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Resistencia a la humedad y al secado de un suelo estabilizado con cal modificado con escoria de acero y reforzado con fibras

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Abstract

The investigation dealt with the stabilization of expansive soil with combinations of lime, steel slag and reinforced with two types of fibres, copper filaments and polypropylene fibres. The investigation began with the characterization of the soil for its geotechnical properties. The initial consumption of lime required for the modification of the soil properties was determined from the Eades and Grim pH test. Cylindrical specimens of soil with dimensions 38 mm x 76 mm were cast using this lime content as a stabilizer along with varying quantities of steel slag for determination of optimum steel slag content. The pure lime stabilized soil as well as lime-steel slag modified soil specimens were reinforced with different proportions of copper filaments for determination of optimum fibre content. One dosage of polypropylene fibres was also adopted as reinforcement in specimen preparation. The optimal combinations identified were then subjected to a maximum of three cycles of wetting and drying followed by determination of unconfined compression strength (UCS). The expansive soil required a minimum of 3% lime for its modification. The optimum dosage of steel slag was identified as 5% and optimum copper filament content as 1%. Polypropylene content of 0.3% was also adopted as one combination. The results of the investigation revealed that lime stabilized fibre-reinforced soil with copper filaments was the most durable combination followed by polypropylene fibres. The introduction of steel slag in the mix could not generate enough beneficial durability to the soil after three cycles of wetting and drying.

Keywords: Soil, Lime, Slag, Fibre, Strength, Durability

Resumen

La investigación se ocupó de la estabilización del suelo expansivo con combinaciones de cal, escoria de acero y reforzado con dos tipos de fibras, filamentos de cobre y fibras de polipropileno. La investigación comenzó con la caracterización del suelo por sus propiedades geotécnicas. El consumo inicial de cal requerido para la modificación de las propiedades del suelo se determinó a partir de la prueba de pH Eades y Grim. Se moldearon muestras cilíndricas de suelo con dimensiones de 38 mm x 76 mm utilizando este contenido de cal como estabilizador junto con cantidades variables de escoria de acero para la determinación del contenido óptimo de escoria de acero. El suelo estabilizado con cal pura y las muestras de suelo modificadas con escoria de acero de cal se reforzaron con diferentes proporciones de filamentos de cobre para determinar el contenido óptimo de fibra. También se adoptó una dosis de fibras de polipropileno como refuerzo en la preparación de muestras. Las combinaciones óptimas identificadas se sometieron luego a un máximo de tres ciclos de humectación y secado, seguido de la determinación de la resistencia a la compresión no confinada (UCS). El suelo expansivo requirió un mínimo de 3% de cal para su modificación. La dosis óptima de escoria de acero se identificó como 5% y el contenido óptimo de filamento de cobre como 1%. El contenido de polipropileno del 0.3% también se adoptó como una combinación. Los resultados de la investigación revelaron que el suelo reforzado con fibra estabilizado con cal con filamentos de cobre fue la combinación más duradera seguida por las fibras de polipropileno. La introducción de escoria de acero en la mezcla no pudo generar suficiente durabilidad beneficiosa para el suelo después de tres ciclos de humectación y secado.

Palabras clave: suelo, cal, escoria, fibra, resistencia, durabilidad

1 INTRODUCTION

Expansive soils are known all over the world for their poor volume stability. Construction on such soils results in disastrous effects on the structures built over them. Lime stabilization of expansive soils has been one of the most common solutions to mitigate the dangerous effects of expansive soils. However, there are also regions wherein the subsoil is subjected to extreme conditions. These include wetting-drying, freezing-thawing, high soil acidity and alkalinity, high soil salinity, high sodic soil conditions, sulphate rich soils, and contaminated soils. In such conditions, the effectiveness of the stabilization used slowly reduces over an extended period. This may lead to a reduction in the durability of the stabilized soil. James and Pandian [1] suggest that lime stabilized soils lose their effectiveness in extreme conditions, especially in tropical climatic conditions and in cold regions. In recent times, there have been several investigations by various researchers addressing the durability of the lime stabilized soils [2–7]. Based on these investigations, the researchers reported that the beneficial effect of lime in swell control and improvement of soil properties was partially lost due to multiple cycles of wetting and drying. Literature suggests that there have been investigations using industrial solid wastes as well as a few combinations of lime and industrial solid wastes for soil stabilization [8]. Over the years, few of the researchers have attempted to improve the performance of lime stabilization by combining it with pozzolans to improve its performance under such extreme conditions. A very early study conducted by Hoover et al. [9] attempted to study the performance of fly ash-lime stabilized mixes. Kampala et al. [10] studied the effect of the addition of fly ash on the wet-dry resistance of carbide lime stabilized soil. Sabat and Nanda [11] researched the performance of marble dust modification of rice husk ash stabilized soil subjected cycles of wetting and drying. Yilmaz and Fidan [12] explored the effect of combinations of lime and perlite on the wetting-drying performance of clayey soil. Harichane et al. [13] attempted to study the effect of lime-natural pozzolana on the durability of clayey soils subjected to multiple cycles of wetting and drying. These studies found that the addition of wastes/pozzolans to lime during stabilization resulted in improved performance during wetting and drying cycles. However, despite the early attempt of using waste pozzolans with lime, studies on the utilization of combinations of lime and solid wastes for resistance against cycles of wetting and drying are still very minimal. Other researchers have also investigated the improvement of wetting-drying resistance of soils by the inclusion of fibres. Malekzadeh and Bilsel [14] studied the effect of polypropylene fibres on the mechanical behaviour of expansive soils. They also investigated the effect of polypropylene fibre reinforcement on the swell and compressibility of expansive soils [15]. Phanikumar et al. [16] investigated the effect of wetting and drying cycles on the heave behaviour of fibre reinforced expansive soils. Greeshma and Joseph [17] included rice straw fibres into Kuttanad expansive clay to investigate its performance. Others went one step further by combining lime/cement with fibres to improve its durability performance. Prajisha and Ajitha [18] explored the performance of banana fibre reinforced lime stabilized soil subjected to cycles of wetting and drying. Anggraini et al. considered the reinforcement benefits of nano modified coir fibre in lime treated marine clay. Sukontasukkul and Jamsawang [20] adopted metallic steel fibres for the strengthening of deep soil-cement columns. Fatahi et al. [21] adopted polypropylene and steel fibres to improve the performance of cement stabilized silty clay. Correia et al. [22] investigated the effect of stabilization of soil with a combination of cement, ground granulated blast furnace slag and steel fibres. The addition of fibres to reinforce stabilized soils provided the advantage of micro-reinforcement by the fibres in resisting crack propagation when stabilized specimens were subjected to durability conditions like wetting and drying. Each fibre type has its own advantages and disadvantages. Natural fibres are renewable and environment friendly. But there is always a question over their durability when exposed to water and require treatment to ensure increased performance. Artificial fibres like polypropylene fibres are readily available in huge quantities and durable. But, they are comparatively costly and have issues of floating in water during their mixing with soil. They also require considerable care and effort to ensure a uniform and intimate mix with the soil. Metallic fibres like steel fibres have the issue of corrosion over an extended period of time. They are however, comparatively stronger and stiffer than other fibres. Polypropylene fibres have been the most common type of fibre reinforcement considered by researchers. Other types of artificial fibres like nylon and polyester as well as natural fibres like banana and coir have also been investigated. But, there seems to be very few investigations considering metallic fibres in soil micro-reinforcement. Thus, in summary, it can

be seen that researchers have attempted to improve the durability of lime stabilized soil by addition of industrial wastes/fibres. However, it was found that very few investigations have focussed on the combinations of lime, industrial wastes and fibres for improving the durability performance like the one done by Muntohar and Khasanah [23]. They examined the performance of clayey soil stabilized with lime and rice husk ash reinforced with polypropylene waste fibres subjected to cycles of wetting and drying. There still exists a great potential for identification of optimal combinations of lime, wastes and fibres. This investigation attempted to address this gap in literature by considering a combination of lime, steel slag and copper filaments as well as polypropylene fibres in the stabilization and durability performance of an expansive soil subjected to alternate cycles of wetting and drying.

