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Experimental Study on the Influence of Polypropylene Fiber on the Swelling Pressure Expansion Attributes of Silica Fume Stabilized Clayey Soil

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Abstract: Expansive soil shows dual swell–shrink which is not suitable for construction. Several mitigating techniques exist to counteract the problem promulgated by expansive clayey soils. This paper explored the potential mecho-chemical reinforcement of expansive clayey soil to mitigate the effect of upward swelling pressure and heave. The polypropylene fiber is randomly distributed in the soil for mechanical stabilization, and the industrial residual silica fume is used as a chemical stabilizer. The experimental analysis was made in three phases which involved tests on mechanically-reinforced expansive soil, using randomly distributed polypropylene fibers with different percentages (0.25%, 0.50%, and 1.00%), and which were 12 mm length. The second phase of experiments was carried out on chemical stabilized expansive soil with different percentages (2%, 4%, and 8%) of silica, and the next phase of the experiment focused on the combination of mecho-chemical stabilization of the expansive soil with different combinations of silica (i.e., 2%, 4%, and 8%) and polypropylene fibers (i.e., 0.25%, 0.50%, and 1.00%). Maximum dry density (MDD), optimum moisture content (OMC), liquid limit (LL), plastic limit (PL), plastic index (PI), grain size, and constant volume swelling pressure tests were performed on unreinforced and reinforced expansive soil, to investigate the effects of polypropylene fiber and silica fume on the engineering properties of expansive clayey soil. The experimental results illustrate that the inclusion of polypropylene fiber has a significant effect on the upward swelling pressure and expansion property of expansive soil. The reduction in the upward swelling pressure and expansion is a function of fiber content. These results also indicated that the use of silica fume caused a reduction in upward swelling potential, and its effect was considerably more than the influence of fiber.

Keywords: expansive soil; polypropylene fiber; silica fume; swelling pressure; expansion

1. Introduction

Expansive clayey soil, which is copious in tenacious hydrophilic minerals such as illite and montmorillonite, is a typically problematic expansive soil conceived in natural geological processes. Expansive soil is characterized by shrinkage, consolidation, and heave (expansion).

Structural damages due to expansive soils occur on roads, buildings, and bridges. Past research focused on perceiving the demeanor of clayey soil and the complications that might emanate due to volume fluctuations [1–4]. Expansive soils, due to their inherent swelling–shrinkage nature, are considered as inadmissible construction materials for building and for transportation engineering applications [5]. Therefore, such soil often needs to be modified to meet the design criteria before application. Expansive soils can be stabilized using mechanical and chemical treatment. Chemical treatment majorly involves the inclusion of chemical admixtures (e.g., polymers, cement, and lime) to the soil [6–10]. The mechanical approach includes the compaction of the soil with the addition of the strengthening material. Common strengthening materials include synthetic fibers (e.g., nylon and polypropylene) [11,12] and natural fibers (e.g., coconut and coir) [13,14], or other fibrous materials. The use of fibers can be considered as one of the most widely accepted propositions in this context. The reinforcement of embankments, slopes, retaining walls, subgrades, and base course are part of transportation infrastructures projects. Soil reinforcement with fibers is an exciting and innovative solution to geotechnical problems. The behavior and beneficial effects of fiber-reinforced soil have been extensively studied and described in the literature. Numerous experiments with fiber-reinforced soil have shown that the unconfined compressive strength of the soil increases with the addition of random fibers to the soil [15–18]. Other studies have investigated the effect of adding artificial or natural fibers [14,19–22].

There is a rapid increase in the waste quantity of plastic fiber and if this waste can be utilized for the stabilization of soil, then a sustainable solution of the expansive soil can be achieved [11]. In recent years, the polymeric fibers have also been used to control the volume change behavior of expansive soil as well as to improve its strength. The performance of the reinforcement is enhanced by the properties of the fiber, volume fraction, modulus of elasticity, type of inclusion, orientation, length, shape, grain size, gradation characteristics, and density [23]. It has also been established that the peak unconfined compressivr strength (UCS) of soil increases with the inclusion of fiber content, and it has shown a meager reduction in shear capacity [19]. Polypropylene fiber does not react with water and soil, and hence can be used for the soil reinforcement [24].

