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Plastic Properties and Collapse Investigation of Fine-grained Soil Rehabilitated with Styrene Butadiene Rubber: A Case Study in Kerman, Iran

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ABSTRACT

Collapsible soils pose significant challenges due to their open structure, which causes settlement when exposed to moisture. Failure to identify these soil types can lead to structural damage when they become saturated or experience changes in moisture content. The presence of such soils in various regions, including Iran, necessitates greater attention and investigation into their behavior and properties. This study examines the impact of butadiene rubber on the stabilization of these soils. Fine-grained soil samples were collected from two different sites in Kerman province (Kerman City). The samples were injected with 2%, 3%, 4%, 5%, 6%, and 7% butadiene rubber for stabilization periods of 4, 7, 14, and 28 days, resulting in a total of 72 tests. The stabilized soils were evaluated using a double consolidation test (ASTM D5333) on intact soil samples. The penetration of butadiene rubber and the resulting rubber columns reduced the degree of collapse. In all cases, the collapse was reduced by more than 88%. The highest reduction was observed with a 7% additive after 28 days of stabilization. Given the increasing use of intelligent systems in predicting the behavior of stabilized collapsible soils, a model was developed to predict the degree of collapse for samples stabilized with butadiene rubber using an adaptive network fuzzy inference system (ANFIS). The accuracy of the model was evaluated, and it successfully predicted the collapse degree. Addition of styrene butadiene rubber additive in the tested soils led to a decrease in the plasticity index of clays with high liquid limits and an increase in the plasticity index of silts with low liquid limits. These changes varied depending on the mineral type. Subsequently, a model was developed to predict the plastic properties of the soil using a fuzzy inference system. The results demonstrate acceptable consistency between the training and prediction data (R^2=0.93).

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1. INTRODUCTION

Soils are one of the most important natural materials that have been extensively used by humans in engineering projects for a considerable period. In general, most constructions are either built on or through the soil. However, not all soils possess suitable conditions for construction. Among these, soils sensitive to moisture (according to the definition of ASTM D-5333) are worth mentioning. It is crucial to consider the changes that occur in the properties of these soils, as their structure tends to become unstable upon exposure to moisture. Collapsible soils are included in this particular group. Naturally, these soils consist of loose deposits with an open structure and are predominantly found in dry and semi-desert regions. The collapse phenomenon can be triggered solely by moisture or in combination with loading. Collapsible soils can originate from transitional soils, particularly alluvial soils, in-situ soils, or inadequately compacted embankments. The issues associated with collapsible soils gained significant attention after the Second World War. Initially, Jennings [1] attributed the collapse of buildings in South Africa to the repositioning of soil particles beneath the structures concerning each other. Traditional stabilizers such as cement, lime, fly ash, etc., have generally been employed to enhance the mechanical properties of collapsible soils.

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Stabilization of collapsible soils has been achieved through injection and mixing techniques. Within the realm of mixed stabilizations, Bell [2], as well as Lutenegger and Saber [3], introduced a polymer additive to fine-grained soil. Gelsefidi et al. [4] attained favorable outcomes through a study on collapsible soil stability in northern Iran, utilizing nanomaterials. Fauziah et al. [5] utilized a novel type of chemical stabilizer called styrene-butadiene rubber, which reduced the soil's plasticity index. They investigated the resistance properties of the soil after adding butadiene rubber to the fine-grained soil. Meanwhile, this study deals with the behavior of the soil after saturation due to the addition of butadiene rubber. Zhang et al. [6] added biopolymer material to improve soil collapsibility properties and achieved acceptable results. Baghini et al. [7] simultaneously investigated cement and styrene butadiene rubber; they examined the effect of this additive on road construction. Similarly, in this article, butadiene rubber has also been used, but the difference lies in the soil type (coarse-grained soil) and the method of adding the material (mixing). Jalali et al. [8] investigated the improvement of soil properties using styrene butadiene rubber polymer, effectively enhancing soil properties. Zimbardo et al. [9] observed a decrease in the collapsibility properties of sandy soil by using a certain polymer in the collapsible sand. Silveira and Rodrigues [10] compacted the collapsible soil and conducted a double consolidation test; they observed a decrease in the collapsibility index of the soil. For injection stabilization, Ayadat et al. [11] worked to improve the soil of Rambandeh utilizing a stone column. Also, in another article, Ayadat and Hanna [12] investigated different methods of soil improvement. Bahrami and Marandi [13] investigated collapsible soil using an age column in the laboratory. Sarli et al. [14] used recycled materials to improve loess soil. Feitosa et al. [15] improved collapsible soil by mixing sewage sludge. Goodarzi and Salimi [16] discussed the improvement of clay soil using granulated blast furnace slag and basic oxygen furnace slag. Alshaba et al. [17] improved collapsible soil by mixing it with iron powder. Ziani et al. [18] investigated the behavior of soil compaction and improved the properties of the collapsible soil by adding these materials. Gibbs and Bara [19] used clay slurry and injected it into a loess mass. Abbeche et al. [20] focused on collapsible soil injected with salt and examined its geotechnical properties. They observed a significant decrease in the collapsibility index. Fattah et al. [21] conducted a study on soil collapsibility behavior by injecting grout composed of water, cement, and sand. They found that the injected grout improved the properties of the collapsible soil. Ajalloeian et al. [22] investigated the effect of polyvinyl grout on the geotechnical properties of the soil. They injected polymer materials mixed with a certain percentage of water into the collapsible soil, resulting in improved soil resistance and an increased modulus of elasticity. Ayeldeen et al. [23] examined the mechanical behavior of collapsible soil using two different types of injected biopolymers. Seiphoori and Zamanian [24] utilized nanomaterials to improve collapsible soil. Silveira and Rodrigues [10] investigated collapsible soil behavior and suggested compaction as a means of improvement. Johari et al. [25] explored the use of nanomaterials to improve the properties of collapsible soil. Khodabandeh et al. [26] investigated the properties of rammed soil using nanomaterials, resulting in improved rammed properties. Sabbaqzade et al. [27] examined the mechanical behavior of collapsible soil improved with cement. Valizade and Tabarsa [28] investigated the improvement of mechanical properties of collapsible soil by using plant roots. Nazir et al. [29] conducted research on the improvement of Rambandeh soil properties. Ogila and Eldamarawy [30] improved the geotechnical properties of collapsible soil by using cement kiln dust. El Sawwaf et al. [31] studied several different types of biopolymers for the improvement of collapsible soil. Ziani et al. [18] investigated the behavior of soils improved with pozzolan. Bakir et al. [32] examined the behavior of collapsible soil improved by waste glass fibers. Intelligent systems serve as powerful tools in geotechnical engineering and can apply fuzzy methods to handle uncertainties. Momeni et al. [33] investigated the potential of collapsibility in different central regions of Iran using qualitative assessment and fuzzy set analysis. The study demonstrated a good agreement between the experiments and the fuzzy inference system. Basack et al. [34] improved the compaction, penetration properties, dry density, and CBR of fine-grained soil by incorporating bagasse ash and stone dust.

