially an increase in the cohesion parameter, absent in the pure sand. This improvement is related to the water/polymer ratio and the curing time.

The mixtures with 1:4 (water/polymer) content showed significant increases in cohesion. The highest cohesion value of the mixture was found in a 1:4 (water/polymer) specimen.

It is concluded that the addition of polymer modifies the behavior of the stress *versus* displacement pattern of the material.

For any mixture studied, the values of the friction angle did not vary more than 8° from the initial value of the pure sand studied (33°). For short curing times, the mixtures showed no significant changes in behavior, while for long curing times, the mixtures showed the best behaviors.

The addition of modified butadiene-styrene copolymer in sands is an advantage for allowing the reduction of the amount of water needed to improve the mechanical characteristics of the soil. In addition, the modified butadiene-styrene copolymer when added to the soil, forming a composite in which there is the presence of cohesive interception that is not common in sandy soils. Thus, the sand with Modified Butadiene-Styrene Copolymer has the friction action coming from the sand (angle of friction) and by the action of the copolymer there is cohesion of the soil grains (cohesive interception).

Finally, the permeability of the pure sand showed no significant variations when compared to the permeability of the soil/polymer mixture. In both the pure and polymer blended condition, the soil exhibits permeability characteristic of fine sands.

Acknowledgements

The authors would like to thank CAPES - *Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior* - Brazil and CNPq - *Conselho Nacional de Desenvolvimento Científico e Tecnológico* for the financial support to this research.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial to report.

Authors' contributions

Thiago Manes Barreto: Conceptualization, Data curation, Visualization, Writing – original draft. Lucas Mendes Repsold: Conceptualization, Data curation, Methodology, Validation, Writing – original draft. Nathália Araújo Boaventura de Souza e Silva: Formal Analysis, Investigation, Methodology, Project administration, Writing – review & editing. Michéle Dal Toé Casagrande: Supervision, Validation, Writing – review & editing.

List of symbols

k	Permeability coefficient
c'	Effective cohesion
R^2	Coefficient of determination
φ'	Effective friction angle

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