Geomechanics and Engineering, *Vol. 19, No. 1 (2019) 21-28*
DOI: https://doi.org/10.12989/gae.2019.19.1.021

Alkali-activated GGBS and enzyme on the swelling properties of sulfate bearing soil

Ansu Thomas*, R. K. Tripathi[a] and L. K. Yadu[b]

Department of Civil Engineering, National Institute of Technology Raipur, Chhattisgargh, India

(Received July 25, 2017, Revised August 18, 2019, Accepted August 31, 2019)

Abstract. Use of cement in stabilizing the sulfate-bearing clay soils forms ettringite/ thaumasite in the presence of moisture leads to excessive swelling and causes damages to structures built on them. The development and use of non-traditional stabilisers such as alkali activated ground granulated blast-furnace slag (AGGBS) and enzyme for soil stabilisation is recommended because of its lower cost and the non detrimental effects on the environment. The objective of the study is to investigate the effectiveness of AGGBS and enzyme on improving the volume change properties of sulfate bearing soil as compared to ordinary Portland cement (OPC). The soil for present study has been collected from Tilda, Chhattisgarh, India and 5000 ppm of sodium sulfate has been added. Various dosages of the selected stabilizers have been used and the effect on plasticity index, differential swell index and swelling pressure has been evaluated. XRD, SEM and EDX were also done on the untreated and treated soil for identifying the mineralogical and microstructural changes. The tests results show that the AGGBS and enzyme treated soil reduces swelling and plasticity characteristics whereas OPC treated soil shows an increase in swelling behaviour. It is observed that the swell pressure of the OPC-treated sulfate bearing soil became 1.5 times higher than that of the OPC treated non-sulfate soil.

Keywords: soil stabilization; alkali activated ground granulated blast-furnace slag; OPC; enzyme; differential free swell; swell pressure

1. Introduction

Lime and cement have been used for stabilising soils at shallow depths. Calcium-based stabilisers form expansive minerals such as ettringite and/or thaumasite in presence of moisture in sulfate bearing soil as shown in equation 1 (Puppala *et al.* 2005). It can form excessive swelling minerals along with the cementitious products. Literature reveals that these minerals can cause large amount of heaving and lead to cracking of the infrastructure built on them such as pavements, building foundations etc. and results in huge repair and maintenance costs (Seco *et al.* 2017, Cheshomi *et al.* 2017, Mohn *et al.* 2016, Zhang *et al.* 2015, Punthutaecha *et al.* 2006 and Puppala *et al.* 2005). Sulfates may exist within the soil naturally, or may be produced from the oxidation of sulfate minerals. Sulfates are present in natural soils as calcium sulfate (gypsum), sodium sulfate (thenardite) and magnesium sulfate (epsomite) (Talluri 2013). Many cases of damages due to sulfate content in soil has been reported in southern, western and southwestern United States (Petry and Little 1992, Rollings *et al.* 1999 and Puppala *et al.* 2004). It is reported that the existence of sulfate can reduce the strength of stabilized soils (Gilazghi *et al.* 2016). The ettringite formation consumes calcium from the binder and hence slows down the rate of hydration to form calcium-silicate-hydrate (Puppala *et al.* 2005 and Talluri 2013).

$$Ca^{2+} + 2Al(OH)_4^- + 4(OH)^- + 3(SO_4)^{2-} + 26H_2 \rightarrow Ca_6[Al(OH)_6]_2 . (SO_4)_3 . 26H_2O \quad (1)$$

In addition to above issues the manufacturing process of Portland cement emits huge amount of sulphur dioxide aerosol emissions, CO_2 emissions (approximately 0.95 t CO_2/t PC), dust generation, high consumption of energy (approximately 5000 MJ/t PC) and resources (approximately 1.5 t limestone and clay/t PC) (Worrell *et al.* 2001, Higgins 2007, Scrivener and Kirkpatrick 2008, Rashad 2016, Yi *et al.* 2014, Khan and Taha 2015, Jin *et al.* 2015 & Sargent 2015). With this background, the demand of more environmental friendly and sustainable materials for ground improvement is explained. Hence, there is a research need to develop and evaluate the performance of the alternative additives to traditional stabilizers so that better stabilization can be provided to sulfate bearing soils.

The stabilization process of cement treated soil includes cation exchange, flocculation, agglomeration, cementitious hydration and pozzolonic reaction (Geiman *et al.* 2005, Mallela *et al.* 2004, Dhakal 2012 and Sargent 2015). Cation exchange and heat of hydration decreases the diffused double layer thickness and its plasticity. The calcium ion from the binder will replace the low valence sodium or potassium ions. Van der Waals forces of attraction make the soil structure flocculated by the edge to face connections (Sargent 2015). The hydration products such as calcium

*Corresponding author, Assistant Professor
E-mail: ansuthomasmace@gmail.com
[a]Professor
[b]Associate Professor

 ISSN: 2005-307X (Print), 2092-6219 (Online)

silicate hydroxide and calcium aluminate hydroxide gels are formed when calcium from binder react with soluble alumina and silica from the clay.