Cement is specially used to improve the shearing strength of the expansive soil, and is thus preferred as a chemical additive to expansive soil if an improvement of their strength is required as a parameter [6,7,25]. The chemical stabilization of expansive soils is a substantiated quick-fix method in the short term. However, concerning the long-term sustainability of these methods, there are considerable problems, concerning the mineralogy of the soil clay and the environmental fluctuations of clay soil, such as water availability and construction methods [26,27]. Chemical stabilization methods make expansive clay soils stable under compression, but contribute minimally to the tension. This becomes a hefty problem in the summer, when expansive soils contract and when stabilization should withstand tensile cracking [28]. A natural way to improve the tensile strength of a material is by mechanical reinforcement.

The primary focus of this paper is to evaluate the performance of the polypropylene fiber as an effective mechanical reinforcement and of silica fume as an environment-friendly chemical stabilizer, as alternatives for the expansive soil [29,30]. Several researchers have studied the effect of polypropylene fiber and silica fume on consolidation and swelling [24]; however, the effect of polypropylene fiber with and without silica fume on the upward swelling pressure and expansion rate of the expansive soil have not been investigated thoroughly. This paper is a contribution toward this, where we have studied the impact of polypropylene fibers with and without silica fume on both reinforced and unreinforced expansive soils. A constant volume swelling pressure test was conducted by varying the percentage of polypropylene fiber content (i.e., 0%, 0.25%, 0.50%, and 1.00%) and silica fume (0%, 2%, 4%, and 8%), to propose the optimum amount of the fiber reinforcement and silica fume needed to mitigate the upward swelling pressure exerted by the expansive soil.

2. Material Properties

2.1. Expansive Soil

The expansive clay soil used for the present study was collected from Indore (India) at a depth of 1.5 m–2 m. The free swelling index of the soil was 120%, which is considered to be of a very high swelling nature. The liquid limit (LL) and the plasticity index (PI) of the soil were 89% and 42%, respectively. Based on LL and PI, the soil is classified as high plasticity (CH) silty clay, according to the unified soil classification system (USCS). The various index properties of the expansive soil considered in the study are shown in Table 1.

Table 1. Index properties of expansive soil considered.

Property	Value
Specific gravity	2.78
Liquid limit (%)	89
Plastic limit (%)	47
Plasticity index (%)	42
Shrinkage limit (%)	11
USCS soil classification	CH
Grain size distribution	
Clay (%)	71.5
Silt (%)	24.5
Sand (%)	4.0
Free swell index (%)	120

2.2. Polypropylene Fiber

Polypropylene fibers have been used in the present study because they have several advantages, such as their properties of high strength, providing microfine reinforcement, and of being chemically inert, non-corrosive, and available in various lengths. For the present study, fibers with a length of 6 mm were provided by Bajaj Reinforcements Nagpur India. The physical, chemical, and mechanical properties of polypropylene fiber (PP) fiber are shown in Table 2 below.

Table 2. Properties of polypropylene fiber considered.

Property	Value
Specific gravity	0.91
Tensile strength (kN/mm^2)	0.67
Young's modulus (kN/mm^2)	4.0
Melting point (°C)	165
Ignition point (°C)	600
Bulk density (kg/m^3)	910
Loose density (kg/m^3)	250–430
Fiber cut length (mm)	6 mm
Dispersion	Excellent
Acid and salt Resistance	Chemical Proof

2.3. Silica Fume

Silica fume is a waste material for industrial applications, which due to its very active and high pozzolanic properties is one of the most valuable by-products of construction activities. It is a by-product of the production of metallic silicon or ferrosilicon alloys, and consists mainly of amorphous silicon (SiO_2). The individual silica fume particles are extremely small: About 1/100 the size of an average cement particle. Silicon smoke is a highly reactive pozzolanic material due to its fine particles, large surface area, and high SiO_2 content. The silica fume used in the research work provided by the Safew Tech System Indore in powder form and air-dried. The chemical composition of the silicic acid vapor is shown in Table 3.

Table 3. Properties of silica fume considered.