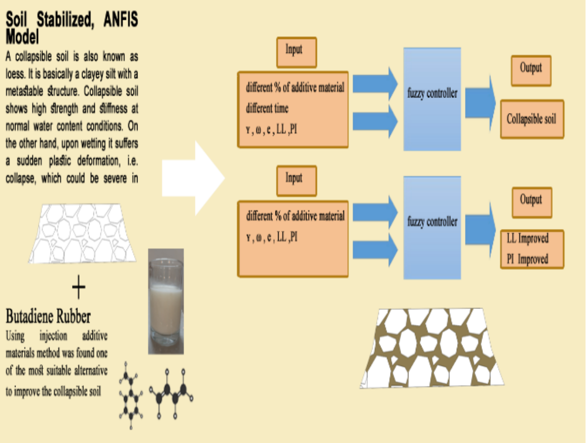
Due to the presence of a large area of collapsible soils worldwide and the need for new eco-friendly chemical materials to improve the collapsibility properties of these soils, the stabilization of such soil types is receiving significant attention. The application of styrene butadiene rubber (SBR), which is both eco-friendly and produced in significant quantities, is increasingly emphasized for improving soil properties. It is worth mentioning that the use of these stabilizers is beneficial from an economic standpoint, as they are produced domestically, reduce the cost of soil improvement, and mitigate the disastrous environmental effects of projects.

Research results demonstrate that stabilizing with green stabilizers like butadiene rubber provides greater resistance and durability compared to traditional materials such as cement and bitumen. Furthermore, SBR is non-toxic, safe, and non-corrosive, forms a hydrophobic layer that prevents rupturing, and effectively hinders the penetration of water into deeper layers. This study aims to evaluate the reduction in collapsibility by adding different percentages of butadiene rubber (2%, 3%, 4%, 5%, 6%, 7%) over varying periods (4, 7, 14, and 28 days). The collapsibility index is evaluated using Adaptive Neuro-Fuzzy Inference System (ANFIS), and a calibrated model is developed based on the results of 72 experiments conducted in Kerman City, located in the central region of Iran. Additionally, the plasticity index of the soil at both sites is assessed by adding the additive, and an ANFIS model is developed to predict the soil plasticity index. In this study, butadiene rubber polymer has been used for stabilizing fine-grained soils. Due to the high surface tension of the added material, it is suggested that this polymer be used in coarse-grained soils, or the mixing method be replaced with the injection method. It should be noted that this study solely investigates the effects of SBR on soil plastic index and collapsibility properties, and the corresponding effects on the resistance parameters have not been scrutinized. ANFIS demonstrates acceptable results in modeling the plastic index and collapsibility of fine-grained soils, although the output models cannot be expressed in the form of distinct functions. The paper's first section presents the materials and methods employed in the experiments, followed by an illustration of the sample preparation and injection process. The subsequent section provides a detailed discussion of the experimental results, followed by an analysis of the soil microstructure combined with the added material. Finally, based on the experimental findings, the ANFIS program has been developed, and the outcomes are briefly presented.

The flowchart of how to work is shown in Figure.

2. MATERIALS AND METHODS

According to previous studies indicating the collapsibility of the soil at the tested sites [16], the soil used in this study was collected from two different areas: the western and eastern parts. The samples were obtained from natural ground surfaces following the guidelines of ASTM D1587 and ASTM D4-7015, in intact and lumpy form. The tests were conducted following ASTM standards (see Figures 1 and 2). The various parameters mentioned in this article hold the following meanings:
"cp" represents the mean collapsible potential.
"LL" signifies the mean liquid limit.
"Ø" denotes the mean friction angle.
"K" represents the permeability of the soil.



A collapsible soil is also known as loess. It is basically a clayey silt with a metastable structure. Collapsible soil shows high strength and stiffness at normal water content conditions. On the other hand, upon wetting it suffers a sudden plastic deformation, i.e. collapse, which could be severe in

Using injection additive materials method was found one of the most suitable alternative to improve the collapsible soil

Figure 1. Flowchart of how to conduct the article

The particle size distribution based on hydrometer analysis is shown in Figure 3. The details of the sampling site are staed in Table 1.

Table 2 presents the results of the initial tests conducted on the soil to determine its initial parameters.