Mechanism of alkali activation can be explained by geopolymerisation. Alumina silicates form alkali alumino-silicates in presence of aqueous alkali hydroxide or silicate solution (Sargent 2015, Mozumder and Laskar 2015 and Khale and Chaudhary 2007). Alkali activation of GGBS transforms the glassy structures (partially or totally amorphous and/or metastable) into very compact well-cemented composites (Palamo *et al.* 1999). This process destructs the Si-O and Al-O bonds in the GGBS and it increases the hydration rate. It depends on the pH of the solution (Yi *et al.* 2014, Jin *et al.* 2015).

Stabilisation of soil using enzymes can be a cost effective alternative to traditional construction materials (Tingle *et al.* 2007 & Rafique *et al.* 2016). It lowers the attraction of water to soil due to the reaction between protein molecules and soil molecules (Velasquez *et al.* 2005).

Several studies have been done for improving the engineering properties of sulfate-rich soils using reactive magnesia- GGBS, lime-GGBS, lime-fiber, cement kiln dust, granulated blast furnace slag and fly ash, sulfate resistant cement stabilisation, rubber-soil technology, polymer stabilisation etc. (Zhang *et al.* 2015, Jin *et al.* 2015, Yi *et al.* 2014, Sargent 2015, Du *et al.* 2016, Du *et al.* 2015, Yu *et al.* 2016, Yi *et al.* 2016, Celik and Nalbantoglu 2013, Carraro *et al.* 2013, Sargent *et al.* 2012, Gilazghi *et al.* 2016 & Talluri 2013). It appears that cement-stabilized soils containing clay are particularly prone to sulfate attack.

The use of GGBS in conjunction with lime has been shown to reduce the degree of heave due to the production of CSH gel (Buttress 2013 & Wild *et al.* 1998). CSH gel which is responsible for the increased is produced by using alumina ions from the clay and lime. Wang *et al.* (2005) reduced the amount of ettringite formation by use of supplementary cementitious materials (SCM). Wild *et al.* (1998) reported that lime along with GGBS improved strength of soil with considerable amount of gypsum.

Jin *et al.* (2015) reported that reactive MgO can be an effective and economical activator for GGBS. Yi *et al.* (2014) concluded that activators such as NaOH, Na_2CO_3 and Na_2SO_4 can contribute the strength development rate of GGBS stabilized marine soft clay. Du *et al.* (2015) found that GGBS–MgO-stabilised kaolin clay display higher dry density up to 7% than the PC-stabilised kaolin clay. MgO activated GGBS accelerated the strength development rate of stabilised clay but excessive MgO with high reactivity is found to have negative effect on its strength performance (Yi *et al.* 2016). It is reported that sodium sulfate attack has much less significant effect on the surface integrity, mass loss, dry density, and unconfined compressive strength of the GGBS-MgO stabilized soil as compared with the OPC-stabilized kaolin clay (Yi *et al.* 2016).

Gilazghi *et al.* (2016) investigated stabilization of sulfate rich high plasticity clay using polymer and reported as dosage of polymer upto 13% leads to increase in strength. The performance of liquid soil stabilisers were studied by various researchers (Velasquez *et al.* 2005, Rauch 2003, Ganapathy *et al.* 2016, Eujine *et al.* 2016 & Latifi *et al.* 2015). Ganapathy *et al.* (2016) found that the plasticity index, maximum dry unit weight and permeability of the soil decreased leading to an increase in California bearing ratio value, unconfined compressive strength and shear strength with increasing dosage of the bio-enzyme. The behaviour of enzymatic lime stabilised soils was investigated and was reported that combination of enzyme and lime stabilise the soil effectively then using enzyme or lime alone. This may be because the enzyme acts as a catalyst in presence of lime (Eujine *et al.* 2016).

It is noticed that only a limited research has been carried out to understand the effect of non-traditional stabilisers on the swelling properties of sulfate bearing soil. The present study focuses on the efficacy of alkali activated GGBS and bio-enzyme in controlling volume changes of soil with added amount of sodium sulfate. Test specimens were subjected to consistency limits, differential swell and swell pressure tests. Analytical techniques such as XRD, SEM and EDX were also done on the untreated and treated soil to identify and characterise the reaction products formed and to study the changes in microstructure which occur in the selected soil when it is stabilised with OPC, AGGBS and enzyme.

2. Experimental programme

2.1 Materials used

The soil samples have been collected from Tilda, Chattisgargh India. The geotechnical characterization of the soil is given in Table 1. The chemical composition of GGBS and OPC obtained from Cement Plant at Bhilai are given in Table 2. Ground granulated blast-furnace slag (GGBS) activated by 1 molar (M) sodium hydroxide solution (NaOH), enzyme and OPC were used for the present study. Sodium hydroxide has greater capacity to liberate silicate and aluminate monomers (Mozumder and Laskar 2015). Bio-enzyme was used for the study as stabiliser. Sodium sulfate was used to make artificial sulfate bearing soil.

