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Review Article

Fibre-Reinforced Soil Mixed Lime/Cement Additives: A Review

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ABSTRACT

Soil modification is a technique for improving poor soil properties to make them suitable for engineering projects. Regarding the previous studies, various types of stabilisations were used to improve mechanical properties in soil. Several methodologies and experimental tests were used to study the positive and negative effects of utilising fibre on lime/cement-modified soil. This paper reviews the strength behaviour and microstructural properties of Fibre-Reinforced Lime Stabilised (FRLS) soil and Fibre-Reinforced Cement Stabilised (FRCS) Soil. First, the impact of FRLS/FRCS soil on strength behaviour under freeze-thaw conditions, the California Bearing Ratio (CBR) value, and compression/tensile strength are all examined. Then synthetic and natural fibres are compared at the microstructure level. FRCS/FRLS soil has been studied for its influence on geotechnical characteristics such as peak strength, residual strength, ductility, bearing capacity, stiffness, and settlement values. In addition, the micro-level evidence demonstrates that lime/cement affects the interlocking between soil particles and fibre. Although lime/cement improves soil strength by making it solid and compact, it makes stabilised soil brittle. Fibre as reinforcement in lime/cement stabilised soil transforms the brittleness of the soil into ductility. Hence building various infrastructures on poor soils is possible if fibre with lime/cement is used as an improvement method. Here, these three most used soil additive materials are investigated in terms of strength, microstructural, mineralisation, and some open issues are suggested for further research.

Keywords: Brittleness, cement, fibre, lime, microstructure, reinforced, stabilized, strength behaviour

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INTRODUCTION

Soil stabilisation and soil reinforcement improve weak soils' shear strength, plasticity, durability, permeability, and density. Generally, soil stabilisation increases the elastic modulus of soil used to construct infrastructure. To improve stability, understanding the properties of the soil and choosing the appropriate modification form is essential. In addition, Atterberg limits, soil mineralogy and composition, required engineering characteristics, stabilisation mechanism, environmental concerns, and budget constraints should be addressed when selecting an additive type (Little & Nair, 2009).

Fibre-reinforced soils have become more popular recently due to their superior strength and ductility compared to parent soils. It improves railway substructure and slope stability (Roshan et al., 2022) while reducing pavement thickness (Valipour et al., 2021). Compared to geosynthetic layers in the soil, using fibre as reinforcement has numerous advantages, for example, fewer catastrophic failures, more utility in complex geometries and constrained places, less chance of weak planes forming, higher ductility and deformability, and more inexpensive pricing than geosynthetics (Han, 2015). Fibres used as reinforcement in soils are categorised into synthetic (polypropylene, polyethene, glass, polyester, steel, and carbon) and natural (palm, coir, sisal, jute, wheat, and bagasse). Although natural fibres are cheaper and more tolerant than synthetic fibres, synthetic fibres are more resilient and durable when exposed to environmental changes (Hejazi et al., 2012).

In geotechnical engineering, soil stabilisation by chemical admixtures such as lime/cement has recently gained popularity (Petry & Little, 2002). Increased modulus of elasticity and resilient modulus under static loading (Yi et al., 2022) or even cyclic loading (Du et al., 2021), strength properties, reduced plasticity index, permeability, decreased swelling potential and volume instability, deformation and settlement, and improved durability are only a few benefits of lime/cement as stabilisation materials (Behnood et al., 2018). However, they are not used in high-velocity rail substructures because their mechanical fatigue behaviour is unknown and undetermined (Preteseille & Lenoir, 2016). Furthermore, although lime has been proved to be an effective binder in soil stabilisation, utilising low lime concentration to improve the geotechnical properties of soil is not an effective strategy since the swelling potential of soil is not greatly diminished (Rosone et al., 2018).

On the other hand, adding lime to expansive clay soils, such as black cotton soil, is beneficial because cation exchange closes clay particles and forms flocs. Flocculation is responsible for improving and modifying the engineering properties of expansive clays when treated with lime (Ghobadi et al., 2014). The Application of lime as a stabiliser agent is not helpful in some cases where soil bearing capacity, density, and hydraulic conductivity are very low (Osinubi et al., 2009). Workability, durability, compressibility, and soil strength are increased by lime stabilisers, while lime has varying effects on permeability. Moreover, sulfate attack, carbonation, and environmental influences are disadvantages of using lime/cement as soil stabilisation.