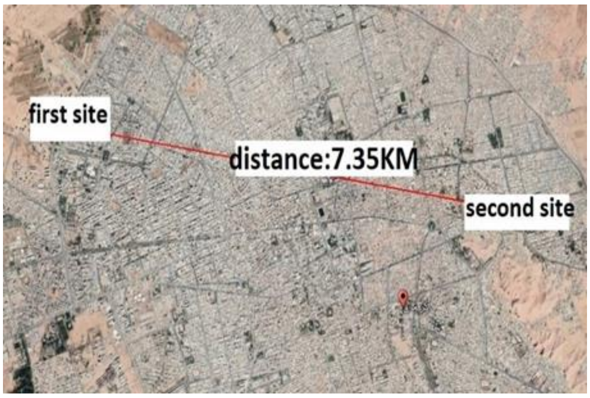


Figure 2. Map showing the sampling location in Kerman City

Figure 3. Particle size distribution (hydrometer analysis)

TABLE 1. Details of the sampling site

Site number	Geographical coordinate	Deep sample(m)	Number of samples
1	30°17′45.7″ 57°01'05.4"E	4	72
2	30°17'49.5"N 57°05'41.8"E	5.5	12

TABLE 2. Results of initial tests on the soil

Moisture content (ω)%	CP%	Degree of collapsible based ASTM	Classification	Special Weight (γ kn/m3)	Moisture content (ω)%	CP%	Degree of collapsible based ASTM	Ø	K (m/s)
1	31.2	15	ML	1.46	21.2	11.1	sever	0/404	$1/3\times10^{-6}$
2	59	23	CH	1.4	23.86	13.1	sever	0/39	$1/8\times10^{-7}$

Polymers are abundant in nature, with DNA and RNA being the most prominent natural examples that play a crucial role in life. At its core, a polymer can be defined as a functional chemical substance composed of repeating units. One of the earliest examples of an elastomer or rubber is styrene-butadiene. Approximately seventy percent of polybutadiene production is allocated for the manufacturing of rubber and tires, while an additional 25% to 30% is used as an additive in other tires to enhance their mechanical strength. In 2001, the annual production of this polymer exceeded 2.1 million tons, making it the most widely consumed polymer for tires. The polymerization of styrene butadiene was first achieved in 1910. In subsequent years, extensive research successfully developed a process to produce butadiene from ethanol in 1926, and in 1928, utilized sodium as a catalyst to pioneer the production of styrene-butadiene. Consequently, the Soviet Union became the first nation to achieve industrial-scale production of this polymer in the late 1930s. Germany and the United States also made significant contributions to the research and development of polybutadiene and styrene-butadiene production. Following World War II, major advancements in catalysts, particularly the Ziegler-Natta catalysts, were made in the mid-1950s.

In this study, a brand named X-SBR, manufactured by Paya Rezin Co. in Isfahan, Iran, was utilized as an additive to enhance collapsible soils. Styrene-butadiene rubber, dispersed in water, has been shown in previous research to increase shear resistance properties and decrease the liquid limit of soil when combined. However, the application of these materials to reduce soil volume changes during humidification has not been explored in the literature. Consequently, acquiring this information is necessary to comprehend the stability and effectiveness of soil stabilization when employing this environmentally friendly substance.

The extensive prevalence of collapsible soils worldwide, coupled with the need for eco-friendly chemicals that can improve their collapsibility properties, has underscored the importance of stabilizing such soil types using various polymers. Styrene-butadiene rubber is considered an eco-friendly polymer, and due to its large-scale production, it is also economically viable. Previous studies have employed this substance to improve coarse-grained soils and examine its effects on problematic fine-grained soils. As a result, this study aims to evaluate the reduction in soil collapsibility by adding different percentages of butadiene rubber (ranging from 2% to 7% of the total weight of the sample) over various periods (4, 7, 14, and 28 days from the time of injection to the commencement of the test). By utilizing Adaptive Neuro-Fuzzy Inference System (ANFIS), the collapsibility index is evaluated, and a calibrated model is developed using data gathered from 72 tests conducted in the central region of Kerman City, Iran.

Fine-grained soils undergo various transformations as the amount of absorbed water increases. As water is added, the grains become coated with a layer of surface water absorption. With further water addition, the thickness of the water layer surrounding the grains increases, facilitating easier sliding of the grains against each other. Therefore, the behavior of soil practically depends on the water content within the complex. Additionally, different fine grains exhibit varying behaviors in terms of surface water absorption. Consequently, the soil's plasticity index will be examined when the additive is introduced at the different percentages mentioned above, and the predicted plasticity index value will be presented in Table 3.

3. RESULTS AND DISCUSSION

3. 1. Investigation of the Possibility of Sterile Butadiene Rubber Penetration into the Tested Soils

In water-based polymer latexes that are sandwiched between fine particles, the water phase is lost through evaporation. This leads to the determination of the effective particle size of the pores (Silveira and Rodrigues, [10]), as explained by the modified Kozeny Carman equation.

$$k = 0.0898\frac{D^2}{\mu} \times \gamma\omega \times \text{Ø}^{3.4}$$

TABLE 3. Styrene Butadiene Rubber Additive Properties

Type of polymer	Brand	Color	Viscosity	Particle size	PH
Sterile butadiene rubber	X-SBR	milky	<200	۱۵۰nm	10

In the aforementioned equation, K represents the soil's permeability, Ø denotes the permeability, and μ signifies the viscosity of water. According to the soil specifications provided in the table, the effective penetration size of soil particles, ML (D1), measures 1.65 micrometers. Similarly, the effective penetration size of soil particles for the second type, CH (D2), is 0.65 micrometers. The particle size of butadiene rubber is 150 nanometers, equivalent to 0.15 micrometers. This indicates that the particles of butadiene rubber, an injection polymer, has successfully infiltrated the desired soils' pores and enhanced their properties.