2.2 Sample preparation and testing methods

Soil is dried, pulverized and sieved through 4.75mm IS sieve. Dosages of GGBS were selected as 6%, 9%, 12%, 15% and 20% of dry weight of soil. Dosage of OPC was selected as 12% dry weight of selected soil based on the compaction and unconfined compression test (UCS) results as shown in Figs. 2-3. Enzyme has been used 70 ml/m^3, 100 ml/m^3, 133 ml/m^3, 400 ml/m^3 and 645 ml/m^3 of soil. Sodium sulfate solution of 5000 ppm has been used instead of water and various tests have been done as given in Table 3. Atterberg limits and differential swelling index (DSI) tests have been done after 28 days of sample preparation on the untreated and treated samples in laboratory as per Indian Standard Codes IS: 2720- 5 (1985) and IS: 2720- 40 (1970) respectively. Swell pressure test (Fig. 1) has been conducted as per IS: 2720-41 1977. This test is used to measure the maximum swelling pressure of the soil specimens at which no volume change of the specimens is anticipated (Punthutaecha *et al.* 2006). The specimens have been

Table 1 Properties of the soil

Property	Value
Liquid Limit (LL)	42.25 %
Plastic Limit (PL)	18.6 %
Plasticity Index (PI)	23.65 %
Optimum Moisture Content (OMC)	13.5 %
Maximum Dry Density (MDD)	17.2 kN/m^3

Table 2 Chemical Composition of GGBS and OPC

Element	OPC (percentage by weight)	GGBS (percentage by weight)
CaO	56.24	36.02
MgO	4.74	7.9
SiO_2	20.65	34.43
Al_2O_3	5.31	9.36
Fe_2O_3	3.7	0.94
LOI	1.78	0.1
IR	1.3	0.16

Table 3 Test details

Test Material	Designation
Non-sulfate soil	NS
Sulfate soil- 5000ppm	S
Non-sulfate soil + OPC 12%	NS+C
Sulfate soil- 5000ppm + OPC 12%	S+C
Sulfate soil- 5000ppm + Enzyme 70 ml/m^3	S+E1
Sulfate soil- 5000ppm + Enzyme 100 ml/m^3	S+E2
Sulfate soil- 5000ppm + Enzyme 133 ml/m^3	S+E3
Sulfate soil- 5000ppm + Enzyme 400 ml/m^3	S+E4
Sulfate soil- 5000ppm + Enzyme 645 ml/m^3	S+E5
Sulfate soil- 5000ppm + GGBS 6%+ 1M NaOH	S+G1
Sulfate soil- 5000ppm + GGBS 9%+ 1M NaOH	S+G2
Sulfate soil- 5000ppm + GGBS 12%+ 1M NaOH	S+G3
Sulfate soil- 5000ppm + GGBS 15% + 1M NaOH	S+G4
Sulfate soil- 5000ppm + GGBS 20% + 1M NaOH	S+G5

Fig. 1 Swell pressure test apparatus

compacted in a mould of 100 mm in diameter and 127.3 mm in thickness at optimum water content by using modified Proctor compaction effort. Two porous stones have been placed at the top and bottom of the soil specimen. The loading plate eliminated the point load effect. A dial gauge was placed on the top of the specimen to monitor volume changes in the specimen due to water absorption. The specimen is saturated under seating pressure of 5 kPa, and allowed to swell. After cessation of swelling is observed, the specimen has been loaded and allowed to compress under load. The loading pressure under which the soil sample compressed to its original volume is the swelling pressure.

XRD, SEM and EDX analysis were done on untreated and treated (optimum dosages of OPC, AGGBS and enzyme) samples after a curing period of 28 days. Samples were sieved through 75 μ IS sieve. Samples were coated with a thin layer of gold for performing SEM and EDX analyses.

3. Results and discussion

3.1 Atterberg limits

Based on the compaction and unconfined compression test (UCS) results as shown in Figs. 2 and 3, the dosage of OPC has been selected as 12% of dry weight of the soil. Figure 4 shows the liquid limit, plastic limit and plasticity index of AGGBS and enzyme treated sulfate bearing soil. It is seen that the Plasticity Index (PI) of OPC stabilized sulfate soil is increased by 70% of that OPC stabilized non-sulfate soil. The higher the PI favours expansiveness of the soil. It indicates that the cementation property of cement is overruled by ettrignite formation. Thereby, the results agree