2 MATERIALS USED

The various materials used in the present investigation were the virgin expansive soil, high-quality industrial-grade lime, steel slag, copper filaments and polypropylene fibres. Lime was used as the primary binder, whereas steel slag was used as an auxiliary additive. The copper filaments and polypropylene fibres were used as random micro reinforcement.

The virgin expansive soil adopted in this investigation was collected from the banks of Thaiyur lake, near Kalavakkam, Tamil Nadu, India. The soil sample was prepared following the Bureau of Indian Standards (BIS) code [24]. The soil sample was subjected to various geotechnical tests in the laboratory according to the various codes of BIS. The properties of soil are tabulated in Table I. High-quality industrial-grade hydrated lime was sourced from M/s. Shiyal Chemicals, Chennai. No specific preparation methods were adopted for lime, which was used as supplied in the commercial packets. Steel slag is a by-product resulting from the manufacturing process of steel. It is obtained during the separation of molten steel from the impurities in the furnace in a liquid state. It is a complex solution of silicates and oxides, which solidifies into steel slag on cooling. Steel slag was obtained from Jindal Steel Works, Salem. Its specific gravity was found to be 2.67. The steel slag was prepared by crushing and sieving it through 75-micron sieve. The finer fraction which passed through the 75-micron sieve was used in the investigation. Fig. 1 shows the various materials after preparation.

TABLE I PROPERTIES OF VIRGIN SOIL

Property	Value	Property	Value
Liquid Limit	70.0%	Maximum Dry Density (MDD)	13.4 kN/m ³
Plastic Limit	22.8%	Optimum Moisture Content (OMC)	28.4%
Plasticity Index	47.2%	Unconfined Compression Strength (UCS)	103.1 kPa
Shrinkage Limit	9.0%	Free Swell Index	120%
Specific Gravity	2.68	Classification	CH

FIG. 1 PREPARED VIRGIN EXPANSIVE SOIL AND STEEL SLAG



Copper filaments were adopted as fibre reinforcement as a replacement for steel fibres adopted by certain investigators in soil stabilization. Copper was bought as wires from a motor winding shop. It had a diameter of 0.14mm. It was cut into filaments of 10mm length based on which the aspect ratio was approximately 77. Polypropylene fibres were used in the investigation to obtain a comparative performance evaluation for copper filament reinforced soil. The polypropylene fibres were purchased from a commercial retailer in Chennai. It had a length of 12mm and a diameter of 0.025mm, based on which its aspect ratio came out to be 480.

3 METHODS

The experimental methodology followed in this investigation consisted of the following stages: Collection and preparation of materials, characterization of materials, determination of initial consumption of lime (ICL), identification of optimum steel slag content, identification of optimum fibre content, preparation of specimens, simulation of wetting and drying and specimen testing. Each of the stages has been described in detail in the following subsections.

3.1 Collection and Preparation of Materials

The soil sample was collected from the source and transported to the laboratory. In the laboratory, it was crushed and pulverized into smaller fractions using a hand rammer. It was then sieved through various sieves as per requirement for various tests done following the codes of BIS. The lime was used as supplied by the manufacturer. Steel slag was crushed and sieved through 75-micron sieve and the fine powder passing through the sieve was used in the study. Copper filaments were cut to an aspect ratio of 77 from long wires. Polypropylene fibres were used as supplied by the retailer.

3.2 Characterization of Materials

The soil obtained for the investigation was subjected to various geotechnical properties as per different codes of BIS. The various properties evaluated include liquid and plastic limit [25], shrinkage limit [26], specific gravity [27], grain size distribution [28], compaction [29], unconfined compression strength (UCS) [30] and free swell index [31]. The soil was then classified based on the guidelines of BIS code [32]. Steel slag was subjected to a specific gravity test following the same procedure that was adopted for soil.

3.3 Determination of Initial Consumption of Lime

Based on the existing literature, for the soil under investigation, the ICL value was determined from the Eades and Grim pH test [33] based on the ASTM code D6276 [34].

3.4 Identification of Optimum Steel Slag Content

To determine the optimum steel slag content of the given soil sample, UCS tests were performed on the soil samples stabilized with lime (ICL). All UCS samples for determination of optimum steel slag content were compacted to MDD and OMC of the stabilized soil obtained from mini compaction tests [29] done based on the BIS code [35] procedure for stabilized soil. A calculated quantity of dry soil was weighed out. To this, minimum lime content and one trial content of steel slag by weight of dry soil was added in dry condition and manually mixed to achieve a uniform dry mix. The quantities of lime, steel slag and soil were calculated such that the final weight of the dry mix was equal to the weight required for achieving the dry density of the UCS sample, which in the present case was fixed as the MDD of the lime stabilized soil. To this uniform dry mix, water content equal to the OMC of the stabilized soil was sprinkled in stages, combined with manual mixing until a uniform wet mix was achieved. This mix was packed into the constant volume split mould of internal diameter, 38 mm and height, 76 mm, and compacted by static loading. After the samples were cast, they were immediately de-moulded and air-cured in sealed polythene covers to prevent loss of moisture. Three specimens were cast for each combination of steel slag adopted for stabilization. The steel slag content was varied from 5% to 20% in increments of 5% by weight of dry soil for determining the optimum content. The samples were cured for 3 days before they were tested. James and Pandian [36] had adopted a curing period of 2 days for identifying the optimum lime content in their investigation. The combination that gave the maximum strength/minimum loss in strength was adopted as the optimum content.

3.5 Identification of Optimum Fibres Content

The optimum fibre content was also determined using the same procedure as adopted for the determination of optimum steel slag content. The soil specimens of 38 mm diameter and 76 mm height were prepared by mixing the minimum lime content and optimum steel slag content. In this mix, the fibre content was varied from 0.5% to 2% in increments of 0.5%. Three samples were prepared for each combination and cured for 3 days. The combination that produced the maximum strength/minimum loss in strength was considered as the optimum fibre

content. Polypropylene fibres being one of the most commonly adopted fibres, its optimum fibre content was adopted from the literature [37], for comparison with the performance of copper filaments.