Property	Value
Density (Mg/m^3)	92.25
Silt (2–75 µm)	0.67
Clay (<2 µm)	4.0
SiO_2	99.39%
Al_2O_3	0.08%
Fe_2O_3	0.02%
K_2O	0.08%
CaO	0.43%

3. Experimental Investigation

In this study, we investigated the optimum moisture content, maximum dry density, upward swelling pressure, and expansion rate of the polypropylene fiber in reinforced and unreinforced silica fume stabilized expansive soil. Polypropylene fiber ratios of 0.25%, 0.50%, and 1.00%, and silica fume ratios of 2.00%, 4.00%, and 8.00% have been mixed with the expansive soil, and tests have been carried out on the both reinforced and unreinforced soil samples to understand the swelling–shrinkage behavior of the expansive soil. Furthermore, constant pressure swelling tests have been conducted for 28 days with the addition of 0.25%, 0.5%, and 1.00% polypropylene fiber as a mechanical stabilizer, and 2.00%, 4.00%, and 8.00% silica fume as a chemical stabilizer. The study also explores the potential use of the combined mixes of silica fume and polypropylene fiber. The initial moisture content and dry unit weight are essential factors affecting the swelling behaviors of expansive soil [31]. The material was prepared at the maximum dry density and with the optimum moisture content. The required amount of expansive soil, polypropylene fiber, and silica fume mixes were compacted statically using a lightweight proctor to achieve the field conditions. To have a well-distributed homogeneous mix, the required quantity of the expansive soil and additive material were weighed in accordance with the total weight of the composite samples, and mixed together using planetary mixture in the dry state. The dry mix of the expansive soil and the additive material were kept in the environmental chamber at 27 °C temperature and 65% humidity for 24 hours to maintain the desired temperature and humidity in all the mixing material. The optimum moisture content was added to the reinforced and unreinforced mixed proportions of the expansive soil at a constant temperature, using a sprinkling method of water inclusion. In this paper, the expansive soil, polypropylene fiber, and silica fume are referred to as BC, PP, and SF, respectively.

4. Results and Discussion

The swelling pressure is defined as the pressure to maintain the volume of the material consistently while undergoing saturation in between two successive readings. The variation of the swelling pressure with and without polypropylene fiber reinforcement is shown in Figure 1. This depicts that the swelling pressure decreases with an increase in polypropylene fiber content and with the increment of the silica fume content. It can be observed from Figure 1 that at the ratio of 2% silica fume content the initial swelling pressure was lower than the expansive soil sample; however, before the saturation state, the 2% silica gives higher swelling pressure. As the results show, higher silica fume and polypropylene fiber contents are capable of reducing the swelling pressure. As the expansive soil is a visible indicator of swelling, its reduction with the addition of PP fiber and silica fume content is noticeable, as shown in Figure 1. The reduction can be due to polypropylene fiber and silica fume replacing the expansive soil and consequently producing a reduction in the specific surface area of the swelling fraction. It also depicts that the swelling pressure of the clay and reinforced clay changes at an exponential rate until 120 minutes, after which it gradually becomes constant due to saturation. Figure 1 shows the combined upward swelling pressure curves of both reinforced and unreinforced expansive soil.

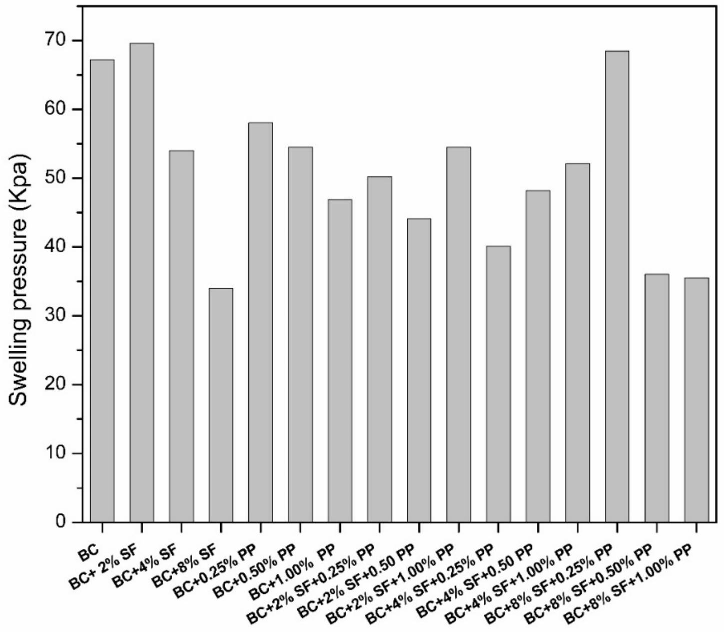


Figure 1. Combined upward swelling pressure curve with and without reinforced expansive soil.