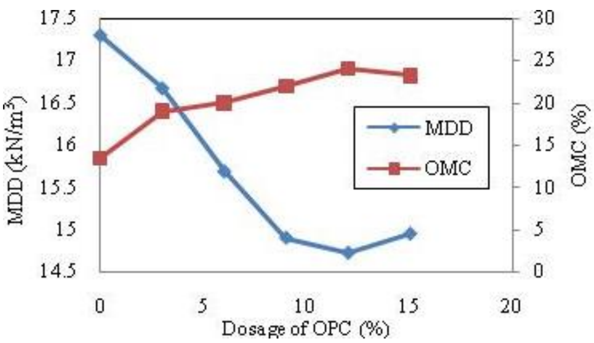

Fig. 2 MDD and OMC with dosage of OPC

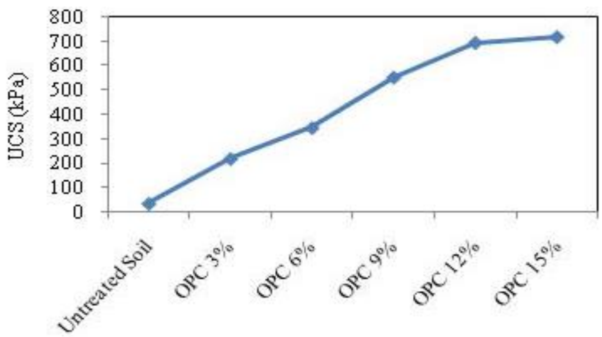

Fig. 3 UCS values with dosage of OPC

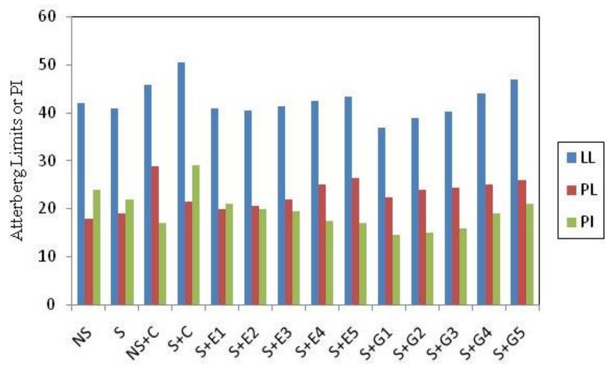

Fig. 4 Atterberg limits

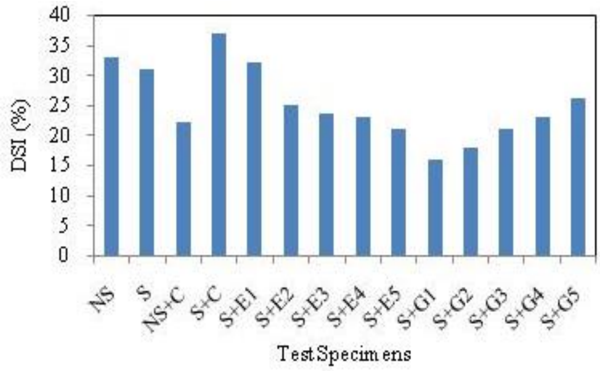

Fig. 5 Differential swell index

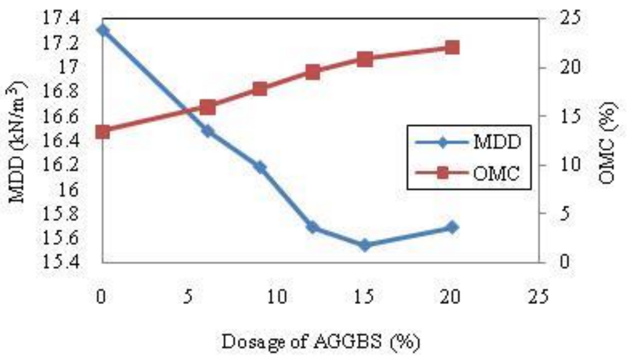

Fig. 6 MDD and OMC with dosage of AGGBS

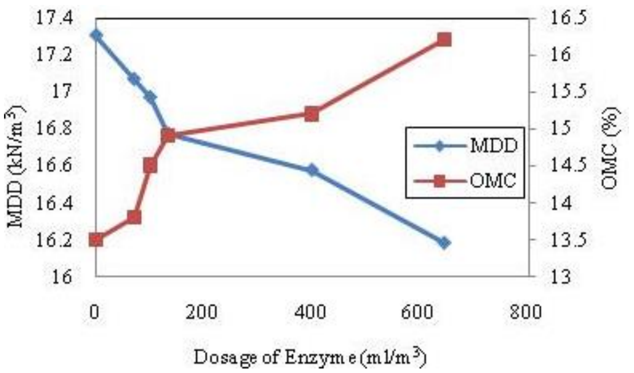

Fig. 7 MDD and OMC with dosage of enzyme

with the formation of expansive minerals such as ettringite/thaumasite in presence of sulfate.

Addition of enzyme of 70 ml/m^3 and 645 ml/m^3

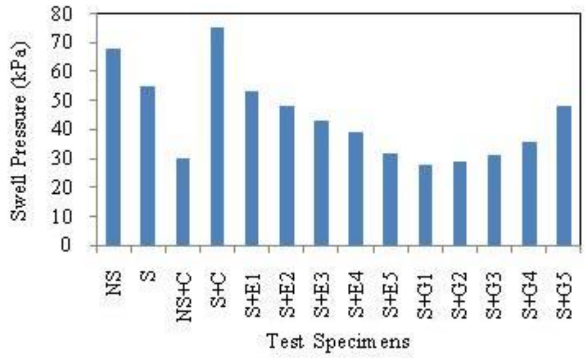

Fig. 8 Swell pressure

decreases PI values of the control soil by 4.5% and 22% respectively. Increased dosage of enzyme increases the liquid and plastic limit of the soil. Addition of enzyme to soil decreases plasticity index of soil can be due to the electrical neutrality maintained on the clay surface which is inturn obtained from the bonding of organic molecules attracted to the clay mineral surface (Scholen 1992 & Tingle *et al.* 2007). Enzyme weakens the diffused double layer which leads to improved plasticity characteristics of soil (Velasquez *et al.* 2005 & Ganapathy *et al.* 2016).