As a reinforcement, synthetic and natural fibre increases tensile strength, improves stability (Tamassoki et al., 2022a) and reduces soil lateral deformation/settlement (He et al., 2021). Furthermore, adding fibre to lime/cement-stabilised soil can reduce the brittleness of treated soil (Hamidi & Hooresfand, 2013). Fibre also minimises the risk of lime/cement stabilisation causing brittle failure. In soil stabilisation with cement, PP fibres increase tensile strength, density, and initial elastic modulus. Fibre added to cement-stabilised clay soil enhances tensile strength and reduces swelling potential, shrinkage, and crack width (Kumar et al., 2016). Fibre positively impacts the flexural behaviour of cement-based soil stabilisation (Jamsawang et al., 2015). In sandy soil, discarded tire textile fibres were used to improve the damping ratio, resilient modulus, and permanent strain (Narani et al., 2020). Fibre content and aspect ratio reduced critical confinement stress and enhanced shear strength in sandy soil (Ranjan et al., 1994; Zhao et al., 2021). Furthermore, using fibre improved the safety factor, strength, and stability of slopes in embankments filled with fibre-reinforced soil (Ramkrishnan et al., 2018). Similarly, when fibre-reinforced soil was exposed to freeze-thaw cycles, SEM pictures revealed that the fibres remained intact despite the repeated freeze-thaw (Kravchenko et al., 2019).

Combining the chemical binder with a different kind of fibre significantly changes the mechanical behaviour of soils. Therefore, many research works investigated fibre reinforcement, lime/cement stabilisation, and the combination of fibre with lime/cement as practical methods for improving the soil. This review paper studies the geotechnical behaviour of FRLR and FRCR soil; first, the impact of fibre, lime, and cement on strength behaviour under freezing and thawing conditions, pavement subgrade, and compression tensile strength is discussed. Then the synthetic and natural fibre at the microstructural level is compared. Finally, the effect of lime/cement on soil improvements is investigated at the mineralisation level.

STRENGTH BEHAVIOUR OF FIBRE REINFORCEMENT STABILISED SOIL

Under Freezing and Thawing Conditions

Previous research works widely studied the advantages of incorporating FRLS/FRCS soil. Here are a few of these studies. Climatic conditions of a place and high-temperature variation can substantially affect soil stability. When the soil layer is continuously frozen and thawed, attention must be paid to enhancing soil resistance to the freeze-thaw response. Soil geotechnical properties alter when exposed to freezing-thawing cycles. Glaciers create and freeze water into smaller gaps when huge voids inside fine-grained soils are exposed to cold temperatures. When water freezes, its volume increases by 9%, resulting in crack formation in the soil (Yldz & Soğanc, 2012). Several types of research were conducted to decrease the adverse impacts of freezing and thawing on the physical properties of soils.

Lime additive is a common approach for chemically converting weak soils into structurally safe building foundation materials. This approach is particularly suitable for modifying base materials, subbase materials, and subgrade soils in road building. The freeze-thaw cycle does not affect the pozzolanic reaction following the lime-water reaction. Nonetheless, the process is delayed in lime-treated clay soil. So, lime treatment is advantageous for clay soils throughout the cold season.

Fibre is another alternative that can improve soil properties, especially tensile strength. Nevertheless, an increase in the number of freeze-thaw cycles results in a 20–25% reduction in the UCS of PP fibre-reinforced and unreinforced clay soil specimens (Ghazavi & Roustaie, 2010).

Roustaei et al. (2015) found that increasing the amount of PP fibre in clay soil does not mitigate the impact under freeze-thaw conditions. PP fibres are a tensile element in the clay soil matrix during the freeze-thaw action. An increasing number of freeze-thaw cycles decreases cohesion, the only component that holds PP fibres and soil particles together and declines the fibre's influences as a tensile element (Roustaei et al., 2015).

Moreover, Boz and Sezer (2018) presented that adding lime, basalt, and PP fibre decreases mass loss in soil under freezing-thawing cycles while increasing it in untreated soil. In this regard, polypropylene FRLS kaolin clay soil was more efficient than basalt fibre (Boz & Sezer, 2018).