3.6 Preparation of Test Specimens

The UCS samples were prepared in a constant volume split mould of dimensions 38 mm x 76 mm, de-moulded immediately and placed inside a sealable polythene cover for curing. Three samples were prepared for testing each of the combinations. Figure 2 shows the preparation and testing of a UCS sample. Calculated quantities of soil, lime, steel slag and filaments/fibres were packed in sealed polythene covers for sample preparation. A steel UCS split mould of height 76 mm and internal diameter 38 mm was prepared by lubricating its interior with oil. The materials were emptied on to a mixing pan and mixed in dry state manually. The required quantity of water was sprinkled on to it and mixed thoroughly to obtain a uniform wet mix. The mixture was then packed into a steel UCS mould in layers with gentle compaction provided by a compaction plug. This was repeated until the entire wet mix was packed into the split mould. The mould was then plugged at both ends using the end plugs. It was loaded on to a universal sample compacter cum extruder and compacted by applying static pressure. Care was taken to introduce the layers of wet mix alternatively from either end of the split mould and compacted from the corresponding end to ensure uniform compaction of the prepared UCS sample [38]. The sample was then ejected after opening the split mould and applying gentle pressure using the compaction plug. The samples were cured at room temperature of 30°C +/- 2°C in sealed polythene covers for 14 days. Fig. 2 shows the preparation of samples for the investigation.

FIG. 2 PREPARATION OF SPECIMENS



3.7 Simulation of Wetting and Drying

The samples were subjected to alternate cycles of wetting and drying by simulating the conditions of wetting and drying. A wet-dry cycle consisted of two phases: A 24 hours wetting phase wherein the samples were covered by soaking wet cotton and a 24 hours drying phase at open-air room conditions. All specimens were subjected to 1, 2 and 3 cycles of wetting and drying after they were cured for 14 days. Various researchers have adopted a different number of cycles for their work. Phanikumar et al. [16] adopted three cycles of wetting and drying whereas Muntohar and Khasanah [23] adopted four cycles. Anggraini et al. [19] adopted five

cycles of wetting and drying. Yilmaz and Fidan [12] had adopted 12 cycles of wetting and drying in their investigation.

3.8 Specimen Testing

After the end of the set period of curing and cycles of wetting and drying, the samples were loaded axially until failure in UCS loading frame of 50kN capacity. The rate of strain adopted for the test was 0.625 mm/min. The various shortlisted combinations that were evaluated for the wetting and drying resistance performance is shown in Table II.

TABLE II STABILIZER AND FIBRE CONTENT COMBINATIONS FOR WET-DRY TESTS

Lime (%)	Steel Slag (%)	Copper Filament (%)	Polypropylene Fibres (%)	Designation
3	0	0	0	S3L
3	0	1	0	S3L1CF
3	0	0	0.3	S3L0.3PF
3	5	1	0	S3L5SS1CF
3	5	0	0.3	S3L5SS0.3PF

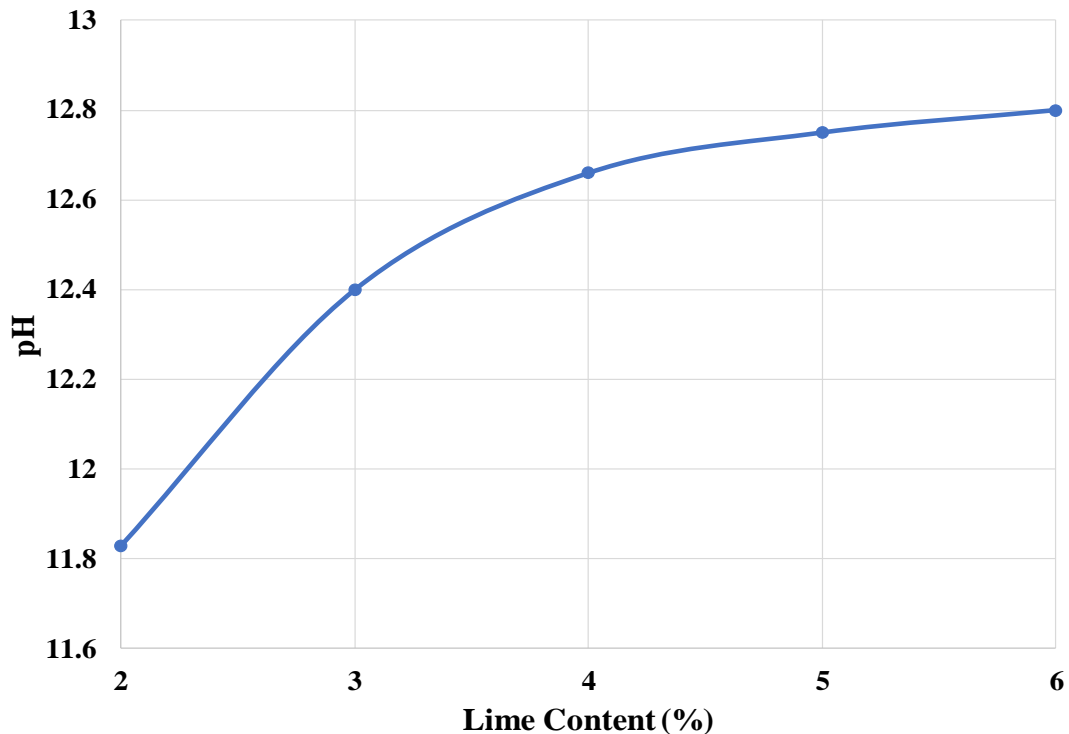
4 Results and Discussion

An expansive soil was stabilized using a combination of lime, steel slag and fibres for improving its strength. It was then subjected to different cycles of wetting and drying to study its durability performance. The results of the investigation are discussed in the following subsections.

4.1 Optimization of Lime, Steel Slag and Fibre Content

The ICL is the minimum lime content required to raise the pH to 12.4. In highly alkaline conditions, the soil silica and alumina dissolve and react with the calcium from lime forming stabilization reaction products. Thus, high pH value is essential for stabilization reactions to proceed. The ICL was determined using the Eades and Grim pH test [33] based on ASTM D6276 [34]. The ICL for the soil under investigation was found to be 3% as shown in Fig. 3.

FIG. 3 DETERMINATION OF INITIAL CONSUMPTION OF LIME



The optimization of steel slag and copper filaments contents was also done by conducting UCS tests. Figs. 4 and 5 show the results of the UCS tests for determination of optimal content of steel slag and copper filaments. It can be seen that increase in steel slag content results in a reduction of the strength of the specimens. Therefore, the steel slag content with the minimum loss in strength was considered to be the optimal dosage. The incorporation of steel slag in the stabilization process is for the utilization of solid waste for effective waste management.