It can be seen that addition of 6% GGBS reduces the PI of the control soil by 34%. Further, increase in dosages of GGBS increases the PI values, but it is less than the control soil. GGBS dosages of 9%, 12%, 15% and 20% decreases the PI value by 31%, 27%, 13% and 4.5% respectively. The more availability of calcium ions might be the reason of increase in PI values.

3.2 Differential free swell

Fig. 5 presents the results of differential free swell index of alkali activated GGBS and enzyme treated sulfate bearing soils. DSI of the OPC stabilized sulfate soil increases by 68% that of OPC stabilised non-sulfate soil. This increase is due to the formation of expansive minerals. DSI values deceases by 48.4% and 32.3% with the addition of GGBS (6%) and enzyme (645 ml/m^3). The decrease in the DSI may be due to the decreased water affinity of the soil.

3.3 Swelling pressure

The swell pressure of the soil is studied for AGGBS and enzyme for sulfate bearing soil and results are shown in Fig. 8. The specimens were compacted at optimum water content by using modified Proctor compaction effort as shown in the compaction test results (Fig. 6 and 7). The sulfate content causes an additional increase in swell pressure of OPC stabilized sulfate soil by 150% than non-sulfate OPC stabilized soil. The swell pressure of the control soil is obtained as 55.2 kPa. The maximum allowable swell pressure for non-problematic soil is 20 kPa (Ranjan and Rao 2000). The swell pressure of the control soil is reduced by 50% and 41.9% for alkali activated GGBS (6%) and enzyme (645 ml/m^3) which is near to the acceptable range. But as the dosage of GGBS increases it

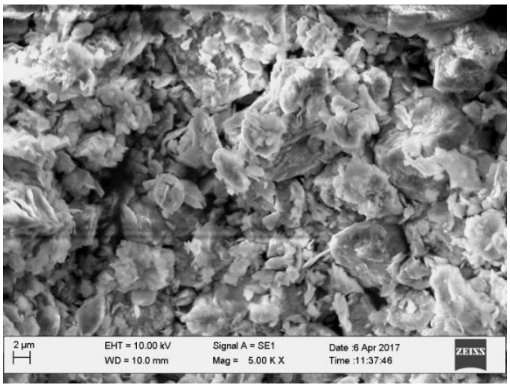

Fig. 9 SEM of untreated soil

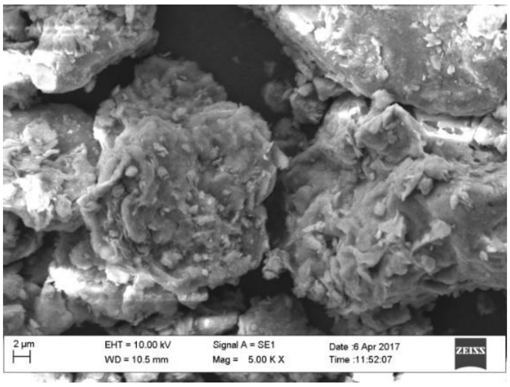

Fig. 10 SEM of OPC (12%) stabilised soil

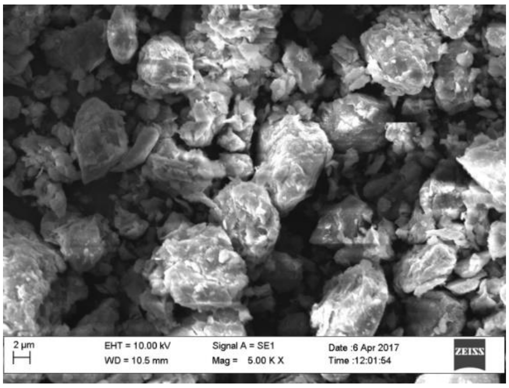

Fig. 11 SEM of GGBS (6%) stabilised soil with 1M NaOH

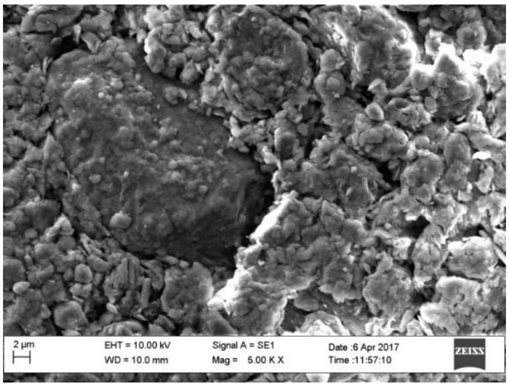

Fig. 12 SEM of enzyme (645 ml/m^3) stabilised soil

shows an increase in swell pressure. GGBS activated by alkali is more effective in reducing the swell pressure of the control soil compared to enzyme. The soil improvement is contributed from the formation of hydration bonds and cation exchange process which leads to decrease in soil porosity (Latifi *et al.* 2015).