Although cement inclusion can increase the strength of clay to a certain level (Wahab, Rashid et al., 2021) cement-treated clay's low frost resistance is one downside. In addition, the mechanical properties of this type of foundation alter significantly during freeze-thaw cycles, resulting in significant freeze-thaw damage and subsequent differential settlement and instability. Ding et al. (2018) illustrated that adding just cement in clay soil with low plasticity increased the dimension shrinkages and expansive ratio in FRCS clay with increasing freeze-thaw cycles and cement content. Furthermore, the freeze-thaw cycle exacerbates the development of existing cracks in cemented clay and results in new fractures (Ding et al., 2018).

In contrast, Tajdini et al. (2018) demonstrated that the fibre type on the corresponding strain and compressive strength is more pronounced in terms of performance and ductility index. Güllü and Khudir (2014) looked at how freezing and thawing cycles affected low-plasticity silt soil reinforced with jute fibre, steel fibre, and lime. Shear strength and UCS testing were carried out with varying concentrations of lime and fibres in different freezing-thawing cycles ranging from 0 to 3. The results showed that after the freeze-thaw cycle, the UCS values of FRLS soil rose (Güllü & Khudir, 2014). Also, Jafari and Esna-ashari (2012) found that tire cord fibre increased lime-stabilised soil's durability and strength under freeze-thaw cycles. However, adding fibre before freezing-thawing and after one cycle did not significantly increase stiffness, stiffness rose after two cycles (Jafari & Esna-ashari, 2012).

Moreover, Saygili and Dayan (2019) showed that the mixture of kaolinite, lime, synthetic fibre, and silica fume boosted the strength and durability of the material under freezing-thawing conditions. Similarly, Thanushan and Sathiparan (2022) presented that banana fibre in cement stabilised soil improved residual compression strength while coconut coir fibre indicated better residual flexural strength. Both fibres increased cement-stabilised soil resistance to freeze-thaw weathering, wet-dry weathering, and alkali/acid attack. Furthermore, compared to the specimen reinforced with banana fibres, the specimens reinforced with coconut coir were more durable (Thanushan & Sathiparan, 2022).

The compound of FRLS/FRCS is more effective than just lime or fibre in clay soil. Most studies employed synthetic fibre as a soil stabilising reinforcement due to durability and loss of water absorption. Natural fibre has more degradation than synthetic fibre under temperature change. However, the lack of investigation of natural fibres is visible and suggested for future research. It is also considerable that freeze-thaw cycles do not affect the pozzolanic reaction in lime/cement-treated soil. Adding cement in low plasticity soil is ineffective due to the negative impact of soil shrinkage and the developing existing crack in soil.

Improve Pavement Subgrade

Subgrade preparation is critical in constructing highways since it is the foundation for flexible pavement. The subgrade may be fully exploited if compacted soil; the subgrade strength is proportional to the CBR value. Subgrades with poor soils have less than 2% CBR value and must be replaced with suitable soil for subgrade construction (Praveen et al., 2020). Significant research has been conducted over the last few decades, and different optimisation approaches have been developed to improve the CBR values of soft soils. For the first time, Little and Nair (2009) selected the effective soil stabiliser based on particle size analysis and Atterberg limits (Plasticity index), as shown in Figure 1 (Board et al., 2009). Although lime/cement is a common method to stabilise base and subbase materials (Senanayake et al., 2022), FRLS/FRCS soil effectively improves weak subgrade soil. However, when fibre reinforcement is used in lime-stabilised soil, it impacts the stability of subgrade material and pavement thickness (Moghal et al., 2018; Boobalan & Sivakami Devi, 2022). The behaviour of discrete plastic FRLS clay soil was studied by Dhar and Hussain (2019). The results showed that discrete plastic fibre on lime-stabilised soil increased toughness, young's modulus, peak strength, CBR value, and secant modulus values, achieved residual strength and changed the behaviour of soil stabilisation failure from fragile to flexible (Dhar & Hussain, 2019).