The reduction in upward swelling pressure was observed with the inclusion of silica fume contents. The swelling pressure in the silica fume-reinforced expansive soil was decreased with silica fume content, as shown in Figure 1. It was also observed that the decrease in the swelling pressure occurred with rising silica fume contents, which ranged from 0% to 8%. The swelling pressure of the 8% silica fume-reinforced samples reduced from 67.21 kPa to 34.02 kPa, which indicated a 49.38% reduction in the swelling pressure, as shown in Figure 2a. The swelling pressure is highly reduced with the inclusion of the silica fume, since SF is a non-expansive material, and its inclusion reduces the specific surface area of an expansive material and as a result the reduction in the swelling pressure is observed. With the inclusion of silica fume as a reinforcement additive, the silica reacted with the calcium and produced calcium silicate hydrate (C-S-H) gel, as shown in Equation (1) [32]. It has been observed that the samples of reinforced soil become more stiffer and brittle [28] than the virgin expansive soil samples, due to the chemical reaction of the silica fume and calcium. Figure 2b depicts that the swelling pressure decreases with an increase in polypropylene fiber content. The swelling pressure for the unreinforced expansive soil samples is observed as 67.21 kPa, and it was found that the values of swelling pressure reduced to 58.05 kPa (13.63%), 54.52 kPa (18.88%), and 46.87 kPa (30.25%) with the inclusion of 0.25%, 0.50%, and 1.00% PP, respectively. Figure 2c shows the swelling pressure behavior of the 2% silica fume content with varying percentages of the polypropylene fiber, and it can be observed that upward swelling pressure reduced by 50.25 kPa (25.23%), 44.13 kPa (34.33%), and 54.53 kPa (18.86%) with the addition of 2%SF + 0.25%PP, 2%SF + 0.50%PP, and 2%SF + 1.00%PP, respectively. The inclusion of a higher amount of PP content with the 2% silica fume shows low reduction in the upward swelling pressure, due to the discrete distribution of PP fiber in the samples. Figure 2d shows the swelling behavior of the inclusion of 4% silica fume with varying percentages of PP fiber i.e., 0.25%, 0.50% and 1.00%. With an inclusion of 4%SF + 0.25%PP, 4%SF + 0.50%PP, and 4%SF + 1.00%PP the swelling pressure reduced by 40.08 kPa (40.36%), 48.19 (28.30%), and 52.08 kPa (22.50%), respectively. The 4% silica fume content with 0.25% polypropylene fiber does not show major swelling pressure for the initial 60 min, and then an exponential increase in the upward swelling curve is shown in Figure 2d. From Figure 2e it can be observed that with the inclusion of 8%SF + 0.25%PP, 8%SF + 0.50%PP, and 8%SF + 1.00%PP, the swelling pressure was reduced by 68.45 kPa (−1.85%), 30.06 kPa (46.34%), and 35.53 kPa (47.13%). The addition of 0.50% and 1.00% PP fiber with 8% silica fume shows an almost similar result, and hence it can be confirmed that the swelling pressure is highly reduced with the inclusion of silica fume content.

$$Ca^{2+} + OH^{-} + soluble\ silica \rightarrow calcium\ silicate\ hydrate \tag{1}$$