3. 2. Preparation and Stabilization by Injecting the Atterberg Limit Test Sample

In this test, an additive comprising 2%, 3%, 4%, 5%, 6%, and 7% of the soil's weight is introduced to the soil, which has been soaked for 24 hours, less than one hour before the test. All test procedures were conducted in a standardized manner. Two tests were performed for each additive percentage, and the average values were reported (Tables 4 and 5).

In the ML-type soil, which initially had a liquid limit of 38, the addition of a 2% additive led to a 10% decrease in the soil. Subsequently, there was an increasing trend (42%) that continued with a further increase in the additive. On average, the liquid limit increased by 33%.

TABLE 4. Results of Liquid Limit Test on ML Soil

Additive material	Liquid limit soil 1 (LL_1)	Liquid limit soil 1(LL_2)	Average liquid limit (LL1)
0	37	39	38
2	37	38	37
3	38	39	38
4	37	40	39
5	45	48	47
6	51	49	49
7	52	52	52

TABLE 5. Results of Liquid Limit Test on CH Soil

Additive material	Liquid limit soil 2 (LL_1)	Liquid limit soil 2 (LL_2)	Average liquid limit (LL2)
0	60	58	59
2	61	57	59
3	54	55	54
4	47	49	48
5	45	44	44
6	43	41	42
7	42	40	41

In clay with a high liquid limit, the liquid limit initially increased. However, after adding a 3% additive, it started to decrease, and this downward trend continued. In this soil, the liquid limit decreased by approximately 18%.

The plastic index also increased with the percentage of additives in the first type of soil, which had a low liquid limit. With a 2% additive, the plastic index initially decreased and then exhibited an increasing trend. When the additive percentage exceeded 5%, the plastic index dramatically increased up to 100%. In clay with a high liquid limit, the maximum plastic index was observed with a 2% additive, after which the plastic index decreased. However, this difference decreased at higher percentages, resulting in approximately a 5% reduction (Figure 4).

Naturally, the clay swells due to the absorption of surface water. Water absorption reduces the friction between soil particles, cohesion, resistance, and bearing capacity of the clay mass. Styrene butadiene rubber is composed of two components: a hydrophilic head and a hydrophobic tail. When this polymer is added to the clay, the hydrophilic ions attach themselves to the clay surface, displacing or trapping them within the metal ions. As a result, their absorptive properties diminish, rendering the clay hydrophobic and oily.

The additive in sludge soil exhibited an almost opposite mechanism. The presence of butadiene rubber polymer in the sludge soil increased water absorption by the silt. As the results demonstrate, the addition of butadiene rubber increased the liquid limit. The increase in the specific surface area of the soil, caused by the addition of the polymer to the sludge soil, will raise the moisture required to transition the soil's physical state from solid to plastic and from plastic to liquid.

3. 3. Preparation and Stabilization by Injecting the Collapsibility Test Sample

The soil samples obtained were prepared and wax-coated in the laboratory.

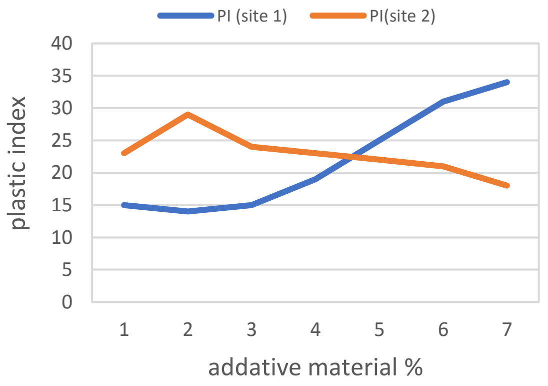


Figure 4. Comparison of the plastic index in type 1 and type 2 soils

The objective was to preserve the natural moisture of the soil and create intact samples with acceptable accuracy following the standard procedure. Firstly, the soil samples were carefully placed inside the ring of the consolidation device (see Figures 5 and 6) using a sharp blade. Then, holes with a diameter of approximately one and a half millimeters (D=1.5mm) and with a distance-to-diameter ratio (S/D=6.5) were drilled using a drill. This distance represents the minimum distance between the centers of each hole created on the consolidation sample, ensuring maximum overlap.

Additives in different weight percentages were poured into a container and mixed thoroughly. Subsequently, the injection process was carried out in three steps, with a time interval of 15-20 minutes, using a syringe equipped with a needle that had holes for all-around injection and maximum penetration into the soil (Figures 7 and 8).

3. 4. Storage and Collapsibility Test

After the slurry was injected into the soil, the sample was placed in a zippered plastic bag and stored in a moisture can with a lid. It was then placed in a temperature-controlled chamber (Figures 9 and 10).

