Sulphate Resistance of Lime Stabilized Clay using Silica Fume

Meenu Krishnan[1] and Manju G. S.[2]

[1] College of Engineering, Trivandrum, 695016, Kerala, India,
meenukrishnan230995@gmail.com
[2] College of Engineering, Trivandrum, 695016, Kerala, India,
Manjusanthosh99@gmail.com

Abstract. Treatment of clayey soil with lime is the most common chemical stabilisation adopted to enhance the geotechnical properties of soil. However, the presence of sulphate ions in the clayey soil adversely affect the durability of lime stabilised clay. An experimental investigation based on the plasticity index and unconfined compressive strength (UCS) was undertaken to study the effect of Na_2SO_4 on soil – optimum lime mixture. The reduced plasticity of lime stabilised clay was found to be increasing with Na_2SO_4. The increased pH in the presence of Na_2SO_4 resulted in an accelerated pozzolanic reaction and a corresponding increase in UCS for a curing period of 7 days. However, UCS value decreased with further curing owing to the formation of ettringite, which is an expansive mineral. In order to improve the performance of lime stabilised clay under sulphate attack, silica fume with an abundance of soluble silica was added, and the tests mentioned above were repeated. As silica fume is acidic, it reduced the pH of the mixture. Under the reduced pH condition, a form of Calcium-Silicate-Hydrate was thermodynamically favoured over ettringite and thus resulted in an improvement in UCS under sulphate attack.

Keywords: Lime, Silica fume, Plasticity index, Unconfined compressive strength.

1 Introduction

Clayey soil primarily consists of fine-grained minerals, which tends to soften with the presence of moisture, causing difficulties in construction. Several methods have been adopted to improve the geotechnical properties of such soils so that the stability and serviceability requirements can be met. As the replacement of unsuitable soil become uneconomical, stabilisation of clayey soil using additives can be considered as a feasible method. Calcium-based stabilisers have emerged as the most viable chemical stabilisation method, and lime stabilisation is the most commonly adopted method among them by virtue of its cost-effectiveness and need for the less-skilled workforce. The whole improvement in the properties of soil due to lime treatment can be classified as soil modification and soil stabilisation; wherein, former is controlled by quick or short-term reactions and pozzolanic or long-term reactions result in the later [1].

Lime stabilised clayey soil exhibited severe damages to infrastructures in the form of cracks and expansion on a later stage if the soil matrix is exposed to a large concentration of sulphate ions. It has been reported that the formation of expansive minerals, ettringite and thaumasite, were responsible for these damages [2]. Ettringite is a calcium alumino-sulphate mineral that precipitates under highly alkaline conditions in the soil, and it has a needle-like structure, which when exposed to moisture undergoes anisotropic growth resulted in an expansive pressure on stabilised soil matrix [3]. Research carried out on plasticity index of lime stabilised clay subjected to sulphate contamination found that stabilisation of the expansive soil altered the soil classification from CH (high compressible clay) to ML (low compressible silt), and upon sulphate contamination of the lime-stabilised soil, the classification changed from ML to MH (high compressible silt) [4]. The effects of Na_2SO_4 and $CaSO_4.2H_2O$ on the geotechnical properties of clayey soils stabilised with lime, natural pozzolana and their combination have been investigated. Both sulphates caused an increase in pH of the soil matrix, whereas the effect of Na_2SO_4 is more pronounced due to the formation of NaOH [5]. This prevailing alkaline condition triggers the formation of ettringite. Furthermore, studies carried out on the swelling property of lime stabilised soil under sulphate attack showed that lime-soil mixtures having high sulphate content showed a significant increase in its swell which confirmed the formation of ettringite [6].

Presence of soluble silica can thermodynamically favour the formation of a type of calcium-silicate- hydrate instead of ettringite. Research carried out on silica fume stabilised expansive clay found that plasticity index of expansive clay reduced with an increase in silica fume content from 0–12 % due to to the replacement of highly plastic expansive clay particles with non-expansive silica fume particles [7]. It has been observed that a reduction of 95% was observed in swell percentage and a reduction of 94% was observed in swell pressure for a soil specimen stabilised with 3 % lime and 10 % silica fume [8].