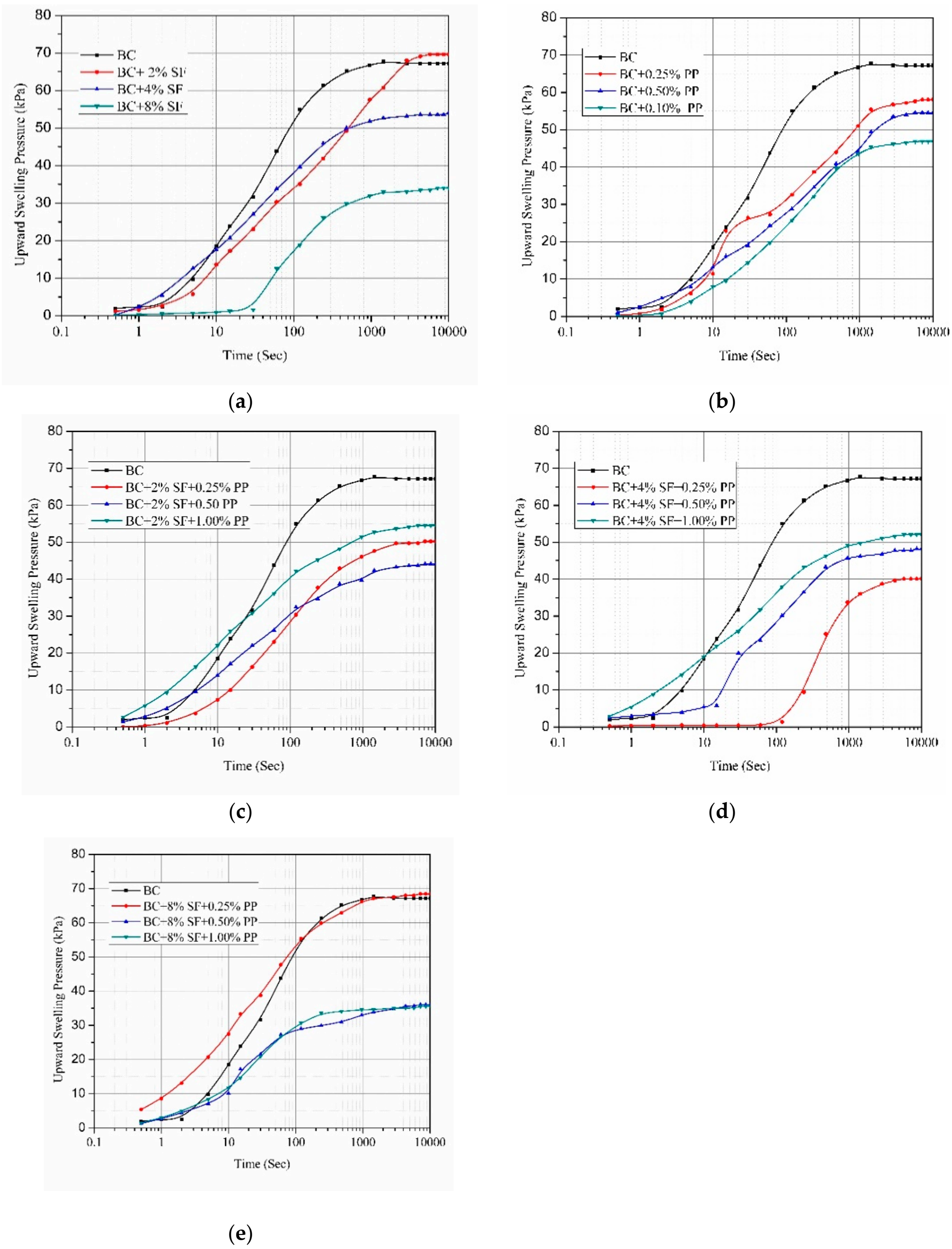


Figure 2. (**a**) Upward swelling pressure curve for silica fume-reinforced expansive soil. (**b**) Upward swelling pressure curve for polypropylene fiber-reinforced expansive soil. (**c**) Upward swelling pressure curve for polypropylene fiber reinforced with 2% silica fume expansive soil. (**d**) Upward swelling pressure curve for polypropylene fiber reinforced with 4% silica fume expansive soil. (**e**) Upward swelling pressure curve for polypropylene fiber reinforced with 8% silica fume expansive soil.

It can be ascertained that expansive soil absorbs water and upon saturation, changes in the swelling ratio without pressure can be roughly divided into three stages: (1) Rapid expansion period. In general, this stage will be finished in 30 min after the expansive soil absorbs water and the swelling amount accounts for about 60–80% of the total. (2) Slow expansion period. In this stage, the expansion rate is slow compared to rapid expansion and will be finished in about 20 hours. (3) Stable expansion period. After the expansive soil absorbs water and becomes saturated, its density is less, and the space between the soil enlarges. The time taken by the water to fill the area is more, so the expansion period lasts longer. However, these changes are minor, and hence the curve shown in Figure 3 is relatively stable. Figure 3 shows a combined expansion rate of curve with and without reinforced expansive soil, which shows that the 4% silica fume inclusion in the soil gives a higher expansion rate than that of the normal soil.