Figure 5. Sample Drilling

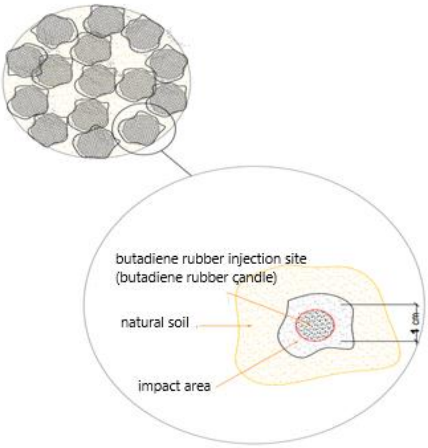


Figure 6. Schematic of Injected Sample

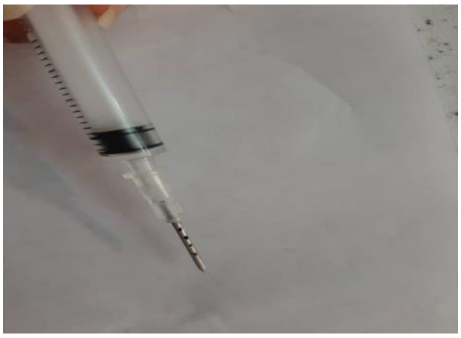


Figure 7. Injection Needle for Sample

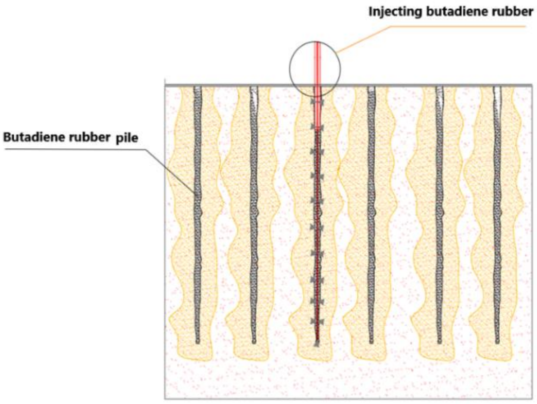


Figure 8. Sample Injection and Drilling Columns of Butadiene Rubber

Figure 9. Sample Storage

Figure 10. Isolating the Samples

To assess the effect of the additive on fine-grained soil, the coefficient of collapsibility index reduction

(Rcp) was calculated using the following formula. RCP directly relates to soil stabilization by butadiene rubber.

$$Rcp = \frac{cp(initial) - cp(secondary)}{cp(inatial)}$$

Rcp = CP(initial) - CP(secondary)

Where Rcp is the coefficient of collapsibility reduction, CP(initial) is the initial soil collapsibility value, and CP(secondary) is the soil collapsibility value after the additive is introduced (Tables 6 and 7).

TABLE 6. Collapsibility Test Results for Type 1 Soil

Initial character γ=1.76(kn/m3) ω=15.32 e=0.68 PI=26 LL=39

Percent of additive material (%)	Time (day)	CP%	average of CP%	RCP%
2	4	1.01	1.26	88.75
2	4	1.1		
2	7	1.8	1.08	90.35
2	7	1.9		
2	14	1.63	1.265	88.7
2	14	0.9		
2	28	1.25	1.242	88.91
2	28	1.23		
3	4	1.1	1.127	89.93
3	4	1.155		
3	7	0.98	1.065	90.49
3	7	1.15		
3	14	1.48	1.055	90.58
3	14	0.63		
3	28	0.39	0.31	93.23
3	28	0.26		
4	4	0.81	0.817	92.7
4	4	0.82		
4	7	0.77	0.69	93.83
4	7	0.61		
4	14	0.96	0.923	94.3
4	14	0.96		
4	28	0.82	0.592	94.71
4	28	0.36		
5	4	0.94	0.766	93.16
5	4	0.585		
5	7	0.713	0.715	93.61
5	7	0.7		
5	14	0.71	0.685	93.88
5	14	0.66		
5	28	0.15	0.252	95.33
5	28	0.16		
6	4	0.46	0.392	93.2
6	4	0.325		
6	7	0.75	0.755	93.25
6	7	0.76		
6	14	0.94	0.720	93.57
6	14	0.5		
6	28	0.53	0.515	95.4
6	28	0.5		
7	4	0.71	0.86	93.32
7	4	1.01		
7	7	0.94	0.82	94.3
7	7	0.92		
7	14	0.61	0.585	94.77
7	14	0.56		
7	28	0.43	0.425	96.2
7	28	0.42		

TABLE 7. Collapsibility Test Results for Type 2 Soil

Percent of additive material (%)	Time (day)	CP%	RCP%
2	4	1.14	91.29
2	7	0.6	95.42
2	14	0.45	96.3
2	28	0.64	95.1
3	4	1.09	91.69
3	7	0.6	95.4
3	14	0.48	96.33
3	28	0.49	
4	4	0.86	93.4
4	7	0.4	96.9
4	14	0.42	97.1
4	28	0.38	97.4
5	4	0.985	92.4
5	7	0.49	96.2
5	14	0.48	96.3
5	28	0.44	96.6
6	4	0.89	93.2
6	7	0.73	94.4
6	14	0.49	96.2
6	28	0.48	96.3
7	4	0.86	93.43
7	7	0.75	94.27
7	14	0.43	96.7
7	28	0.39	97.1

As the processing time increased, there was a further decrease in the collapsibility property due to the reaction between the polymer and soil particles. One of the positive effects of the polymer is coagulation and coagulability. To investigate the impact of processing time and additive percentage on the collapsibility properties of the modified samples, collapsibility reduction diagrams were plotted at different times (Figure 11).

Diagrams illustrating the reduction in collapsibility as a percentage of additive over different periods in site-1 soil reveal that RCP% exceeded 88% in all cases, with the lowest reduction observed at 2% additive. As time progressed, an increase in RCP% was observed. After 7 days, significant increases in RCP% were noted for all additive percentages, with the highest increase occurring at 28 days.

For site-2 soil situated in Shohadaye Darlek Street, the addition of a 2% additive resulted in a reduction in the trend. However, after adding a 5% additive, the trend stabilized (Figure 12).

The collapse phenomenon is a process in which the absorption of water by soil particles leads to the loss of molecular forces between particles through various mechanisms, such as softening, the disruption of capillary forces, the elimination of suction force due to saturation, increased shear stress resistance, and so on.