Table 4 EDX microanalysis of the samples

Element	Untreated soil		OPC stabilised soil		AGGBS stabilised soil		Enzyme stabilised soil	
	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)	Weight (%)	Atomic (%)
Na	-	-	-	-	0.80	1.07	-	-
Mg	1.60	2.05	2.67	3.44	3.26	4.14	2.12	2.70
Al	13.84	15.97	14.18	16.47	14.30	16.36	14.67	16.83
Si	59.36	65.80	54.32	60.59	53.86	59.21	58.94	64.95
S	1.53	1.48	0.92	0.90	0.87	0.84	1.11	1.07
K	2.99	2.38	2.69	2.15	2.83	2.24	3.31	2.62
Ca	2.94	2.28	11.26	8.8	13.02	10.03	3.23	2.49
Ti	1.45	0.94	1.51	1.01	1.45	0.94	1.46	0.94
Fe	16.29	9.08	11.11	6.23	11.06	6.12	15.16	8.40

3.4 Scanning electron microscope and energy dispersive X-ray

SEM images of the untreated and treated soil at optimum dosage of stabilisers are shown in Figs. 9 to 12. The untreated soil shows discrete particles as shown in Fig. 9. Addition of stabilisers increases bonding of different particles to form aggregates or reaction products. The EDX analyses of the selected area of the untreated and treated samples are shown in Table 4. EDX identifies the elemental composition of the untreated soil which contains Mg, Al, Si, K, Ca, Ti and Fe. For OPC and AGGBS stabilised soil, EDX shows an increase in percentage of calcium. Calcium is found in small amount for the enzyme stabilised soil.

3.5 X-ray diffraction

The minerals or the reaction products of the soft and stabilised soil can be identified from the diffraction lines (Ouf 2001). The XRD patterns for the soft and stabilised soils at optimum dosage of stabiliser are shown in Figs. 13 to 16. XRD of untreated soil shows montmorillonite mineral presence in the soil. Montmorillinte peaks have been disappeared for AGGBS and OPC stabilised soil. AGGBS stabilised soil shows zeolite, hydradrated aluminosilicates of sodium such as hydroxysodalite ($Na_4Al_3Si_3O_{12}$)OH or herschelite ($NaAlSi_2O_6$. $3H_2O$), which is the reason behind improvement of mechanical properties of the AGGBS stabilised soil. Whereas, in OPC stabilised soil, XRD shows calcium silicate hydroxide (CSH) and calcium aluminate hydroxide (CAH) and hydrocalcite peaks which leads to the improvement in the stabilised soil (Ouf 2001). The swelling behavior in OPC stabilized soil can be due to the traces of ettringite. XRD of enzyme stabilised soil does not show any cemented products whereas it detects montmorillonite peaks.

GGBS activated by an alkali helps in further hydration by breaking the impermeable silicate/aluminate oxide layer

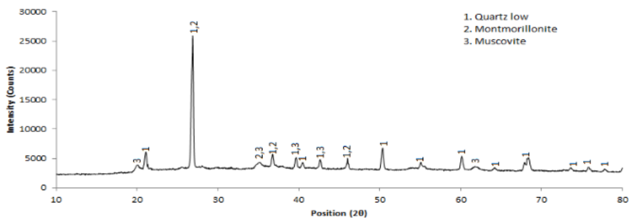

Fig. 13 XRD pattern of untreated soil

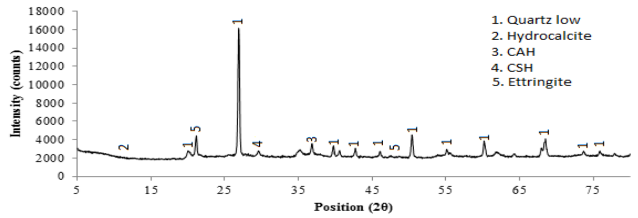

Fig. 14 XRD pattern of OPC (12%) stabilised soil

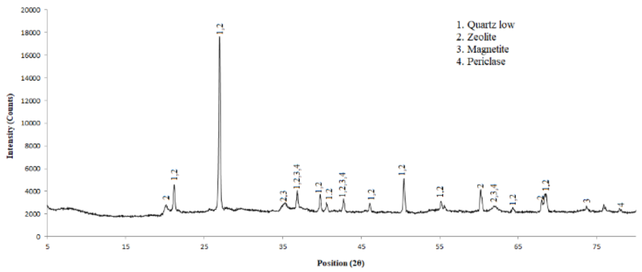

Fig. 15 XRD pattern of GGBS (20%) with 1M NaOH stabilised soil

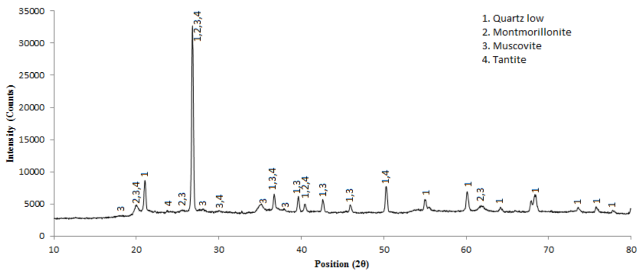

Fig. 16 XRD pattern of enzyme (645 ml/m^3) stabilised soil

on the surface of slag grains (Jin *et al.* 2015, Yi *et al.* 2014, Sargent 2015, Mozumder and Laskar 2015, Khale and Chaudhary 2007 & Song *et al.* 2000). GGBS posses high amount of alumina and silica which is quickly available to react with calcium forming cementitious gels preventing the formation of ettringite (Talluri 2013). It is expected that adding 6% GGBS to the control soil produces denser cementitious matrix, reduces the permeability and increases the durability against the internal and external sulfates attack (Wild *et al.* 1998 & Tasong *et al.* 1999). This reduction in swelling properties may be because of the decrease in permeability due to the addition of more fine material. However, further addition of GGBS increases the amount of calcium and soluble silica and alumina which leads to ettringite formation. Researchers reported that the formation of ettringite is favored in high alumina content whereas formation of monosulfate hydrate is favored in low alumina content (James 2013, Talluri 2013). Ettringite formation is controlled by the molar ratio of Al_2O_3 and SO_4 (Talluri 2013).