FIG. 4 DETERMINATION OF OPTIMUM STEEL SLAG CONTENT

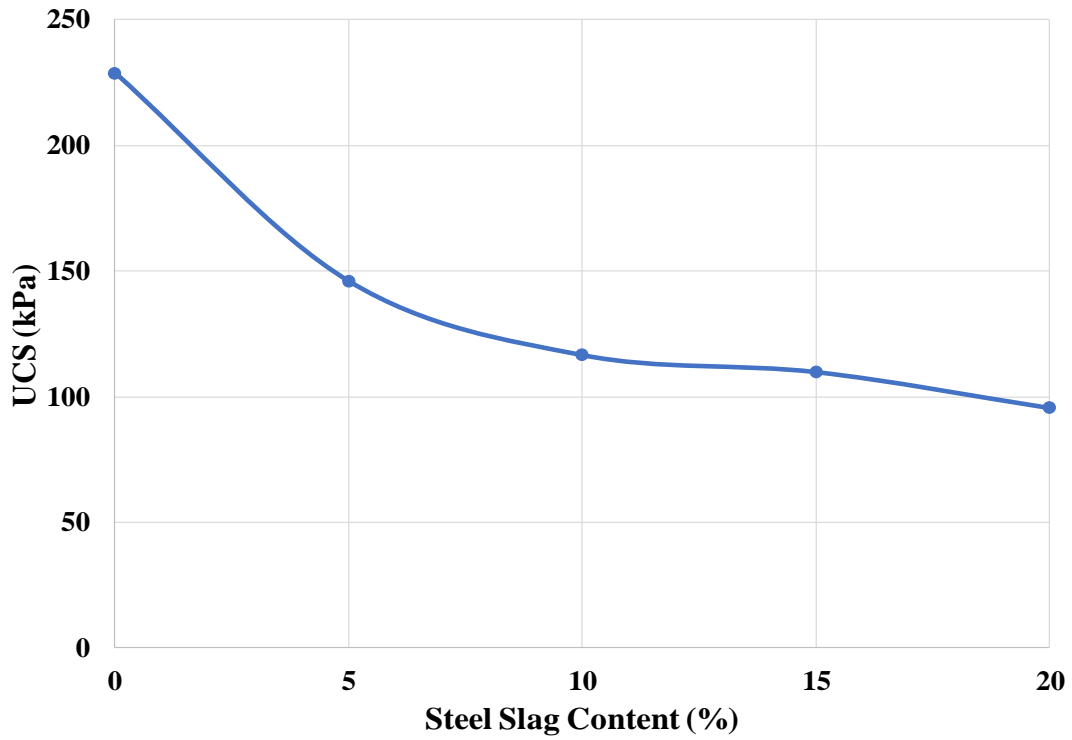
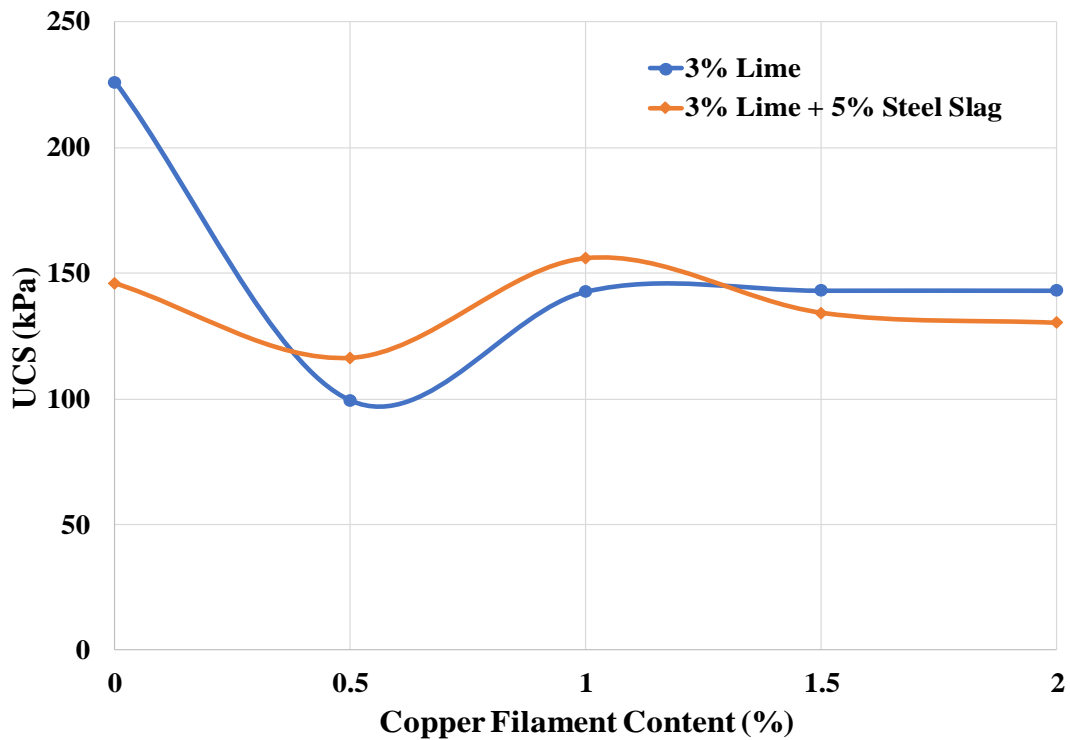


FIG. 5 DETERMINATION OF OPTIMUM COPPER FILAMENT CONTENT



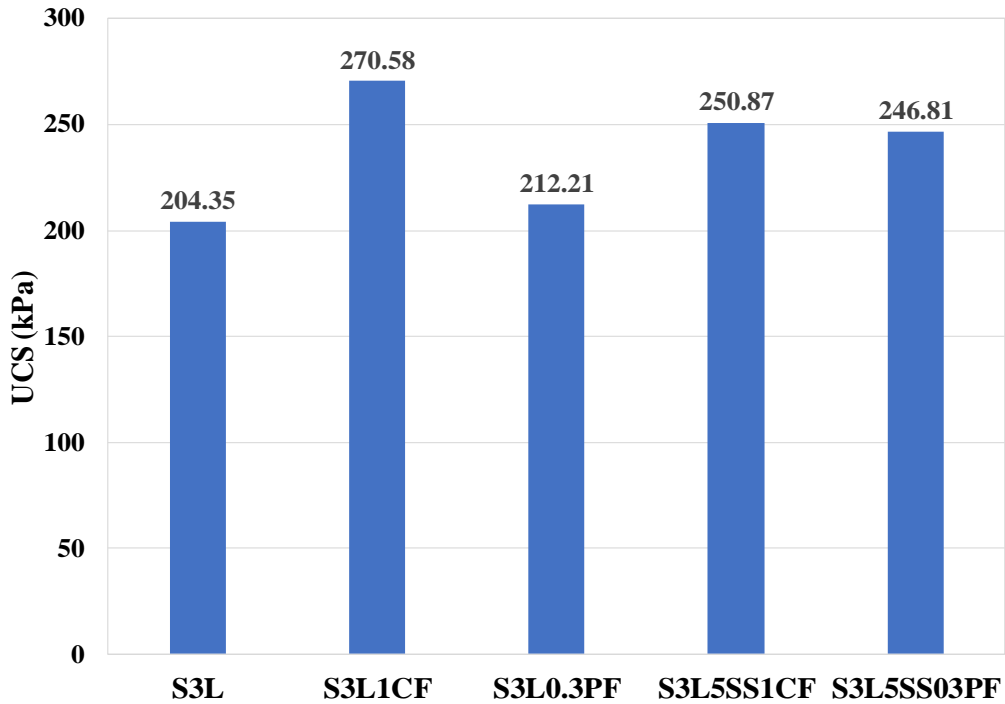
The optimization of copper filament content for fibre reinforcement of the specimens was performed using a similar procedure. The soil stabilized with 3% lime was amended with copper filaments starting from 0.5 % in increments of 0.5 % up to 2 %. Fig. 5 shows the variation in the strength of the specimens amended with different proportions of copper filaments by the weight of the soil. From the graph, it can be seen that there is an initial reduction in strength of the stabilized specimen reinforced with 0.5 % copper filaments. Further increase in the filament content to 1% leads to a rise in strength of the specimen. However, no further variations in the strengths were noticed for higher contents of copper filaments. Hence, it was concluded that a minimum of 1% copper filaments was the optimal dosage that resulted in the least loss in strength. Fig. 5 also shows the optimal copper filament content for 3% lime and 5% steel slag stabilized soil. It can be seen that the optimal copper filament content for steel slag amended lime stabilized soil was also 1%. Thus, irrespective of the steel slag amendment, the optimum copper filament content for reinforcing the soil came out to be 1%. Fatahi et al. [21] identified 10% of steel fibre content developed the maximum strength for cement-treated silty clay soil. Sukontasukkul and Jamsawang [20] found that 1% of steel fibres resulted in the maximum flexural strength of fibre reinforced deep soil-cement column. This was irrespective of long or short fibre steel adopted in the study. The optimal dosage of polypropylene fibres (0.3%) was adopted from the work done by Jiang et al. [37], who had done extensive work on optimizing the fibre content based on aspect ratio and dosage. Muntohar and Khasanah [23] had adopted a similar polypropylene waste fibre content of 0.4%.

