# Evaluation of the Mechanical Properties and Durability of Aeolian Sand Stabilized with Emulsion Copolymers

**Zohreh Ghafouri Fard[1], Maryam Mokhtari[1*], Mohammad Mehdi Khabiri[1] , Seyed Mehrdad Jalilian [2]**

[1]Faculty of Civil Engineering, University of Yazd, Yazd, Iran
[2]Iran Polymer and Petrochemical Institute, Tehran, Iran

**ABSTRACT**

**The stabilization and improvement of the engineering properties of weak soils, particularly aeolian sandy soils (windblown sand), represent one of the major challenges in geotechnical engineering and pavement construction projects. The use of conventional stabilizers such as cement and lime is subject to significant limitations due to their high carbon dioxide emissions and adverse environmental impacts. The present study investigates, through experimental and statistical approaches, the performance of two environmentally compatible emulsion copolymers, namely styrene–acrylate copolymer (A70) and styrene–butadiene copolymer (B70), in the stabilization of desert aeolian sand collected from South Khorasan Province, Iran. For this purpose, the polymers were prepared at concentrations of 10%, 30%, and 50%, and added to the soil at different dosages by dry weight. After a 14-day curing period under laboratory conditions, the treated specimens were subjected to a series of tests, including compaction, unconfined compressive strength (UCS), direct shear, indirect tensile strength (Brazilian test), California Bearing Ratio (CBR), and durability tests involving freeze–thaw and wetting–drying cycles. In addition, microstructural analyses were conducted using scanning electron microscopy (SEM) to examine the bonding mechanism between soil particles. The results indicated that the effect of polymer content on compressive, tensile, and shear strength was nonlinear. The optimum pure polymer contents were determined as 6.03% for A70 and 4.02% for B70. Specimens stabilized with B70 exhibited higher compressive strength and elastic modulus, whereas those treated with A70 demonstrated more ductile behavior and superior durability under wetting–drying and freeze–thaw cycles, owing to the formation of a continuous polymeric network. Statistical analyses performed using Design-Expert and SPSS confirmed the validity of the proposed regression predictive models, with coefficients of determination (R^2) greater than 0.9.**

**KEYWORDS**

**Soil stabilization; Eco-friendly polymers; Styrene–acrylate copolymer; Styrene–butadiene copolymer; Aeolian sand.**

* Corresponding Author: Email: mokhtar@yazd.ac.ir

## 1. Introduction

Since civil infrastructure is constructed directly on soil, ensuring that the subgrade possesses adequate engineering properties is essential; otherwise, the implementation of soil improvement and stabilization techniques becomes inevitable [1]–[3]. Concurrently, given the global warming crisis and the environmental pollution stemming from energy consumption and carbon dioxide emissions in construction projects, utilizing eco-friendly materials to minimize these adverse impacts has gained significant importance [4], [5]. In this regard, the application of polymers as a novel and environmentally friendly approach has attracted substantial attention in geotechnical engineering [6]–[8]. The primary novelty of this research lies in the introduction and application of two novel, eco-friendly emulsion copolymers for soil stabilization, which have not been previously explored in the literature. In addition to introducing these agents, this study presents a laboratory evaluation of their efficacy in enhancing the geotechnical properties and engineering behavior of the soil, thereby establishing their viability as sustainable and efficient alternatives.

## 2. Methodology

This study investigates the stabilization of aeolian sand sourced from the deserts of South Khorasan Province, Iran. The stabilization process was conducted using two types of eco-friendly polymer emulsions: styrene-acrylate copolymers (designated as A70) and styrene-butadiene (designated as B70) at three concentrations of 10%, 30%, and 50%. Both polymers comprise 70% styrene monomer in their chemical structure and were applied as a milky liquid with a density of approximately 1.2 g/cm³ and a neutral pH (ranging from 6 to 7).

To evaluate the performance of the stabilized specimens (coded **A1–A3** and **B1–B3** according to their respective concentrations), compaction tests were initially performed to determine the optimum emulsion content for each concentration. The prepared specimens were subjected to a 14-day curing period under dry conditions, followed by a series of mechanical and durability tests. This experimental program included Unconfined Compressive Strength (**UCS**), direct shear, and indirect tensile strength tests. Furthermore, the stability of the specimens against wetting-drying and freezing-thawing cycles was assessed to determine the efficacy of these two polymers in enhancing the geotechnical properties of aeolian sand.