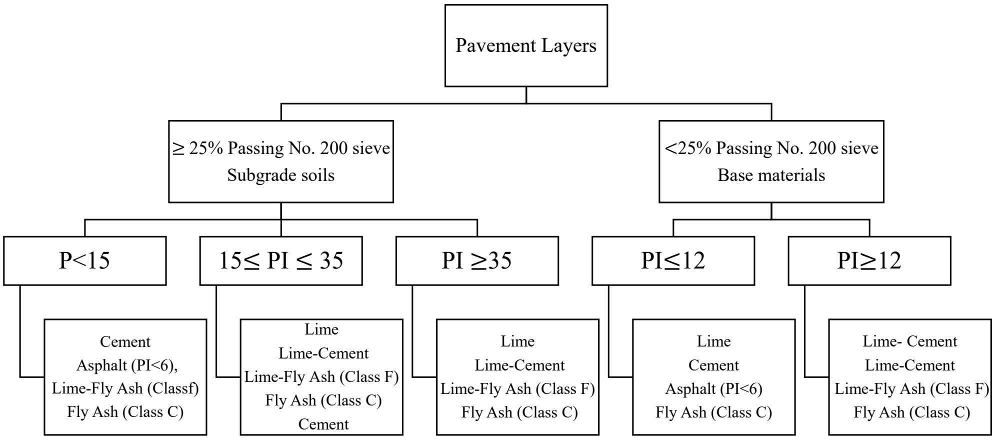

Figure 1. Determination of the appropriate stabiliser based on the plastic index and per cent smaller than 75 µm (Board et al., 2009)

Tiwari and Satyam (2020) investigated expansive soil improved with silica fume, lime, and coir geotextile. Expansive soils exhibit significant shrinkage and swelling characteristics and low shear strength (Punthutaecha et al., 2006). The lime-modified coir geotextile reduced swelling potential and improved the shear resistance and bearing capacity of costly soil, reducing the thickness of the base course layer and subbase in the pavement (Tiwari & Satyam, 2020). Moreover, Praveen et al. (2020) demonstrated that the CBR values had increased dramatically for a mixture of steel fibre, fly ash, and cement, effective for subgrade in country roads with low traffic flow (Praveen et al., 2020). Mishra and Gupta (2018) investigated the effects of PET fibre on fly ash-stabilised clay soil. Although the composite containing fly ash and PET fibre improved shear strength and CBR, the plasticity index deteriorated (Mishra & Gupta, 2018).

Additionally, Otoko and Pedro (2014) showed that adding waste shredded rubber FRCS clayey laterites soil enhanced UCS and CBR values. Although the highest CBR values were obtained after 14 days of curing, this is not attributed solely to cement. Fibre addition created an interlocking effect on the soil (Otoko & Pedro, 2014). Fibre positively impacts the CBR values and increases toughness because of fibre's energy absorption capacity under tension that the length of fibre crossover the weak zones (Onyejekwe & Ghataora, 2014). Increasing the toughness of fibre-reinforced stabilised soil has significant practical implications for pavement performance, such as strength to fatigue failure and extending their service life.

The effect of lime and cement on elastic modulus and CBR values are significant (Rizal et al., 2022) while fibre has a minor influence on CBR values. In contrast, fibre increases residual strength, so lime/cement does not contribute to this. Consequently, combining fibre with lime/cement in various weak soil increases CBR values, such as in expansive and lateritic soil.

Compression and Tensile Strength

Compared to unreinforced stabilised soil, using fibre as reinforcement in stabilisation soils reduces soil stiffness while increasing flexible behaviour, ductility, and toughness (Ateş, 2016). Due to the brittle nature of lime/cement stabilised soil- which shows no evidence of failure- the rapid collapse of structures happens when stability is slightly greater than the failure limit (Abdi et al., 2021). However, the UCS increases with increasing lime/cement percentages and curing time (Eskisar, 2015; Yoobanpot et al., 2020). According to Sobhan (2008), chemically stabilised soil is resistant to compression but makes a negligible contribution to tensile strength. It becomes a significant issue when a tensile crack occurs in the soils due to shrinkage, and the stabilisation is supposed to resist it. As a result, it is essential to enhance the tensile strength, hardness, and ductility of lime-treated soil with fibre reinforcement (Sobhan, 2008). Wang et al. (2019) and Li et al. (2012) discovered that incorporating wheat straw fibres and lime into soil increased strain-softening behaviour, secant modulus, and shear strength. Furthermore, when added as reinforcement, fibre improves samples' ductility and strength (Kafodya & Okonta, 2018).