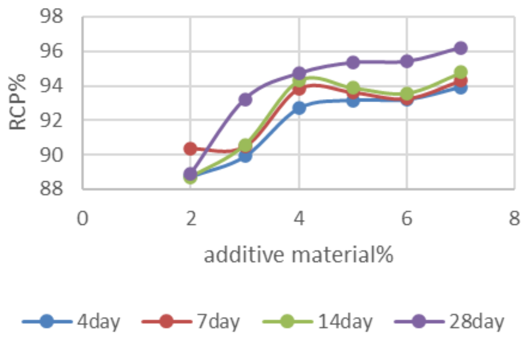


Figure 11. Percentage of Collapsibility Reduction at Different Times and Days

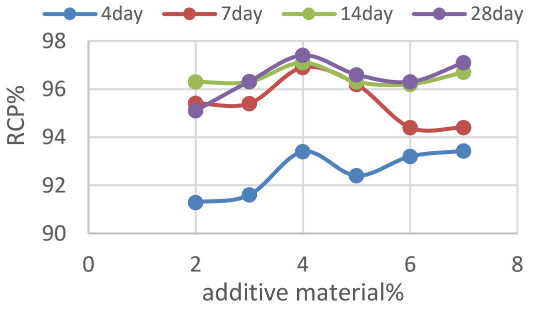


Figure 12. Percentage of collapsibility reduction versus time in site 2

As a consequence, the natural structure of the soil suddenly collapses and is destroyed. These problematic soils, normally dry, stable, and strong, experience numerous deformations, rapid settlement, and a significant decrease in porosity ratio with increasing moisture content and loading. By examining the testresults conducted on this soil type, it can be observed that the nature of the polymer breaks a double bond between carbon atoms and replaces it with a single covalent bond. Consequently, the two free ends of this monomer become free radicals. This basic molecule, capable of undergoing reactions, serves as the building block of polymers and is repeated frequently along the polymer molecule chain. Over time, this chain forms and prevents softening between the soil particles when exposed to water. The injection of the additive into the soil fills the soil pores, maintaining the capillary force between the particles unchanged when the collapsible soil is exposed to water, thereby preserving its cohesive structure. The injection of the polymer into the clay with a high fluid limit results in the formation of piles of butadiene rubber in the soil, which act as concrete piles when the soil is saturated and loaded. Consequently, a lower reduction in bearing capacity is observed, and the collapsibility of the soil experiences a significant decrease. In silty soil, the polymer improves the soil around the pile based on the size of soil particles, leading to a reduction in soil collapsibility upon loading and saturation. However, in clay with a high fluid limit, the reduction in collapsibility is more pronounced. Overall, the most substantial decrease in soil collapsibility was observed with a soil additive weight of 7% over 28 days.

3. 5. Microstructural Investigations

To understand the structural changes in the soil samples, SEM photos were taken. Two sets of soil samples were prepared: one without additives and another with additives. Figures 13 and 14 clearly show the effect of styrene butadiene rubber on the formation of new bonds between the soil particles. The introduction of rubber has transformed the soil structure from a discontinuous state to a more continuous form. This enhanced continuity, reduction in existing voids, and increased cohesiveness have improved the collapsibility properties of the soil. The extent of this improvement and void reduction varied based on the percentage of butadiene rubber and the processing time.

Since conducting tests may not always be feasible under certain conditions, a model can be employed to address this issue. In this study, the results obtained from the liquid limit test and plastic index, in conjunction with collapsibility data, were utilized as inputs for MATLAB software and fuzzy logic. The aim was to develop a model capable of determining the plastic index and potential soil collapsibility. To predict the soil's plastic index, 20 data points were used for training, and 8 inputs

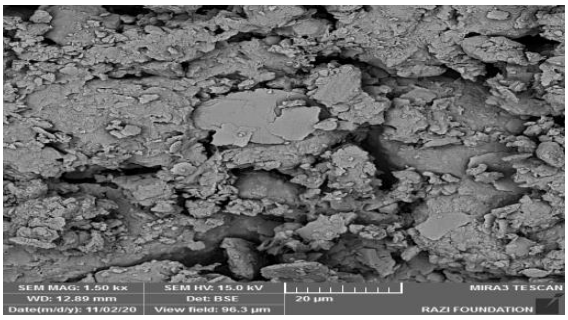


Figure13. SEM Photo of the Soil without Additive

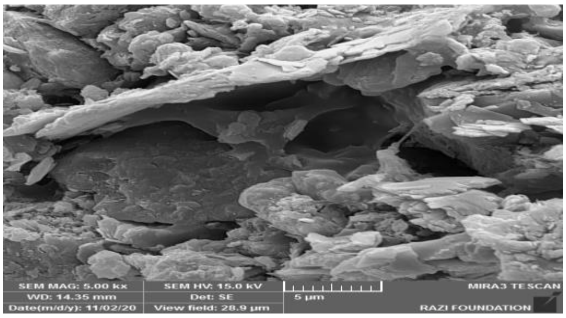


Figure 14. SEM Photo of the Soil with Additive

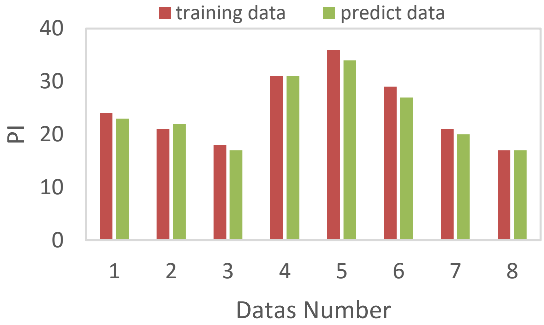


Figure 15. ANFIS results versus laboratory values corresponding to prediction data