4.2 Effect of Stabilization and Reinforcement on the Strength

Fig. 6 shows the effect of the amendment of 3% lime with the various optimal doses of additives, viz. 5% steel slag, 1% CF and 0.3% polypropylene fibres in different combinations. It can be seen that all the optimal amendments have resulted only in a positive gain in strength due to the modification. The polypropylene fibre modification developed the least gain in strength when compared to all combinations. On the other hand, the samples reinforced with copper filaments produced the maximum gain in strength under normal conditions. The result was in contrast to the results obtained by Fatahi et al. [21] and Sukontasukkul and Jamsawang [20]. Both the studies reported polypropylene fibres developing better strength when compared to metallic steel fibres. This may be because the polypropylene fibre dosage for the soil under investigation was not identified but rather chosen from literature for comparison. Introduction of steel slag resulted in a slight reduction in strength in the case of copper filament reinforcement

whereas it resulted in an increase in strength in the case of polypropylene reinforced lime stabilized soil. Thus, different reinforcement materials produce different degrees of improvement and modification of lime stabilization. The same can also be said for steel slag amendment of lime stabilization.

FIG. 6 EFFECT OF OPTIMAL AMENDMENTS ON LIME STABILIZATION



4.3 Effect of Wetting and Drying on the Strength of Stabilized Soil

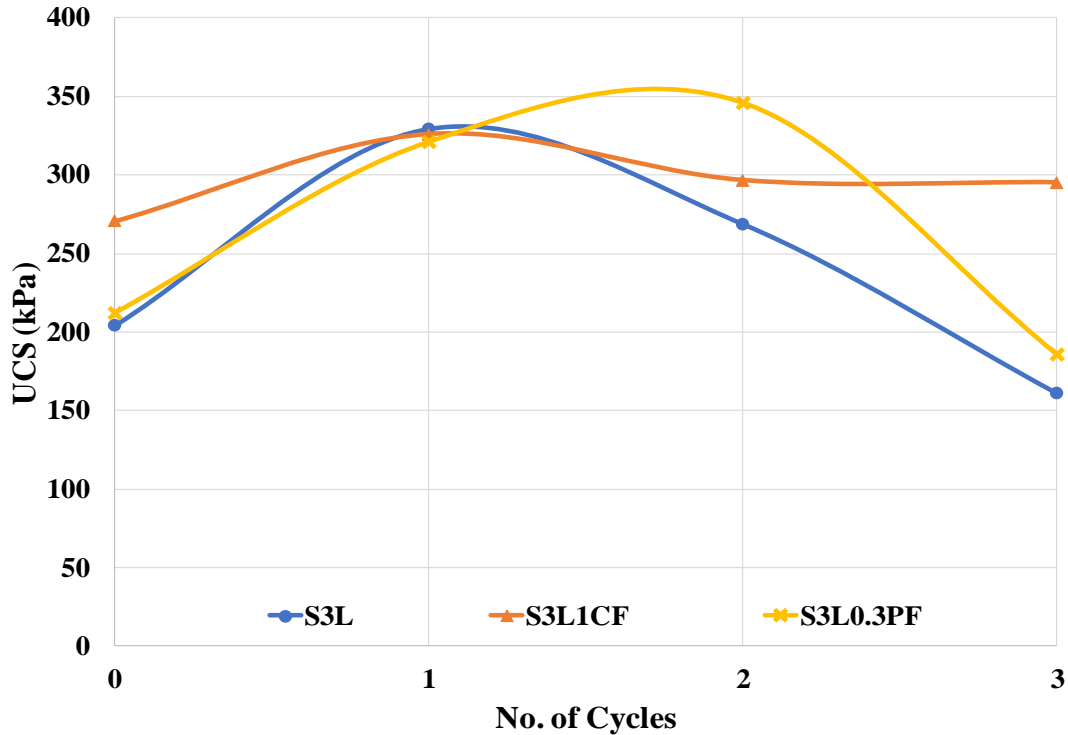
The effect of wetting and drying cycles on the compressive strength of the various specimen combinations were studied by conducting UCS tests on the samples after subjecting them to multiple cycles of wetting and drying.

4.3.1 Effect of Fibres on Durability of Lime Stabilized Soil

Fig. 7 shows the effect of fibre reinforcement on the wetting and drying resistance of pure lime stabilized soil. For comparison of performance, the wetting and drying resistance of pure lime stabilized soil without fibre reinforcement (control) has also been shown in the figure. The strength of the lime stabilized soil increases from 204.35 kPa to 329.31 kPa after the first cycle of wetting and drying. The increase in strength of the stabilized soil after the first cycle of wetting and drying may be indicative of a deficiency in water content during the moulding process. This deficiency may have been fulfilled during the first immersion cycle leading to an increase in the strength. The lime stabilized soil loses strength on a further increase in the number of wetting and drying cycles. The strength of the stabilized soil decreases to 161.15 kPa for three cycles of wetting and drying. Anggraini et al. [19] also reported a reduction in the strength of lime treated marine clay with an increase in cycles of wetting and drying. In the case of copper filament reinforced lime stabilized soil as well, there is an increase in the strength of the stabilized soil after the first cycle of wetting and drying. Again, this may be indicative of a deficiency in water content, fulfilled by the wetting stage of the cycle resulting in improved strength. The strength of the copper filament reinforced lime stabilized soil increases from 270.58 kPa to 325.82 kPa after the first cycle of wetting and drying. On the subsequent increase in the number of cycles, there is a reduction in the strength of the specimens. However, even after three cycles of wetting and drying, the strength of the specimens has not lowered below that of the control specimens. The reduction in strength seems to have stabilized after the second cycle with no big difference in the strength of the specimens subjected to two and three cycles of wetting and drying. In general, it can be seen that the strength of the specimens

subjected to cycles of wetting and drying is higher than the control specimens. This indicates a better resistance to wetting and drying due to the reinforcement of the specimens with copper filaments.

FIG. 7 EFFECT OF WETTING AND DRYING CYCLES ON FIBRE REINFORCED LIME STABILIZED SOIL



From Fig. 7, it is clear that the trends of polypropylene reinforced lime stabilized soil are similar to that of pure lime stabilized soil. The major difference is an increase in strength up to two cycles of wetting and drying beyond which there is a reduction in strength of the specimens. Muntohar and Khasanah [23] reported an increase in the strength of the specimens stabilized with a combination of lime-rice husk ash-polypropylene fibres up to three cycles of wetting drying. Anggraini et al. [19] reported an increase in the strength of coir fibre reinforced lime treated marine clay up to five cycles of wetting and drying. Muntohar and Khasanah [23] also report that samples prepared with moisture content lesser than optimum (dry side of optimum) have a higher strength development. In the present study as well, polypropylene fibre reinforced lime-steel slag stabilized soil specimens had an increase in the strength for more than one cycle of wetting and drying. The presence of the fibres may have resulted in improved hydration of the soil specimens while resisting the spread of cracking. Anggraini et al. [19] state that the presence of the fibres increased the number of wetting cycles by which sufficient moisture for hydration was supplied, resulting in improved strength of the specimens. Muntohar and Khasanah [23] attribute the increase in strength with wetting and drying cycles to two reasons. First, the increase in the duration of chemical reactions during wetting and drying cycles and second, the increase in the quantum of cementitious compounds during wetting and drying cycles.