In this study, the effect of different percentages of Na_2SO_4 on the geotechnical properties of lime stabilised soil and their improvement with the addition of silica fume has been investigated

2 Experimental Studies

2.1 Materials used

The soil was collected from Coromondal clay suppliers, and it was found out to be clay of high plasticity (CH). Laboratory tests were conducted to determine the properties of the soil such as specific gravity, Atterberg limit, optimum moisture content (OMC), maximum dry density (MDD) and pH. Table 1 shows the engineering properties of the soil, and table 2 shows the chemico-mineralogical properties of soil found out using XRF spectrometer test. Lime used in this study was a commercially available hydrated lime ($Ca(OH)_2$) of specific gravity 2.2. Sodium sulphate was used to induce sulphate contamination. Moreover, white silica fume in powdered form having a specific gravity of 2.23 was also used.

Table 1. Physico-mechanical properties of soil.

Property	Standard	Value
Specific gravity	IS 2720 (Part 3)	2.6
Clay (%)	IS 2720 (Part 4)	54.77
Silt (%)	IS 2720 (Part 4)	45.23
Liquid limit (%)	IS 2720 (Part 5)	54.85
Plastic limit (%)	IS 2720 (Part 5)	25.49
Plasticity index (%)	IS 2720 (Part 5)	29.36
MDD (g/)	IS 2720 (Part 7)	1.63
OMC (%)	IS 2720 (Part 7)	24
pH	IS 2720 (Part 26)	5.90

Table 2. Chemico-mineralogical properties of soil.

Constituents	Value
SiO_2	59.80
Al_2O_3	35.10
TiO_2	1.13
MnO	-
Fe_2O_3	1.31
CaO	0.09
MgO	0.09
Na_2O	0.44
K_2O	0.29
P_2O_5	0.07
SO_3	0.10
Total	98.81

2.2 Methodology

The soil was first treated with different percentages of lime (4%, 8% and 12%) and standard Proctor test followed by UCS tests were carried out on each soil sample to determine the optimum lime content. Soil specimens prepared using solution of optimum lime content and varying Na_2SO_4 content (2%, 4% and 6%) were tested to determine the effect of sulphate contamination on plasticity index and unconfined compressive strength test were determined. With the optimum lime content as constant, the soil was further treated with different percentages of silica fume (2.5%, 5%, 10%, 15% and 20%) and standard Proctor test and UCS tests were carried out on each soil sample to obtain the optimum lime-silica fume (L-SF) mixture. Furthermore, soil treated with this corresponding optimum percentage of L-SF was confirmed with the pH test in order to ensure that the pozzolanic reaction would not be hindered. With the optimum L-SF content as constant, Na_2SO_4 content is varied (2%, 4% and 6%)

and the effect of sulphate contamination on plasticity index and unconfined compressive strength test were determined.

3 Results and Discussions

3.1 Optimum lime content

Standard proctor test

Standard Proctor tests were carried out on soil samples treated with 4%, 8% and 12% lime in order to find out the optimum moisture content (OMC) and maximum dry density (MDD). Figure 1 shows the variation of MDD and OMC of samples with varying lime content. The results showed a decreasing trend in MDD with an increase in lime content whereas, OMC showed an increasing trend. One reason behind this trend is the replacement of soil with lime having low specific gravity. It can also be attributed to the increase in porosity of soil from the flocculation and agglomeration process.

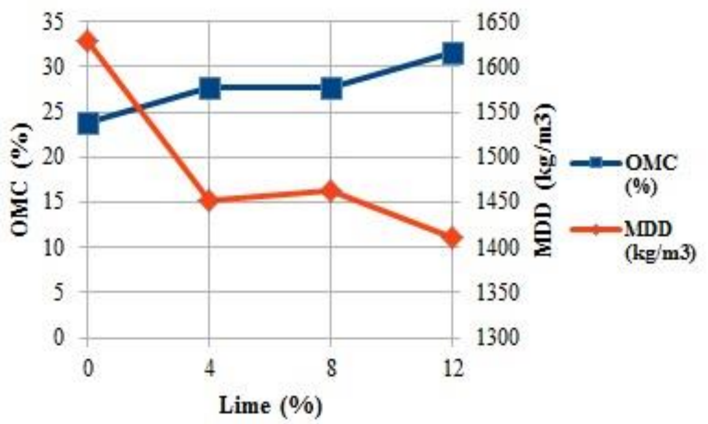

Fig. 1. Variation of MDD and OMC with different lime content

Unconfined compression test

Unconfined compression tests were carried out on untreated, and lime treated (4%, 8% and 12%) soil sieved through 425µ and compacted at their corresponding MDD and OMC to a sample of 38mm diameter and 75mm height. Tests were carried out in accordance to IS 2720 (Part 10). Figure 2 shows the variation of UCS with the increasing lime content for different curing periods (0, 7 and 28 days). Increase in UCS value with curing period can be attributed to the formation of pozzolanic cementitious compounds as obtained by Zhao et al. (2015) [9]. They carried out SEM analysis of lime stabilized Nanyang expansive clay after a curing period of 7, 28 and 90 days.