Surface of clay particles surrounded by large organic cations from enzymes reduces its affinity of water by maintaining its electrical charges neutral (Scholen 1992 & Tingle *et al.* 2007). Enzymatic layer may develop an osmotic pressure gradient in the soil by working as a semi permeable membrane. Thus it helps to maintain the equilibrium of the cation concentration by controlling the movement of moisture. This loss of moisture results in a strengthening of the molecular structure of the clay (Velasquez *et al.* 2005, Scholen 1992 & Mitchell and Soga 2005). The combined effect of encapusalation of clay minerals and osmostic pressure gradient reduces the adsorbed layer thickness which leads to improved plasticity characteristics.

The enzymatic soil stabiliser acts as a biosurfactant which also prevents water (Terrazyme 2016). Surfactants are organic compound that reduces surface tension. It is a surface active agent and is made of hydrophilic head and hydrophobic tail. Hydrophillic head of surfactant envelopes the negatively charged clay surface whereas the hydrophobic end inhibits the entry of additional water. The alcohol content present in enzyme may also contribute towards restriction of water entry to reduce the thickness of adsorbed layer with the effect of its dielectric constant (Terrazyme 2016 & Mitchell and Soga 2005).

4. Conclusions

The effects of dosage of AGGBS and enzyme on the swelling properties of sulfate bearing soil have been studied through Atterberg limits, DSI, swell pressure, SEM, EDX and XRD. The following conclusions may be drawn from the test results.

- There is considerable variation in the swelling characteristics of the OPC stabilized sulfate bearing soil when compared to the OPC stabilized non-sulfate soil.
- Swell pressure of OPC stabilized sulfate soil increases by 150% than non-sulfate OPC stabilized soil due to 5000 ppm sulfate content. The swell pressure of the control soil (55.2 kPa) is not desirable since it exceeds the maximum allowable swell pressure (20 kPa) as per Ranjan and Rao (2000).
- The swell pressure of the control soil can be brought near to allowable pressure by adding 645 ml/m^3 of enzyme or 6% of GGBS activated by 1 M NaOH.
- Addition of stabilisers increases bonding of different particles to form aggregates or reaction products. For OPC and AGGBS stabilised soil, EDX shows an increase in percentage of calcium. Calcium is found in small amount for the enzyme stabilised soil.
- Formation of zeolite, hydradrated aluminosilicates of sodium can be the reason for improvement in mechanical properties of the AGGBS stabilised soil. The swelling behavior in OPC stabilized soil can be due to the presence of ettringite. XRD of enzyme stabilised soil does not show any cemented products whereas it detects montmorillonite peaks.
- Non-conventional stabilizer such as alkali activated GGBS and enzyme can be used as an environmental

friendly stabilizer for sulfate bearing soils to avoid excessive swelling as compared to OPC.

References

Butscher, C., Mutschler, T. and Blum, P. (2016), "Swelling of clay-sulfate rocks: A review of processes and controls", *Rock Mech. Rock Eng.*, **49**(4), 1533-1549. https://doi.org/10.1007/s00603-015-0827-6.

Buttress, A.J. (2013), "Physicochemical behaviour of artificial lime stabilised sulfate bearing cohesive soils", Ph.D. Thesis, University of Nottingham, Nottingham, England, U.K.

Carraro, J.A.H., Budagher, E., Badanagki, M. and Kang, J.B., (2013), "Sustainable stabilization of sulfate-bearing soils with expansive soil-rubber technology", Report No. CDOT-2013-2, Colorado Department of Transportation, U.S.A.

Celik, E., and Nalbantoglu, Z. (2013), "Effects of ground granulated blastfurnace slag (GGBS) on the swelling properties of lime-stabilised sulfate-bearing soils", *Eng. Geol.*, **163**, 20-25. https://doi.org/10.1016/j.enggeo.2013.05.016.

Cheshomi, A., Eshaghi, A. and Hassanpour, J. (2017), "Effect of lime and fly ash on swelling percentage and Atterberg limits of sulfate-bearing clay", *Appl. Clay Sci.*, **135**, 190-198. https://doi.org/10.1016/j.clay.2016.09.019.

Dhakal, S.K. (2012), "Stabilisation of very weak subgrade soil with cementitious stabilisers", Ph.D. Thesis, Louisiana State University, Baton Rouge, Louisiana, U.S.A.