4.3.2 Effect of Fibres and Steel Slag on Durability of Lime Stabilized Soil

The effect of fibre reinforcement was also studied on lime stabilized soil modified with optimal steel slag content. The procedure adopted was the same as for fibre reinforced pure lime stabilized soil. Fig. 8 shows the effect of wetting and drying cycles on lime-steel slag stabilized soil. The inclusion of steel slag in the stabilization process results in a slight modification in the response of the stabilized specimens subjected to wetting and drying cycles. It can be seen that the lime-steel slag stabilized specimens modified with 1% copper filaments result in better resistance to wetting and drying up to two cycles. Further increase in the cycles

results in a drastic reduction in strength of the stabilized specimen. Thus, the inclusion of steel slag in the stabilization process results in strength benefits only up to two cycles of wetting and drying.

FIG. 8 EFFECT OF WETTING AND DRYING CYCLES ON FIBRE REINFORCED LIME STABILIZED SOIL AMENDED WITH STEEL SLAG

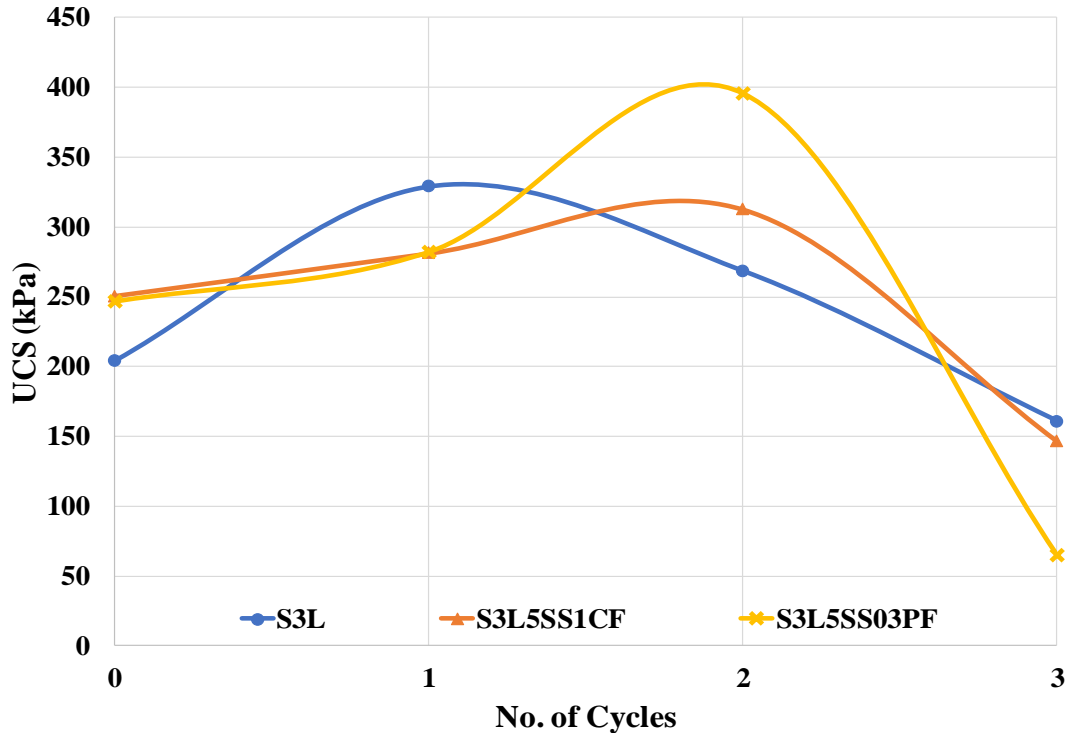


Fig. 8 also shows the effect of wetting and drying on the 0.3% polypropylene reinforced lime-steel slag stabilized soil. The inclusion of steel slag in the stabilization process results in a similar trend as for copper filament reinforced lime-steel slag stabilized soil. There is a significant benefit in the resistance to wetting and drying cycles until two cycles. Beyond two cycles, there is a drastic reduction in the strength of the stabilized soil. Thus, in both the cases of copper filaments and polypropylene fibres, the beneficial effect of steel slag was obtained only up to two cycles of wetting and drying. The introduction of steel slag as a pozzolan in the mix could not extend the resistance to a higher number of wetting and drying cycles. Hasan et al. [39] found that the introduction of bagasse ash in lime stabilization resulted in the stabilized composite becoming more durable when subjected to ten cycles of wetting and drying. A similar objective attempted with steel slag in the present investigation could not be achieved.

4.3.3 A Comparative Discussion

To understand the extent of strength development of fibre reinforced lime stabilized soil subjected to alternate cycles of wetting and drying, a comparison with similar studies was attempted. Two studies were identified for comparison with the present study viz. the work done by Angraini et al. [19] and Muntohar and Khasanah [23]. These two were selected because the former adopted a combination of lime and fibres and the latter adopted a combination of lime, waste and fibres. However, there are inherent limitations of such a comparison. At the outset, the obvious differences in the type of soil, type of binder/stabilizer and its content, type of auxiliary additive and its content and lastly, the type of fibre and its contents do not allow a direct one to one comparison. Therefore, this comparison is a superficial one. Secondly, both the studies subjected these combinations to multiple cycles of wetting and drying. But, the comparison was limited to only 3 cycles of wetting and drying adopted in the present study. Lastly, other studies with a combination of lime and metallic fibres subjected to wetting and drying could not be found and hence, were not included. Table III gives a brief overview of the combinations used in the investigations. The combinations shown in the table have been

modified according to the same naming convention used in the present study. Only the optimal dosage combinations from the present study have been shown in Table III.