It has been observed that ratios of 8% silica fume and 0.50% polypropylene fiber are effective in the initial phase, as shown in Figure 4e. However, ratios of 4% silica fume and 1.00% polypropylene fiber exhibited more potential to reduce the expansion rate of expansive soils, as shown in Figure 4d.

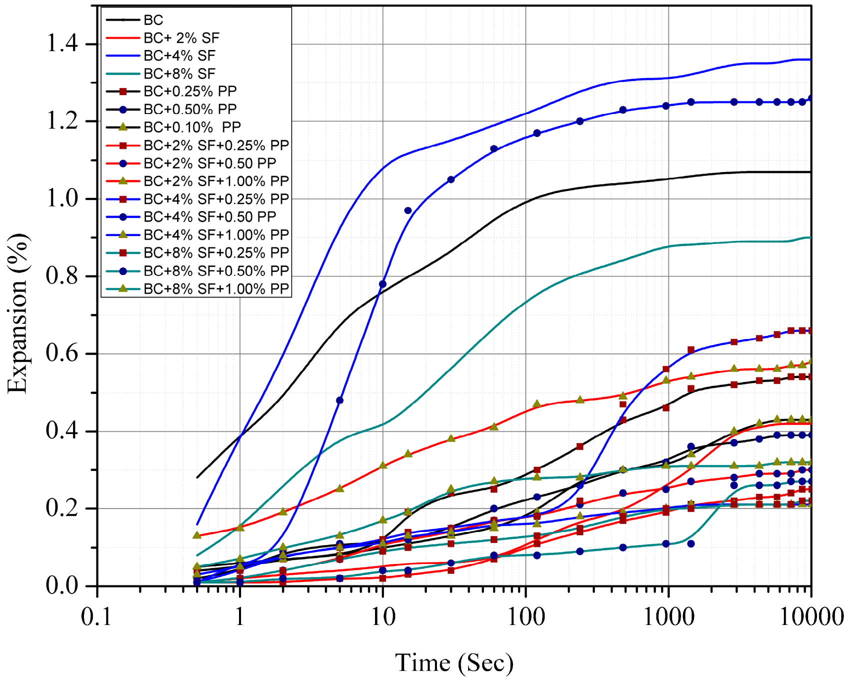
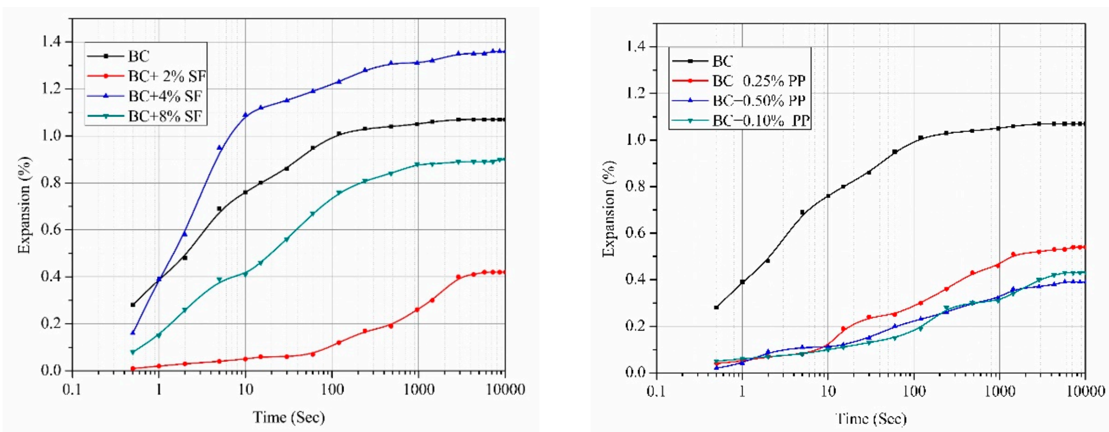
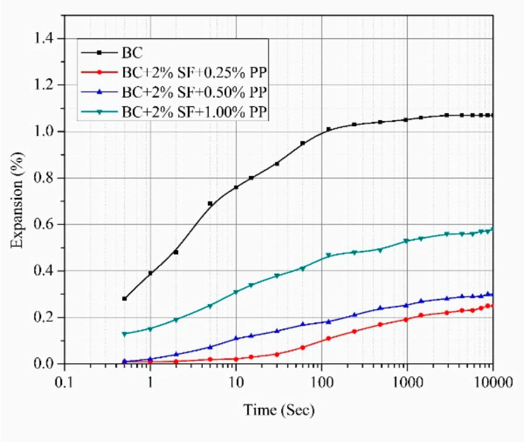


Figure 3. Combined expansion curves with and without reinforced expansive soil.