They observed that original microstructure of the clay was destroyed and fibrous structure indicated that there were $Ca(OH)_2.nH_2O$ particles and pozzolanic reaction products (C-A-H and C-S-H) in the late curing period. Figure 2 also showed a reduction in UCS value after a particular lime content (8 %). As the lime content increases beyond a limit, it will remain in the soil matrix unreacted. Therefore, 8% lime is selected as the optimum lime content for analyses.

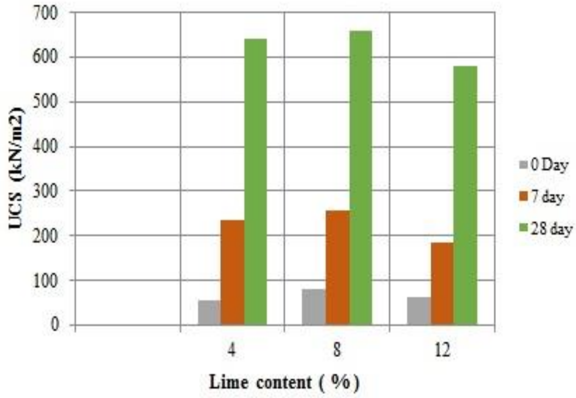

Fig. 2. Effect of lime on UCS of soil for different curing period

3.2 Optimum lime-silica fume (L-SF) content

Standard Proctor test

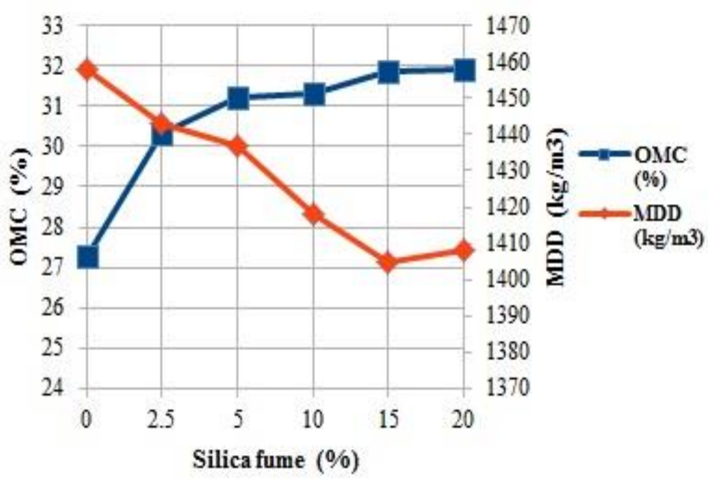

Fig. 3. Variation of MDD and OMC of lime stabilised soil with different silica fume content

Standard Proctor test was carried out on soil samples treated with optimum lime content and different percentages of SF (2.5%, 5%, 10%, 15% and 20%) in order to find out the optimum moisture content (OMC) and maximum dry density (MDD) as shown in figure 3. The results showed a decreasing trend in MDD as the SF content increases whereas, OMC showed an increasing trend due to the replacement of soil with SF having low specific gravity as well as due to the increase in porosity of treated soil.

Unconfined compression test

Unconfined compression tests were carried out on optimum lime treated and lime -SF treated soil sieved through 425µ and compacted at their corresponding MDD and OMC. Figure 4 shows the variation of UCS with the increasing SF content, which showed a gradually increasing trend with the same. Pozzolanic reaction between SF and soil at a lesser rate results in the increased UCS of soil. However, the increase in UCS became insignificant for a silica fume content above 10 %. Therefore, 10% SF is selected as the optimum value. This result is further confirmed with pH tests on soil treated with 8% lime and different percentages of SF. Figure 4 also shows the variation in pH of lime treated soil (8%) with different percentages of silica fume. As silica fume is slightly acidic in nature, pH of soil decreased with an increasing percentage of the same. By analysing the results of UCS test and pH test, 10% silica fume is selected as the optimum amount as it can maintain a pH above 12.