Marine soil characteristics vary significantly between wet and dry soils. When lime-treated coconut fibre was combined with high-salinity marine clay soil, an improvement in strength was seen. It implies that saltwater improved the flexural stiffness of the treated coir fibre in cemented soil (Anggraini et al., 2017). Moreover, Kamaruddin et al. (2020) found that adding coir fibre boosted compressive strength, and tensile strength. Labiad et al. (2022) also found that sisal fibres in cement stabilised compressed earth blocks (produce brick waste and clay) improved tensile strength. Moreover, marginal soil modified with coir fibre, fly ash, and cement exhibited higher shear strength (1.5 to 2 times) than unmodified marginal soil (Praveen & Kurre, 2020). According to the results, coir fibre combined with cement and fly ash promoted interlocking between soil particles, and the UCS value for this composite was the greatest. Additionally, Tamassoki et al. (2020) exhibited coir fiber in activated carbon stabilised lateritic soil improved shear strength, post-peak residual strength, compressive strength, and Elastic Modulus (Tamassoki et al., 2022b).

Furthermore, Sukontasukkul and Jamsawang (2012) investigated using PP and steel FRCS soil. Although PP fibre outperformed the steel FRCS soil in flexural performance, fibre and cement enhanced the flexural performance of modified soil, which exhibited more significant peak and residual strengths (Sukontasukkul & Jamsawang, 2012). Moreover, Tharani et al. (2021) show that CBR, UCS, and Direct shear values were enhanced when PP fibre, basalt, and lime were added to black cotton soil. In contrast, Oliveira et al. (2016) found that utilising PP fibre and steel fibre as reinforcement on cement stabilised soft soil (OH) had a negative impact on UCS values (17–32%), only employing steel FRCS soil increased STS values, while PP fibres did not affect it.

One of the common failure modes of transportation infrastructure is fatigue. Fatigue is a term that refers to the gradual, permanent internal structural changes which occur in a material under repetitive loads (Lee & Barr, 2004). These repetitive loadings cause repetitive tensile stress at the bottom of the layers for hydraulic materials employed in the layers of transportation infrastructures (Preteseille et al., 2013). Therefore, it appears appropriate to include fibres in the materials to improve cement-modified soils' fatigue and tensile strength performance (Consoli et al., 2011). The surface kanaf fibre is pitted and grooved, so cement materials easily adhere to them and increase their friction with soil particles. Hence, the tensile tension in kenaf FRCs sand soil increased as the kenaf fibre length increased (Ghadakpour et al., 2020). However, Lenoir et al. (2016) showed that the initial elasticity modulus does not affect the flexural strength of FRCS sandy clay soil.

In comparison, the flexural stress was lowered by FRCS coarse-grained with a tiny percentage of clay (Ghadakpour et al., 2020). Furthermore, microcracks decreased in FRCS sandy clay soil and were ineffective in FRCS coarse-grained soil when both soils were subjected to cyclic loading(Lenoir et al., 2016). Moreover, Kutanaei and Choobbasti (2017) used several tests to investigate the influence of randomly distributed polyvinyl alcohol fibre, nano-silica, and cement on the mechanical properties of sandy soil. They found that adding fibres to the sandy soil reduces the modulus of elasticity but enhances the energy absorption capacity.

Since the tensile strength and seismic reactivity are strongly associated as severe issues with RE structures, limiting their practical applicability. Zare et al. (2020) studied cement stabilised RE reinforced with Waste Tire Textile Fibres. Due to improved cohesion between soil and fibre, STS values and ductility rose when fibre was added to cement-stabilised soil (Tang et al., 2007). FRCS soil's tensile behaviour mobilised tensile strength and prevented abrupt failure. When the fibre content increases, the abrupt strength loss between the first peak and strength restoration is significantly reduced (Zare et al., 2020). In addition, Shen et al. (2021) confirmed that cement enhanced peak strength more than lime, while residual strength increased similarly for both FRLS and FRCS soils.

However, Consoli et al. (2002) presented that increasing the length of PET fibres had no significant influence on the tensile strength impelled by the splitting tensile test and attributed this to a lack of friction between the cement matrix and the fibres due to smooth surface of the fibres. Also, some research found that employing FRCS clay soil can lower UCS and shear strength values (Correia et al., 2015).