(**a**) (**b**)

Figure 4. *Cont.*



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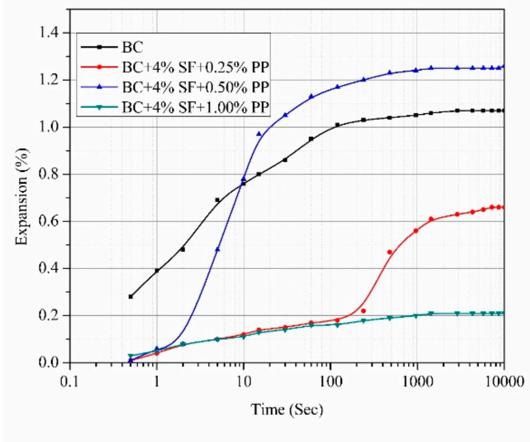
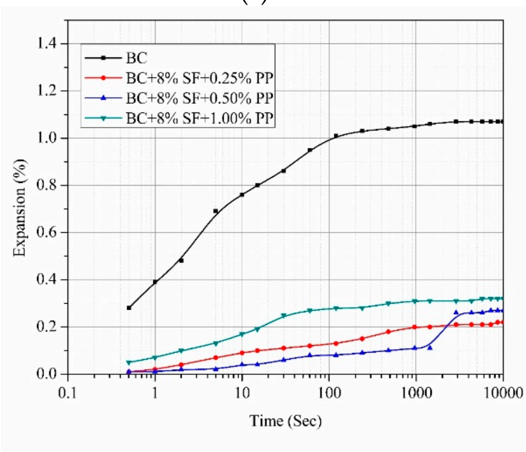


(**d**)



(**e**)

Figure 4. (**a**) Expansion rate curves for silica fume-reinforced expansive soil. (**b**) Expansion rate curve for polypropylene fiber-reinforced expansive soil. (**c**) Expansion rate curve for polypropylene fiber reinforced with 2% silica fume expansive soil. (**d**) Expansion rate curves for polypropylene fiber reinforced with 4% silica fume expansive soil. (**e**) Expansion rate curves for polypropylene fiber reinforced with 4% silica fume expansive soil.

5. Conclusion

The results of the study on the potential use of polypropylene fiber and silica fume to improve the behavior of expansive soil and reduce upward swelling pressure show that the inclusion of silica fume and polypropylene fiber reduces the plastic index (PI) and liquid limit (LL) of expansive soil, and increases the plastic limit. Due to this alteration in the property of expansive clayey soil, the soil changed its USCS classification forming high-plastic clays (CH) to low-plastic clays (OH). Due to the transformation of the CH to OH, the plasticity of the reinforced sample reduces, and hence the reinforced expansive soil shows a stable nature.

A significant improvement in the swelling pressure was obtained with the inclusion of silica fume content, as the swelling pressure decreased for all the test samples. The lowest swelling pressure was calculated at the 8% ratio of silica fume content, with a reduction of approximately 49.38%; however, the lowest expansion % rate was observed with a ratio of 2% silica fume content. The investigation shows that silica fume is a valuable material to modify the property of expansive clayey soil, due to the silica reaction with the calcium and the produced calcium silicate hydrate (C-S-H) gel. The inclusion of silica fume content in pavement expansive soil subgrade reduces the upward swelling pressure, and subsequently enhances the pavement performance

The use of PP fiber shows significant improvements in the engineering properties of expansive clay soil. The reinforced soils of different percentages of PP content can be used for controlling the swelling pressure of the expansive soil subgrade. It has been observed that a 1.00% PP fiber mix exhibited an exponential reduction in the upward swelling pressure. A 0.50% PP mix shows a 30.25% reduction in the swelling pressure. The expansion % rate of the 0.5% PP and 1.00% PP content shows an almost similar nature, with a 59.81% and 63.1% reduction in the expansion % respectively, which should be used as the optimum percentage in the PP fiber for the field applications.

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