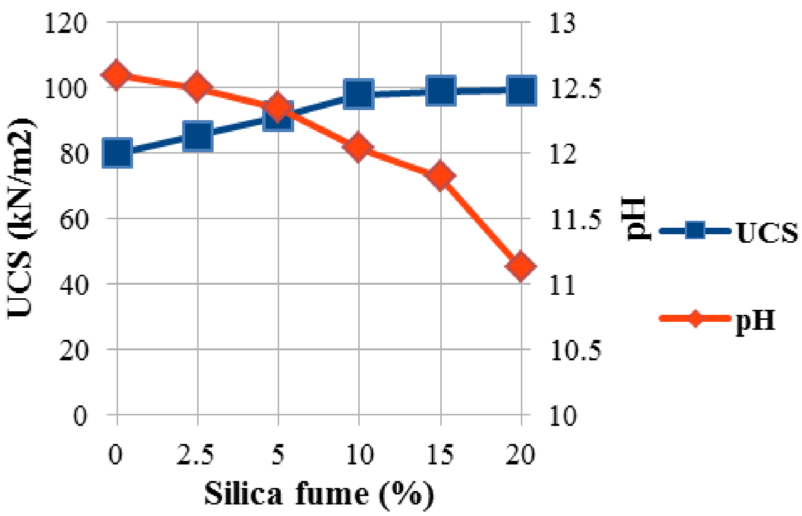

Fig. 4. Variation of UCS and pH of lime treated soil with silica fume

3.3 Effect of sulphate ions on plasticity index and soil classification

Soil stabilised with optimum lime content

Soil samples stabilised with optimum lime content (8%) were treated with different percentages (2%, 4% and 6%) of Na_2SO_4 in order to initiate sulphate contamination and these samples were subjected to Atterberg limit tests as per IS: 2720 (Part 5)-1985 in order to determine their liquid limit and plastic limit. Plasticity index (PI) of each soil sample was determined as the difference of corresponding liquid limit and plastic limit. Figure 6 shows the variation of PI of untreated and lime treated soil with varying Na_2SO_4 content. Addition of lime resulted in a decreased PI and a subsequent improvement in workability. This can be attributed to the decrease in liquid limit and increase in the plastic limit of soil with lime content due to the contraction of the diffused double layer as a result of the cation exchange between calcium cations and clay particles. Due to sulphate attack, PI showed an increasing trend, as sodium cations resulted in an increased particle-particle separation.

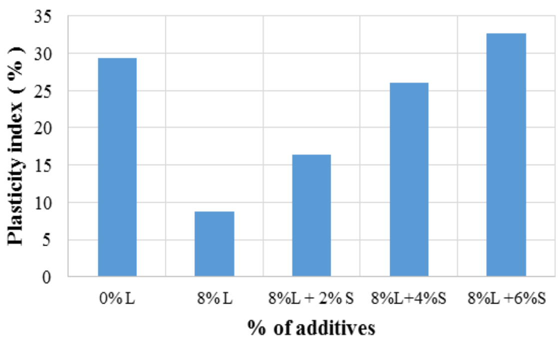

Fig. 5. Effect of sulphate ions on the plasticity index of lime stabilised soil

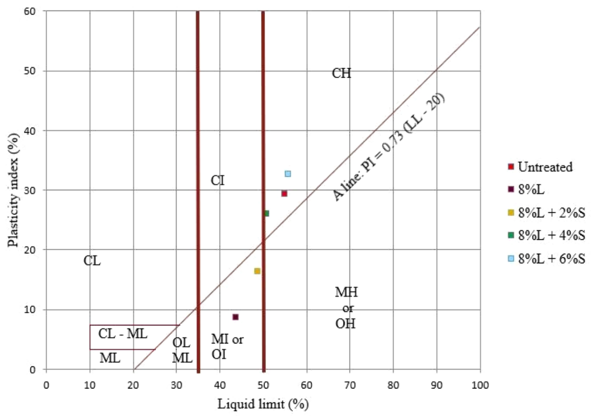

Fig. 6. Effect of sulphate ions on the classification of lime stabilised soil

Both untreated and treated clayey soil samples are classified by plotting the values of their plasticity index and liquid limit on a plasticity chart in order to determine the new soil classification according to the IS soil classification system (ISSCS) as shown in figure 7. Untreated soil classified as clay of high plasticity (CH) was changed to the class, the silt of intermediate plasticity (MI) when treated with lime. However, the addition of Na_2SO_4 increases LL and PI of soil, resulting in adverse soil classification. Addition of 6% Na_2SO_4 transformed the treated soil back to extremely high plasticity clay range.