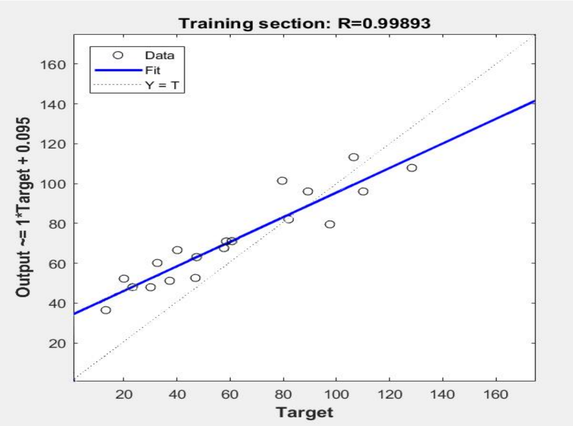


Figure 16. ANFIS results versus laboratory values corresponding to experimental data

were utilized for prediction using ANFIS in MATLAB software. For each data point, the following five parameters were taken as inputs: liquid limit of the base soil (LL), plastic index of the base soil (PI), specific weight of the soil (γ), time (t), and percentage of additive. The output was the plastic index of the soil, which was determined for model development. Gaussian membership function was employed as the membership function, and a total of 6 rules were used (Table 8).

The two plastic index functions are in good agreement with the inputs from the laboratory results and the plastic index predicted by ANFIS (Figure 15).

The coefficient of determination (R) used to determine the soil plastic index is 0.99, indicating a high correlation between the experimental and predicted values (Figure 16).

To predict the soil collapsibility index, this model utilizes 36 input data for training and 12 data for prediction from two different sites. The data from Table 9, including moisture percentage (W%), basic soil plastic index (PI), porosity ratio (e), soil specific gravity (γ), time (t), and additive percentage, were considered as input, and collapsibility index (CP%) as output for modeling. The number of input data was 6, and the number of rules used was 8.

In the production model, the parameters used for ANFIS training are listed in Table 9. The membership functions employed are Gaussian. The membership functions (rules) resulted in accurate modeling based on

TABLE 8. Parameters Used in ANFIS for Plastic Index

ANFIS parameter type for PI	ANFIS
MF type	Gaussian
Number of linear parameters	٥
Number of nonlinear parameters	3
Number of training data pairs	20
Number of checking data pairs	8
Number of fuzzy rules	6

TABLE 9. Parameters Used in ANFIS for Collapsibility Index

ANFIS parameter type for CP	ANFIS
MF type	Gaussian
Number of linear parameters	٦
Number of nonlinear parameters	٣
Number of training data pairs	51
Number of checking data pairs	21
Number of fuzzy rules	٨

the available data. Choosing a low number of rules would weaken the model while increasing the number of rules would complicate calculations. The created FIS for the soil collapsibility prediction model is shown in Figure 17. The determination coefficient, denoted as R, indicates the explanatory power of the model. It quantifies the percentage of variation in the dependent variable (criterion) explained by the independent variables (predictions). This coefficient serves as one of the model fit indices, reflecting the strength of the dependent variable based on the independent variables. Figure 18 depicts the regression diagram, which is highly effective for analyzing model errors. The diagram illustrates the correlation between actual and estimated values produced by the model. The closer the fitted line to the data (blue line) is to unity, the stronger the correlation between the actual and estimated values. The actual values closely align with the estimated values, demonstrating a reasonable and desirable performance of the model. The coefficient of determination (R) for the soil collapsibility index is 0.87, indicating a high correlation between the experimental and predicted values and acceptable performance. According to literature, an RMSEA value below 0.1 suggests an excellent fit for the model. A value between 0.1 and 0.5 indicates a good fit, while a value between 0.5 and 0.8 implies an average fit. The obtained RMSEA value is 0.12558, indicating a good fit for the model. Overall, the results obtained from the plastic index test and potential collapsibility, along with their comparison with the models developed in the fuzzy inference system, demonstrate a well-fitted model aligned with the experimental results.

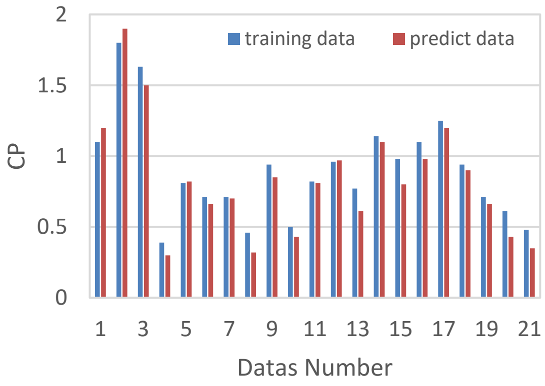


Figure 17. ANFIS results versus laboratory values corresponding to prediction data

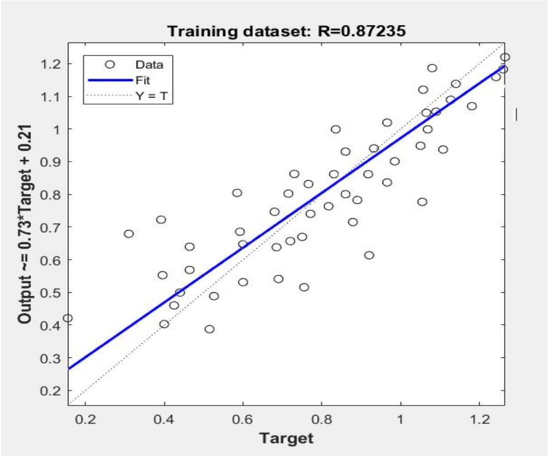


Figure18. ANFIS results versus laboratory values corresponding to experimental data

4. CONCLUSIONS

Over time, various additives have been utilized to enhance the collapsibility properties of soil, and their effects have been investigated extensively. This study specifically focuses on the impact of a novel polymer called styrene-butadiene rubber on improving the properties of fine-grained collapsible soil in the central region of Iran, specifically Kerman. After determining the fundamental characteristics of the base soil, such as granularity, moisture percentage, specific gravity, and Atterberg limits, the collapsibility of two types of fine-grained soil (ML, CH) was examined using varying proportions of the aforementioned additive at different time intervals. To evaluate the soil properties, the additive was mixed with soil samples at weights of 7%, 6%, 5%, 4%, 3%, and 2%. Subsequently, collapsibility tests were conducted after different durations (14, 7, 4, and 28 days). A total of 84 tests were performed, and the results were compared.