## 3. Results and Discussion

This research demonstrated that polymer emulsions A70 and B70 significantly enhance the engineering behavior of sandy soil; however, this improvement follows a parabolic trend, peaking at an optimum content. At low concentrations, the polymer acts as a lubricant, facilitating particle rearrangement and thereby increasing the dry density. Conversely, at high concentrations, the increased viscosity hinders efficient particle packing, leading to a reduction in density. The optimum net polymer content for maximum dry density was determined to be 6.03% for A70 and 4.02% for B70.

Regarding mechanical strength, both polymers proved effective as stabilizing agents. The maximum Unconfined Compressive Strength (UCS) was achieved by the specimen containing 4.02% B70 (3.85 MPa), indicating the formation of robust inter-particle bonds. Furthermore, B70 exhibited a stiffer and more brittle response, whereas A70 demonstrated higher failure strain, reflecting a more ductile and flexible behavior (Figure 1). Consequently, B70 is more suitable for maximizing ultimate strength, while A70 offers superior deformation tolerance.

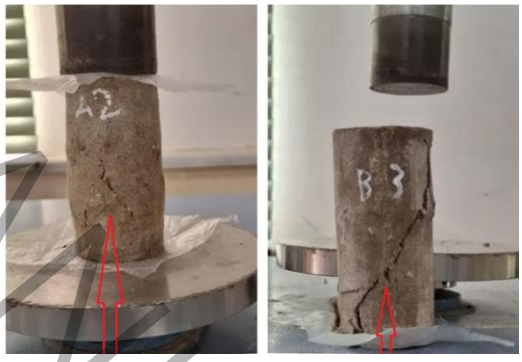


**Figure 1. Failure patterns of polymer-stabilized specimens**

Polymer stabilization also led to a substantial increase in shear strength parameters. The untreated sand exhibited negligible cohesion and an internal friction angle of approximately 31°. Post-stabilization, both cohesion and the internal friction angle increased. This improvement is attributed to the formation of a cohesive polymeric film and increased particle surface roughness upon curing, which effectively restricts inter-granular slippage.

The results for tensile strength and durability were equally favorable. Post-treatment, the sandy soil developed significant indirect tensile strength. All optimized specimens maintained a weight loss of less than 6% after 12 durability cycles, well below the 14%

permissible limit. Notably, A70 performed better in freeze-thaw cycles, likely due to the higher flexibility of its molecular chains.

The California Bearing Ratio (CBR) followed a similar trend; polymer addition up to the optimum level enhanced the CBR, but excessive dosages led to a decline. This reduction is attributed to excessive lubrication, decreased direct grain-to-grain contact, and the formation of localized soft zones.

Statistical modeling using Response Surface Methodology (RSM) via Design-Expert software showed excellent agreement with experimental data ($R^2$>0.9). Additionally, SEM analysis revealed that A70 forms continuous films and flexible polymeric bridges, making it superior for long-term durability. In contrast, B70 develops shorter but stiffer and stronger bonds, making it the preferred option for achieving higher strength and cohesion.

## 4. Conclusion

The present study evaluated the effectiveness of two environmentally friendly emulsion copolymers in improving the geotechnical properties of aeolian sand. The main findings of this research are summarized as follows:

1. The incorporation of emulsion copolymers into aeolian sand significantly enhanced its mechanical properties, including compressive, shear, and tensile strength. The variation in strength with polymer content was nonlinear and exhibited a distinct optimum value.

2. The optimum pure polymer contents were determined to be 6.03% for styrene-acrylate (A70) and 4.02% for styrene-butadiene (B70).

3. Owing to the formation of stiff and concentrated bonds at interparticle contact points, B70 produced higher unconfined compressive strength (3.85 MPa), tensile strength (0.48 MPa), and shear strength than A70.

4. Due to the formation of a continuous and flexible film-like structure, A70 exhibited a softer response, characterized by a larger failure strain, as well as superior durability under wetting-drying and freeze-thaw cycles, reducing specimen weight loss to less than 5.5%.

5. The mathematical regression models developed using response surface methodology (RSM) showed excellent agreement with the experimental results and can therefore serve as a reliable tool for the design of soil stabilization mixtures in practical engineering applications.

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