Although using FRLS/FRCS improves the compression and tensile strength in diverse poor soil types, such as clay, marine, and expansive soils, they create minor enhancements in the strength of coarse-grained soil. The surface and length of fibre impact better interlocking particles in the mixture. Improving in UCS value happens due to lime and cement, while fibre is the cause of enhancing tensile strength.

Microstructure of FRLS/FRCS Soils

Microstructure analysis is a powerful tool for uncovering more objective evidence in changed soil at the micro-level. For example, Mobini et al. (2015) demonstrated that by adding synthetic fibres (steel and PP) into concrete mixtures, a dense zone between the fibres and the concrete matrix is created, which increases the flexural and tensile strengths of concrete samples. In contrast, Rivera-Gómez (2014) showed that when natural fibre (jute) is added to soil, this connection is not created, resulting in a more uncomplicated fracture under tension. It is because natural fibres have greater moisture absorption capacity when compared to synthetic fibres. Figure 2 compares moisture absorption between some natural and synthetic fibres (Rivera-Gómez et al., 2014).

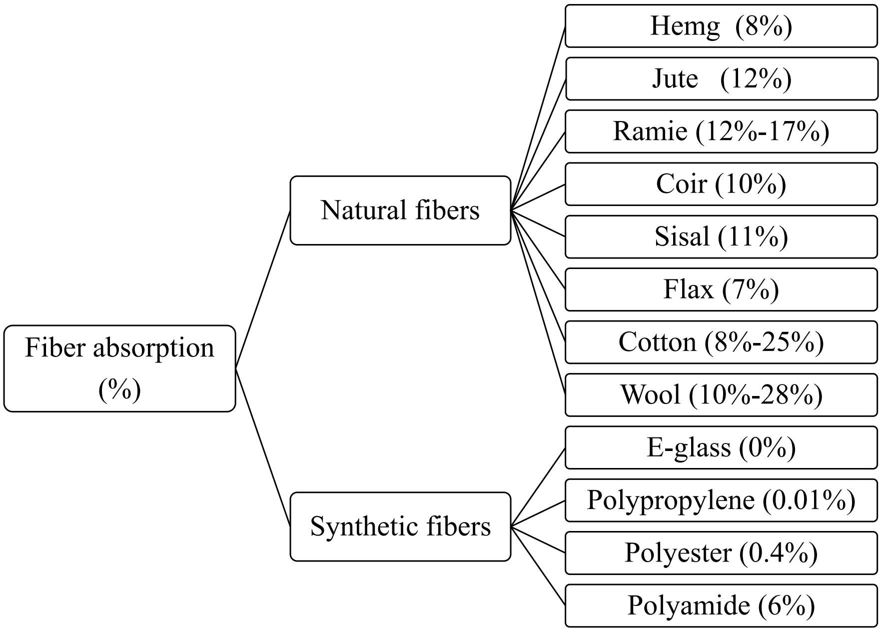

Figure 2. Comparison of moisture absorption between some natural and synthetic fibres (Rivera-Gómez et al., 2014)

Due to absorbing water during the thawing stage, lime-stabilised clayey soil reinforced with waste tire fibre loses 62% of its strength after just one freeze-thaw cycle (Jafari et al., 2012). In addition, Miller and Rifai (2004) showed that PP is a hydrophobic and chemically ineffective polymer. This substance is impervious to soil moisture and leachates and does not absorb or react with them (Miller & Rifai, 2004).

In contrast, Wang et al. (2019) showed honeycomb pattern of wheat fibres created a practical situation in lime-stabilised soil. Due to the water channels provided by the surfaces and honeycomb structure of wheat straw fibres, the chemical reaction between lime and water proceeds was quicker, resulting in a greater secant modulus than just adding lime (Wang et al., 2019). Cai et al. (2006) also demonstrated that the contact area of fibre with lime-stabilised soil is higher than with un-stabilised soil because lime reduces the pores between clay particles. Lime-soil reactions caused soil particles and the pores in the soil to become smaller and more detached (Cai et al., 2006). Also, soil-fibre contact is exceptionally minimal due to the low frictional properties and smooth surface of PP fibres. Forming cementitious chemicals in lime-stabilised clays binds soil particles and fibres with clay that tensions the fibres and gradually enhances the shear strength in the mixture (Abdi et al., 2021).