Soil stabilised with optimum L-SF contents

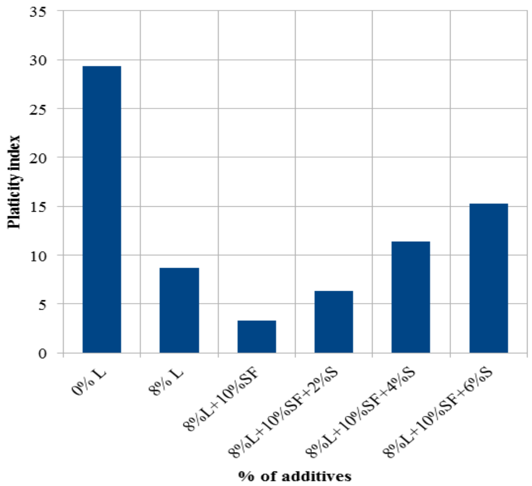

Fig. 7. Effect of sulphate ions on the plasticity index of L-SF stabilised soil

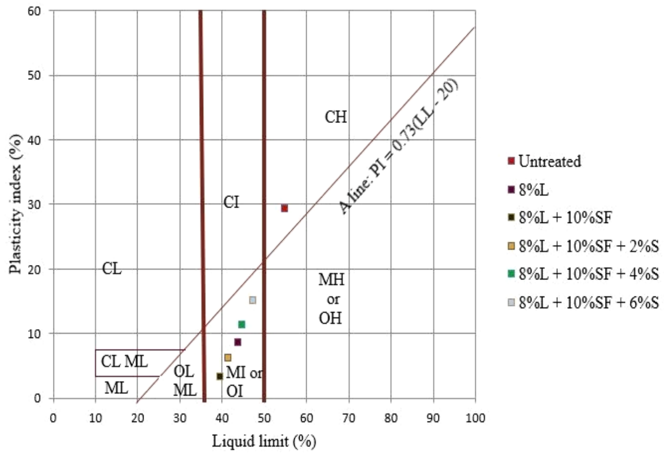

Fig. 8. Effect of sulphate ions on the classification of L-SF stabilised soi

Plasticity index of Soil samples stabilised with 8% L-10% SF were determined for different percentages of Na_2SO_4 and the results obtained are shown in figure. With the addition of SF, a further reduction in clay content occurs, which leads to a decreased liquid limit and plasticity index. PI value of lime treated soil increased to 32.72% with 6% Na_2SO_4, making it highly plastic. At the same time, the addition of 10% SF to the lime treated soil restricted the PI value to 15.27% (medium plasticity). As shown in the figure, presence of silica fume resisted the change in soil classification in the presence of sulphate as lime stabilised soil remained as silt of intermediate plasticity (MI) even after the addition of 6% of Na_2SO_4.