The theory of fuzzy sets was employed for the proposed modeling. The developed model serves to predict potential soil collapsibility when the additive percentage and initial potential of the soil are known, even in the absence of the necessary conditions for injection and the desired tests. In this model, 80% of the data was used for input, while the remaining 20% was utilized for training purposes. Based on the tests conducted on two different soil samples, ML and CH soils, it was observed that they had moisture contents of 21.2% and 23.86%, and specific gravities of 17.1 g/cm³ and 17 g/cm³, respectively.

Finally, the obtained results can be summarized as follows:

1. The Atterberg limit test results on ML soil indicated that the addition of the additive resulted in an approximately 33% increase in the liquid limit and a 100% increase in the plastic index.
2. Test results on the second type of soil, CH soil, revealed that the additive generally reduced the Atterberg limit and decreased the plastic index by 90%.

3. The most significant reduction in potential soil collapsibility was observed with a 7% additive content over 28 days.
4. A fuzzy inference system was proposed to predict the plastic index using five data inputs and one output. The prediction model demonstrated the highest degree of concurrence with the actual model.
5. The diagram used to determine the soil plastic index yielded an R-value of 0.99 for the trained and predicted data in ANFIS modeling, indicating the model's high accuracy.
6. Based on the test results, it can be concluded that butadiene rubber effectively reduced collapsibility, with a reduction percentage exceeding 90% in most cases.
7. Adding styrene-butadiene rubber to fine-grained collapsible soil at various times and percentages led to the finding that the lowest level of soil collapsibility was attained after a 7-day testing period. Moreover, the optimal percentage of the additive was approximately 4% or higher.
8. The developed ANFIS model was trained using 51 input data points and 21 prediction data points, with the output being the collapsibility index. For the training data, an R2 value of 0.99 and an RMSE value of 20.5% were obtained, confirming the model's accuracy.
9. In comparison to a previous study (Seiphori et al., 2020) that employed clay and cement slurry at varying percentages (1.5%, 2%, 3%, etc.) over similar periods (4, 7, 14, and 28 days) and resulted in a 76% improvement in the collapsibility of fine-grained soil (CL), this study utilizing SBR demonstrates an improvement of 88% and 92% respectively for ML and CH soil types. Both clay slurry and SBR are environmentally safe, but the latter is more affordable and accessible, making it a recommended option for similar research and projects.

5. ACKNOWLEDGEMENTS

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Persian Abstract

چکیده

خاک های رمبنده در طبیعت خاک های مشکل ساز هستند. به دلیل ساختار باز، در صورت قرار گرفتن در معرض رطوبت دچار نشست می شوند. در صورت عدم شناسایی این نوع خاک ها، سازه های ساخته شده بر روی آنها در صورت اشباع و تغییر رطوبت خاک آسیب می بینند. وجود این خاکها در بسیاری از نقاط جهان از جمله ایران نیازمند توجه و بررسی بیشتر رفتار و خواص خاکهای انباشتنی است. این مطالعه به بررسی اثر لاستیک بوتادین بر تثبیت این خاکها پرداخته است. خاکهای ریزدانه مورد آزمایش از دو مکان مختلف واقع در استان کرمان، شهر کرمان، خیابان شهدای دارلک و میدان کوثر نمونه برداری شدند. نمونه ها با لاستیک بوتادین ۲، ۳، ٤، ٥، ٦ و ۷ درصد به مدت ٤، ۷، ١٤ و ۲۸ روز برای تثبیت (۷۲ آزمایش) تزریق شدند. خاکهای تثبیت شده با آزمون تحکیم مضاعف (ASTM D5333) بر روی نمونه های خاک سالم مورد ارزیابی قرار گرفتند. نفوذ لاستیک بوتادین و همچنین ستون های لاستیکی بوتادین تشکیل شده باعث کاهش سطح ریزش شد. در همه موارد، فروپاشی بیش از ۸۸٪ کاهش یافت. بیشترین میزان کاهش در ۷ ماده افزودنی و به مدت ۲۸ روز رخ داد. با توجه به گسترش سیستم‌های هوشمند در پیش‌بینی رفتار خاک‌های جمع‌شونده تثبیت‌شده، مدلی برای پیش‌بینی درجه ریزش نمونه‌های تثبیت‌شده با لاستیک بوتادین با سیستم استنتاج فازی شبکه تطبیقی (ANFIS) ساخته شد و دقت آن مورد ارزیابی قرار گرفت. با افزودن درصدهای ذکر شده افزودنی لاستیک استایرن بوتادین به خاک های مورد آزمایش، کاهش شاخص پلاستیک خاک رس با حد مایع بالا و همچنین افزایش شاخص پلاستیک سیلت با حد مایع کم نشان داده شد. این با توجه به نوع ماده معدنی تغییر کرد. سپس این مدل برای پیش‌بینی خواص پلاستیک خاک با استفاده از سیستم استنتاج فازی توسعه داده شد. نتایج نشان می‌دهد که داده‌های آموزش و پیش‌بینی به طور قابل قبولی سازگار هستند (R2=۰/۹۳)