Yoobanpot et al. (2020) discovered that increasing curing time in dredging sediments stabilisation with cement and fly ash increases the concentration of CSH, CAH, and CASH. Because of the CSH gel-filled voids and gaps, the proportion of micropores in the treated soil was lower than in untreated. It was discovered that pore spaces were reduced due to better pozzolanic reactions in amended soil (Yoobanpot et al., 2020). Chemical components of modified soil with lime and coir fibre are different in the range of zero to 28 days curing period, according to Jairaj et al. (2020). When the soil was treated with coir fibre and lime, the temperature rose to 38 degrees Celsius, while there was no increase in temperature when the soil was only treated with coir fibre without lime. It was discovered that a pozzolanic reaction generated the heat of hydration in soil treated with lime and fibre. It influenced coir fibre surface properties, and the degradation of coir fibres reduced the UCS value for more than seven days of curing (Jairaj et al., 2020). According to Boz et al. (2018), PP fibre drew out of the soil due to weaker superficial adhesion on the soil-fibre interaction surface, resulting in a gap between soil and fibre. The interlocking and bonding between soil particles and basalt fibre improved when basalt fibre was used as reinforcement in lime-stabilised soil. The energy-dispersive spectroscopy results revealed that Si, Al, O, and Ca were all made up of soil and the presence of water, kaolin, and lime (Boz et al., 2018).

Saygili and Dayan (2019) evaluated the influence of freezing-thawing cycles on silica FRLS soil. The findings showed that CSH gel filled the holes before freezing-thawing cycles, resulting in better durability and strength in treated soil. Increased cracking and gaps in modified soil caused by freezing and thawing cycles, on the other hand, decreased UCS values (Saygili & Dayan, 2019).

Ghadakpour et al. (2020) demonstrated that increasing kenaf fibre concentration increased heterogeneity in cement-treated soil, resulting in various UWV findings. Fibre generated heterogeneity when the percentage of fibre in specimens rose. As a result, the waves diverged and could not travel through the samples, resulting in UWV errors (Ghadakpour et al., 2020).

After employing lime/cement as a stabilising agent, the CSH gel is the primary substance that fills holes and gaps between soil particles. Microstructure studies revealed that lime/cement alone impacts to soil, resulting in improved interlocking between soil particles. Figure 3 illustrates the reasons that cause cracks and gaps in FRLS/FRCS soils.

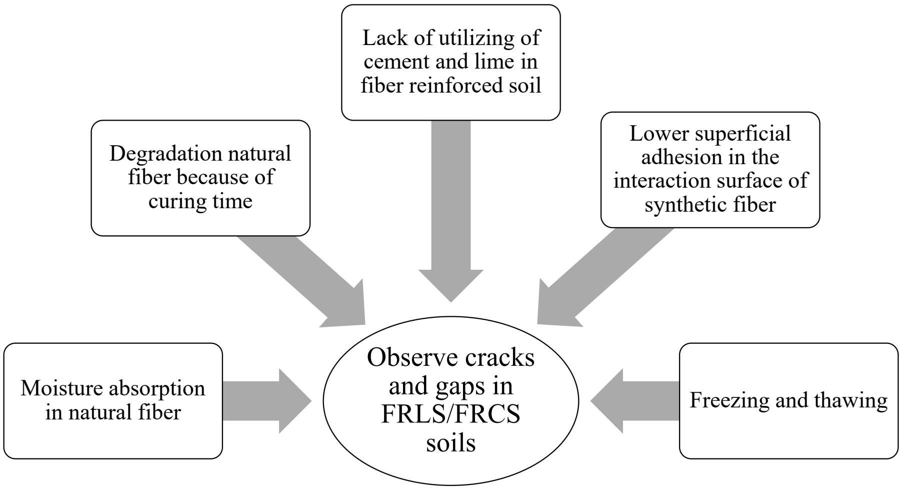

Figure 3. Causes for observing cracks and gaps in FRLS/FRCS soils

Impact of Lime/Cement on Soil in Terms of Mineralisation

Although cement and lime differ in their chemical nature, they can provide calcium to stabilise different soil types. By adding lime to the soil, an elementary environment ($pH > 12$) is created in the pore fluid, allowing the Alumina (Al_2O_3) and Silica (SiO_2) in the soil to dissolve gradually. The dissolved Alumina and Silica form a cementitious gel (similar to CSH and CAH) that covers the coarser particles and creates a strong bonding between them, improving strength and increasing the brittleness of the mixture. Moreover, adding more lime have a negative effect on strength. Strength declines in higher content of lime (9%); this reduction in strength might be caused by an excessive amount of lime (CaO), which produces a large number of calcium ions (Ca^{2+}) and cling to the clay surface. As a result of these ions altering the surface charge to a high positive net charge, osmosis occurs in the pore fluid system. The flocculated structure of the clay particles disperses due to the osmosis process. This structure has negligible compressive resistance and decreasing strength with greater lime concentration (Dhar & Hussain, 2019).