3.3 Effect of sulphate ions on unconfined compressive strength

Soil stabilised with optimum lime contents

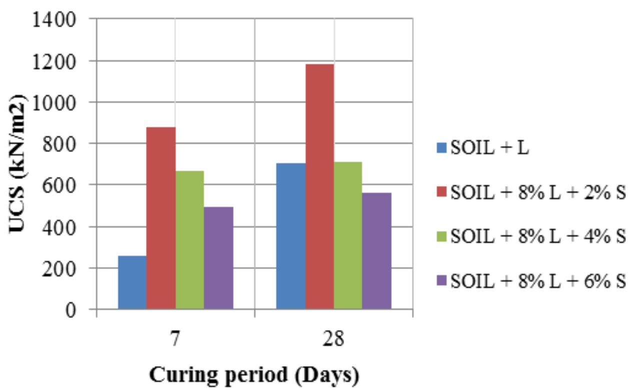

Fig. 9. Effect of sulphate ions on UCS of lime stabilised soil

Figure 9 shows the effect of sulphate attack on UCS of soil stabilised with 8% lime. The graph shows that clayey soil produced a significant increase in UCS with lime and curing period due to the pozzolanic reaction. It is also observed that the addition of Na_2SO_4 caused an early increase in UCS for a curing period of 7 days. This can be attributed to the presence of NaOH, which causes an increase in the pH and subsequent dissolution of a large amount of SiO_2 and Al_2O_3, which leads to an accelerated pozzolanic reaction. However, for a curing period of 28 days, UCS of soil did not show any significant increase except for 2% of Na_2SO_4. Formation and expansion of ettringite mineral are responsible for the reduced strength of stabilised soil. As the results of UCS test after 28 days were not determined, it can be analysed with respect to the research carried out by Gadouri et al. (2019) [10]. As per their research, lime treated soil undergo complete degradation after a curing period of 120 days in the presence of a higher amount of Na_2SO_4.

Soil stabilised with optimum L-SF contents

Figure 10 shows the improvement in unconfined compressive strength of lime stabilised soil with the addition of silica fume for a curing period of 7 days. UCS of soil increased by 75% with the addition of 10% silica fume, as it is a pozzolanic material. Unfortunately, time did not permit to run UCS test of soil samples after a curing period of 28 days which might have encompassed a more realistic scenario.

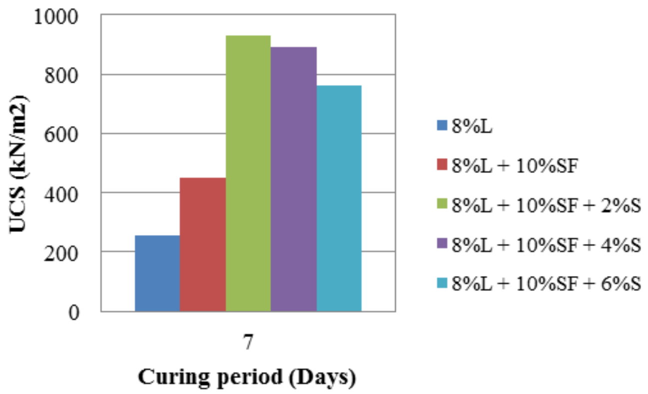

Fig. 10. Effect of sulphate ions on UCS of lime-SF stabilised soil

Similar results were obtained for Mccarthy et al. (2011) [11]. They stabilised Oxford test clay containing 3.4% gypsum with 3% CaO and varying quantity of fly ash (0-24%). It has been reported that UCS of lime stabilised clay improved with 18% fly ash maintained a higher value even after a curing period of 90 days, which is due to the availability of abundant soluble silica from fly ash, thus thermodynamically favour the formation of cementitious calcium silicate hydrate instead of ettringite. As silica fume contains 85-97% silica, much higher than that in fly ash, improvement in UCS of lime stabilised clay during sulphate contamination may be more prominent with 10% silica fume as compared to the results obtained for Mccarthy et al. (2011). Thus the addition of silica fume can resist the sulphate attack on lime stabilised clay.

4 Conclusions

The study was carried out to investigate the effect of sulphate ions on the geotechnical properties of lime stabilised soil and the improvement that can be achieved in the corresponding properties by adding silica fume to the soil. The following conclusions were drawn from the study;

1. Addition of lime to the soil caused a decrease in plasticity index and suitable soil classification by transforming the soil class from clay of high plasticity (CH) to silt of intermediate plasticity (MI).
2. Addition of Na2SO4 resulted in an increase in plasticity index and an unsuitable soil classification by transforming soil back to extremely high plasticity range.

3. Presence of non-plastic silica fume in lime stabilised soil resisted the transformation of soil class during sulphate contamination by resisting the increase in plasticity index.
4. Addition of lime to the soil produced a significant increase in UCS due to the pozzolanic reaction. Furthermore, Na2SO4 caused an early increase in UCS due to the accelerated pozzolanic reaction for a short curing period.
5. Formation of ettringite and its swelling with curing period resulted in a decrease in UCS of lime stabilised soil subjected to sulphate contamination.
6. UCS of lime stabilised soil slightly increased with the addition of 10% silica fume, as it is a pozzolanic material. Furthermore, the availability of abundant soluble silica in silica fume thermodynamically favoured the formation of calcium silicate hydrate instead of ettringite during sulpahte contamination.

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