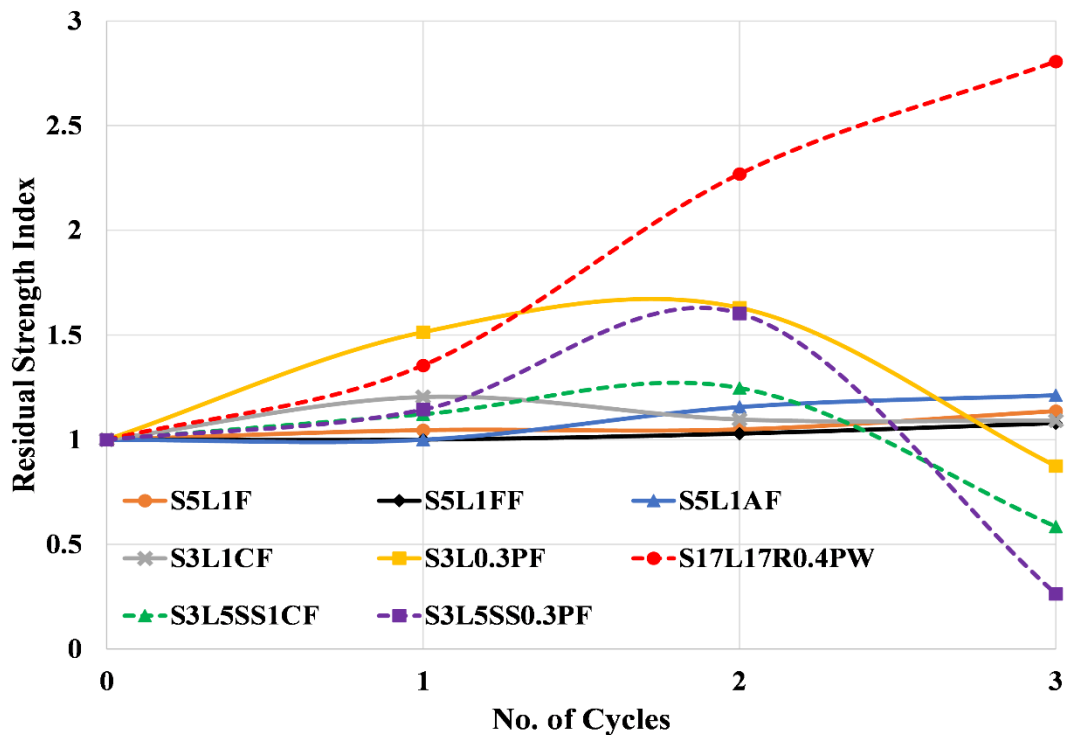
TABLE III OVERVIEW OF STABILIZER AND FIBRE COMBINATIONS OF THE TWO INVESTIGATIONS

Detail	Anggraini et al. [19]	Muntohar and Khasanah [23]	Present Study
Stabilizer Type	Lime	Lime	Lime
Stabilizer Content	5%	17%	3%
Fibre Type	Coir Fibre	Polypropylene Waste Fibre	Copper Filaments Polypropylene Fibres
Fibre Content	1%	0.4%	1% (CF); 0.3% (PF)
Auxiliary Additive	-	Rice Husk Ash	Steel Slag
Auxiliary Additive Content	-	17%	5%
Combinations	S5L1F* S5L1FF* S5L1AF*	S17L17RHA0.4PW	S3L1CF S3L0.3PF S3L5SS1CF S35SS0.3PF

F – Natural coir fibre, AF – Al(OH)₃ modified coir fibre, FF – Fe(OH)₃ modified coir fibre

Figure 9 shows a graph between the residual strength index (RSI) and no. of cycles. RSI may be defined as the ratio of the UCS of the samples subjected to wetting and drying cycles to that of the control samples (no wetting and drying) [40]. The same was also adopted by Anggraini et al. [19] as well as Muntohar and Khasanah [23]. Figure 9 represents the data under two categories. The curves for fibre reinforced lime stabilized soil is represented by solid lines and the curves for fibre reinforced, waste amended lime stabilized soil is represented by dotted lines. At the outset, it can be seen that RSI curves of Anggraini et al. [19] are different from that of the present study. S5L1F and S5L1FF are very similar to each other in terms of wet-dry resistance represented by the RSI curves. S5L1AF differentiates itself after the first cycle of wetting and drying and shows improved resistance compared to the other two. S3L1CF of the present study is different from them in the fact that it shows very good wet-dry resistance for the first cycle but that resistance reduces thereafter. But all these combinations lie within the RSI range of 1 to 1.2. The combination S3L0.3PF of the present study, however, shows a vastly different wet-dry resistance as seen from its RSI curve. Its RSI goes as high as 1.63 at cycle two and then drastically drops to 0.87. Comparing the work of Muntohar and Khasanah [23] and the present study, there is a vast difference between their corresponding RSI curves. The wet-dry resistance of the former shows a steady improvement with the number of cycles (considered up to three), with RSI value up to 2.81. In comparison, both the combinations in the present study show improved wet-dry resistance only up to two cycles of wetting and drying. This may be due to a significantly high lime content adopted by Muntohar and Khasanah [23], in their investigation compared to the present study. Secondly, the difference in auxiliary additives and their contents in both investigations could have also played a significant role.

FIG. 9 COMPARISON OF PRESENT STUDY WITH PREVIOUS INVESTIGATIONS



4.3.4 Percentage Strength Change Analysis

To better understand the effect of wetting and drying on the strength of the stabilized soil samples, a percentage strength change analysis was performed. This analysis was performed from two perspectives. The first perspective was the change in strength with the number of cycles of wetting and drying. The second perspective was the strength change from that of pure lime stabilized soil for corresponding cycles of wetting and drying. Fig. 10 shows the strength change with the number of cycles of wetting and drying. It can be seen that all the combinations, gain strength after the first cycle of wetting and drying when compared to the control specimens. However, the combinations S3L and S3L0.3PF gave the maximum strength gain of 61% and 51% respectively. For the second cycle as well all the combinations produced positive strength gain. But, the combinations of polypropylene reinforced stabilized soil (S3L0.3PF and S3L5SS0.3PF) produced the maximum strength gain of 63% and 60% respectively. After three cycles of wetting and drying, all the combinations resulted in a loss in strength barring the combination reinforced with copper filaments (S3L1CF). It still had a strength of around 9% higher than the control specimens, though marginally lesser than the 9.7% gain achieved after the second cycle of wetting and drying. Thus, it can be seen that copper filament reinforced lime stabilized soil (S3L1CF) was the most durable of all the stabilized soil combinations. Fig. 11 shows the percentage strength change from pure lime stabilized soil for corresponding cycles of wetting and drying.