Cement addition alters the structure of lateritic soil. Lateritic soil mainly consists of SiO_2 and Al_2O_3, whereas cement mainly consists of calcium ions. The CASH, CSH, and CAH are formed because of the pozzolanic interaction between the soil's alumina-silica in soil and the calcium ions of the cement in the presence of water. Pore and crack sizes were reduced, suggesting improved mechanical characteristics (Wahab, Roshan et al., 2021). According to research by Broderick and Daniel (1990), organic compounds in concentrated form have significantly increased the hydraulic conductivity of compacted clay. Lime/cement stabilised soils are less sensitive to organic chemical attacks than untreated soils (Broderick & Daniel, 1990).

When cement reacts with water, calcium ions (Ca^{2+}) are released onto the surface of soil particles and raise the soil pH value (Chew et al., 2004). The pH value continuously lowers in lime/cement stabilised soil as cure time increases regardless of binder amount. The cement dropped its pH value significantly within the first 28 days. It is due to the increased CSH and CAH components resulting from hydration and pozzolanic processes (Al-Jabban et al., 2019). In this respect, accelerated curing guarantees a rapid pH decrease due to the formation of pozzolanic products (CAH and CSH) at high temperatures (Al-Mukhtar et al., 2010).

When soil with a pH value is smaller, it needs more cement content to improve soil strength (Al-Jabban et al., 2019). Because of significant hydration products formed (such as CAH, CSH, and hydrated lime), lime/cement stabilisation decreases volume change and Atterberg limits of soils. Still, it increases the strength and shrinkage limit of the soil-cement matrix (Chen & Wang, 2006).

The most often recurring issue, particularly in cement stabilisation, is sulfate attack caused by the deposition of ettringite. When lime/cement-treated soils with a certain quantity of gypsum or the treated soil are exposed to sulfated waters, sulfate attacks have frequently weakened the soil and resulted in the enlargement of the soil layer. As a result, lime/cement stabilisations have several disadvantages, including damage to the environment and groundwater and a high degree of brittleness. For example, making one ton of cement leads to around 1.3 tons of CO_2 emission, one of the primary disadvantages of the cement stabilisation process (Ta'negonbadi & Noorzad, 2017).

CONCLUSION

This literature review investigates the effects of adding lime, cement, and fibre on weak soil enhancements from different aspects. The following is a summary of the important points:

i. The fibre in lime/cement stabilized soil improves peak strength, residual strength, and stiffness and changes failure behaviour from brittle to ductile. Although several elements are considered under this circumstance, such as the length, percentage, and type of fibre, the percentages of lime/cement and the water ratio are most important.

Depending on the amount of water, it has both good and negative impacts on tensile strength and USC values. In contrast, when frost heave develops, friction between the matrix and fibre is a restraining force against expansion. The fibre will be ineffective if the natural soil is vulnerable to freeze-thaw and saturation. The load-transfer mechanism operates more efficiently in lime/cement stabilised soil, and adding fibre increases soil strength.

ii. The CSH gel is the major substance that fills holes and gaps between soil particles in FRLS/FRCS soils, while fibres create bridges between soil particles and restrict matrix cracks and gaps after forming gels. So, additional pressures and energy are necessary to pull out the fibres to deflect further. Apart from protecting the soil's integrity, this procedure enhances the bearing capacity of the soil.

iii. Although one reason to observe gaps and cracks is water absorption in natural fibres, rough surfaces in natural fibre help the reaction between cement/lime and water proceed more quickly. Still, natural fibre degradation may occur in stabilised soil due to hydration and curing time heat. Also, absorbing water during the thawing stage creates gaps in FRLS/FRCS soils, mainly in the bonding zone.

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