FIG. 10 PERCENTAGE STRENGTH CHANGE WITH NO. OF CYCLES OF WETTING AND DRYING

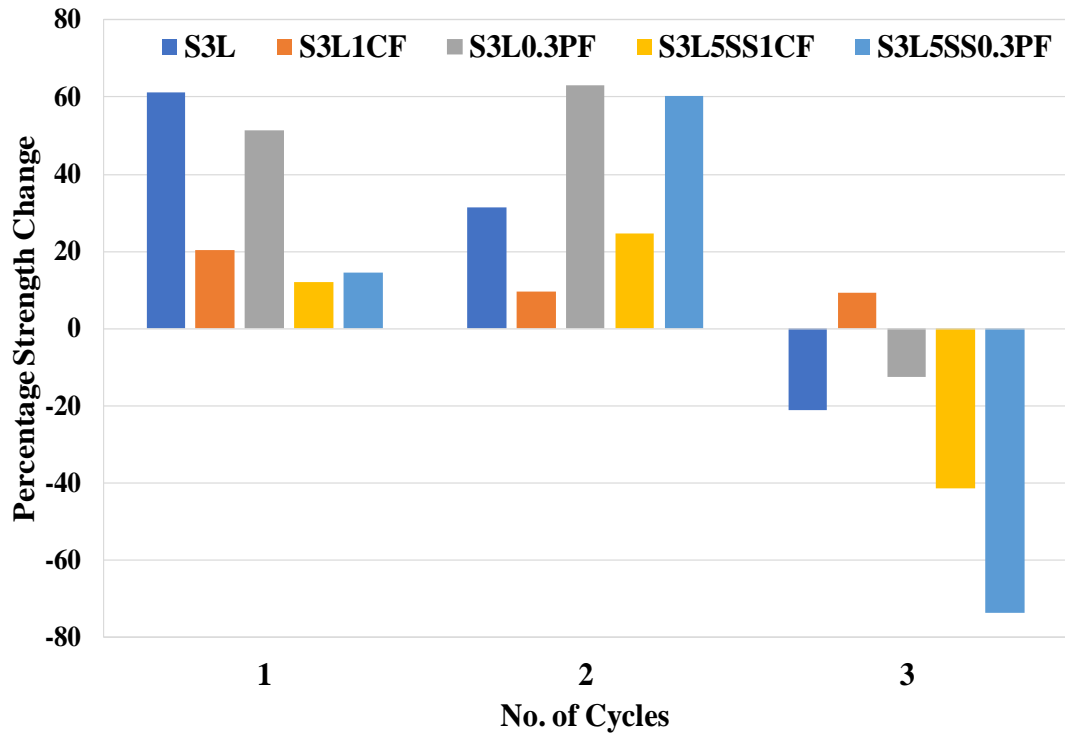
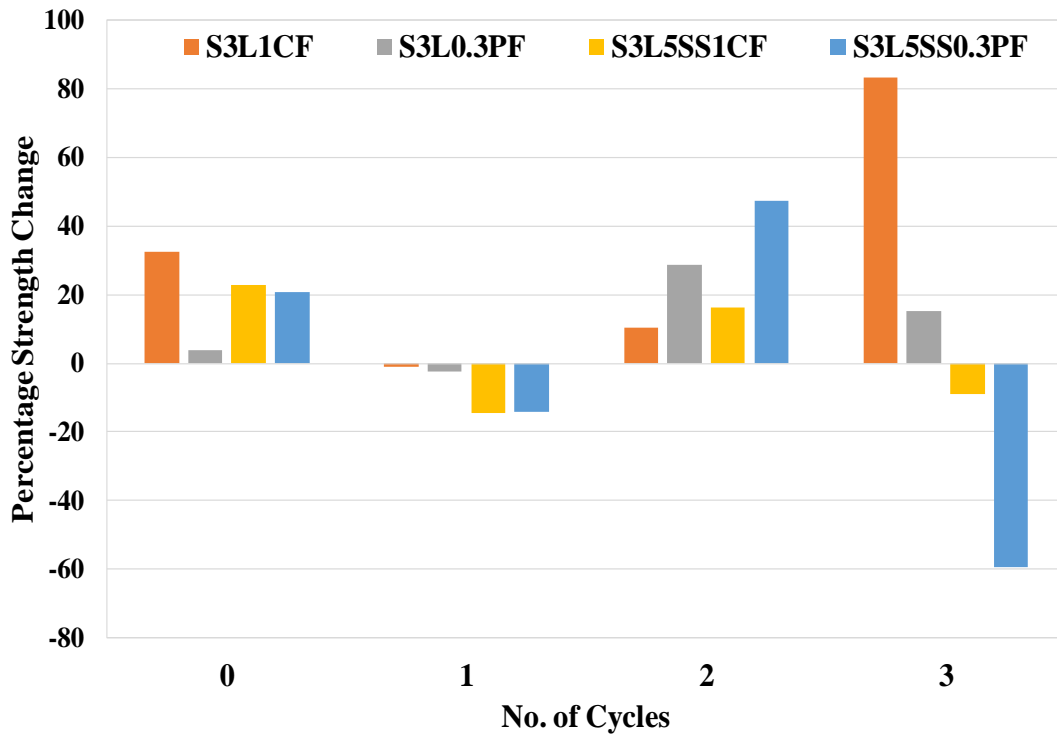


FIG. 11 PERCENTAGE STRENGTH CHANGE FROM THAT OF PURE LIME STABILIZED SOIL



It can be seen from the figure that all the combinations have given positive strength benefits when compared to the pure lime stabilized soil, when not subjected to wetting and drying cycles (0 Cycle). After the first cycle of wetting and drying, pure lime stabilized soil was better than all the combinations as there was a strength loss when compared to lime stabilized soil. But, copper filament (S3L1CF) and polypropylene fibre (S3L0.3PF) reinforced lime stabilized soil specimens were more durable compared to the steel slag amended combinations. Their loss in strengths were around 1% and 2.5% respectively. After two cycles of wetting and drying, all the combinations were better than pure lime stabilized soil. However, in this case, the polypropylene fibre reinforced combinations (S3L0.3PF and S3L5SS0.3PF) were better than pure lime stabilized soil (by 29% and 47% respectively). After three cycles of wetting and drying, it is evident that the steel slag amendment did not perform as expected, losing strength. But, on the other hand, the fibre reinforcement of lime stabilized soil resulted in good resistance to wetting-drying. The copper filament reinforced specimen (S3L1CF) and polypropylene fibre reinforced specimen (S3L0.3PF) performed 83% and 15% better than the pure lime stabilized combination (S3L), respectively. Thus, fibre reinforced lime stabilized soil performed better than fibre reinforced lime-steel slag stabilized soil, under conditions of wetting and drying. The choice of including steel slag in the stabilization can be decided based on the extent of wet-dry cycles and the location of stabilization. However, extensive studies with a greater number of wet-dry cycles need to be conducted before an effective combination can be suggested for such field conditions.

5 Conclusion

The investigation involved studying the resistance of various combinations of lime, fibres and steel slag stabilized soil to alternate wet-dry cycles. Steel slag was adopted as the auxiliary additive whereas copper filaments and polypropylene fibres were used as reinforcement. The UCS of the specimens exposed to 1, 2 and 3 cycles of wetting and drying was evaluated to study the resistance to the loss in strength against control specimens. Based on the experimental investigations carried out on various combinations of lime, steel slag and fibres, the following points can be concluded.

- i. The soil under investigation was found to be an expansive soil, classified as high plastic clay. This soil required a minimum of 3% of lime for modification of its properties. The optimal steel slag content was found to be 5%. The optimal dosage of copper filaments required for maximum strength gain/minimum strength loss was found to be 1%. This 1% filament content was found to be the optimal dosage irrespective of whether the soil was stabilized using lime or combinations of lime and steel slag.
- ii. All combinations of additives and fibres identified to be optimal dosages resulted in UCS higher than pure lime stabilized soil. This indicates that the introduction of steel slag as an auxiliary additive in combination with fibre reinforcement improves lime stabilization. Thus, steel slag can be effectively used in soil stabilization applications, but definitely along with fibre reinforcement.
- iii. Irrespective of combinations, all specimens investigated increased in strength after wetting and drying, which may be indicative of a water deficiency in the specimens. It can be suggested that for soils subjected to wetting and drying cycles, stabilization on the dry of optimum water content can prove to be beneficial. However, more detailed investigations need to be conducted to confirm the veracity of the inference.
- iv. Introduction of auxiliary additive and fibre reinforcement resulted in improved resistance to the loss in strength when compared to pure lime stabilized soil, irrespective of the combination of additive and fibre adopted. However, the beneficial effect of the additive could be seen only till two cycles of wetting and drying. The fibre reinforcement of lime stabilized soil resulted in good resistance to wetting and drying cycles even up to three cycles. Thus, the choice of introducing an auxiliary additive like steel slag can be decided based upon the expected severity of the cyclic conditions of wetting and drying.
- v. Based on the investigation, it can finally be concluded that copper filament reinforcement of lime stabilized soil was found to be more effective in resisting wetting and drying cycles.

This can open up an avenue for potential reuse of waste copper filaments from old wiring as soil reinforcement. To conclude, waste copper filaments can be effectively used in soil stabilization activities, especially under conditions of wetting and drying.

Future investigations are needed with a higher number of wetting and drying cycles for identifying an effective and durable combination of stabilizers and fibres for resisting extreme field conditions.

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