Du, Y., Bo, Y., Jin, F. and Liu, C. (2015), "Durability of reactive magnesia-activated slag-stabilized low plasticity clay subjected to drying-wetting cycle", *Eur. J. Environ. Civ. Eng.*, **20**(2), 215-230. https://doi.org/10.1080/19648189.2015.1030088.

Du, Y., Yu, B., Liu, K., Jiang, N. and Liu, M.D. (2016), "Physical, hydraulic, and mechanical properties of clayey soil stabilized by lightweight alkali-activated slag geopolymer", *J. Mater. Civ. Eng.*, **29**(2), 1-10. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001743.

Eujine, G.N., Chandrakaran, S. and Sankar, N. (2016), "The engineering behaviour of enzymatic lime stabilised soils", *Proc. Inst. Civ. Eng. Ground Improv.*, **170**(1), 1-11.

Ganapathy, G.P., Gobinath, R., Akinwumi, I.I., Kovendiran, S., Thangaraj, M., Lokesh, N., Muhamed, A.S., Arul, M.R., Yogeswaran, P. and Hema, S. (2016), "Bio-enzymatic stabilization of a soil having poor engineering properties", *Int. J. Civ. Eng.*, **15**(3), 401-409. https://doi.org/10.1007/s40999-016-0056-8.

Geiman, C.M. (2005), "Stabilisation of soft clay subgrades in Virginia", Virginia Polytechnic Institute and State University, Blacksburg, Virginia, U.S.A.

Gilazghi, S.T., Huang, J., Rezaeimalek, S. and BinShafique, S. (2016), "Stabilizing sulfate-rich high plasticity clay with moisture activated polymerization", *Eng. Geol.*, **211**, 171-178.

Higgins, D.D. (2007), "GGBS and sustainability", *Constr. Mater.*, **160**(3), 99-101.

IS: 2720- 40 (1970), "Methods of test for soils: Determination of free swell index of soils", Bureau of Indian Standards, New Delhi, India (Reaffirmed 2002).

IS: 2720 -5 (1985), "Methods of tests for soils: Determination of liquid and plastic limit", Bureau of Indian Standards, New Delhi, India (Reaffirmed 2006).

IS: 2720-41 (1977), "Methods of test for soils: Measurement of swelling pressure of soils", Bureau of Indian Standards, New Delhi, India (Reaffirmed 2002).

Jin, F., Gu, K. and Al-Tabbaa, A. (2015), "Strength and hydration properties of reactive MgO-activated ground granulated blastfurnace slag paste", *Cement Concrete Compos.*, **57**, 8-16. https://doi.org/10.1016/j.cemconcomp.2014.10.007.

Kestler, M.A. (2009), "Stabilisation selection guide for aggregate and native-surfaced low- volume roads", National Technology and Development Program, Forest Service, U.S. Department of Agriculture, Washington, D.C., U.S.A.

Khale, D. and Chaudhary, R. (2007), "Mechanism of geopolymerization and factors influencing its development: A review", *J. Mater. Sci.*, **42**(3), 729-746. https://doi.org/10.1007/s10853-006-0401-4.

Khan, T.A. and Taha, M.R. (2015), "Effect of three bioenzymes on compaction, consistency limits, and strength characteristics of a sedimentary residual soil", *Adv. Mater. Sci. Eng.*, 1-9. http://dx.doi.org/10.1155/2015/798965.

Latifi, N., Marto, A. and Eisazadeh, A. (2015), "Analysis of strength development in non-traditional liquid additive-stabilized laterite soil from macro- and micro-structural considerations", *Environ. Earth Sci.*, **73**(3), 1133-1141. https://doi.org/10.1007/s12665-014-3468-2.

Mallela, J., Quintus, H.V., and Smith, K.L. (2004), *Consideration Of Lime-Stabilized Layers In Mechanistic-Empirical Pavement Design*, National Lime Association.

Marto, A., Latifi, N. and Sohaei, H. (2013), "Stabilisation of laterite soil using GKS soil stabilizer", *Elec. J. Geotech. Eng.*, **18**(18), 521-532.

Mitchell, J.K. and Soga, K. (2005), *Fundamentals of Soil Behavior*, Third edition, Wiley, U.S.A.

Mohn, D., Cutright, T.J., Senko, J. and Abbas, A. (2016), "Assessment of sulfate concentrations in water used during chemical stabilization and its potential impact on sulfate induced heave", *Geotech. Geol. Eng.*, **34**(1), 285-296. https://doi.org/10.1007/s10706-015-9944-y.

Mozumder, R.A. and Laskar, A.I. (2015), "Prediction of unconfined compressive strength of geopolymer stabilized clayey soil using artificial neural network", *Comput. Geotech.*, **69**, 291-300. https://doi.org/10.1016/j.compgeo.2015.05.021.

Ouf, M.E.S.A.R. (2001), "Stabilisation of clay subgrade soils using ground granulated blastfurnace slag", Ph.D. Dissertation, University of Leeds, Leeds, U.K.

Palomo, A., Grutzeck, M.W. and Blanco, M.T. (1999), "Alkali-activated fly ashes-A cement for the future", *Cement Concrete Res.*, **29**(8), 1323-1329. https://doi.org/10.1016/S0008-8846(98)00243-9.

Petry, T.M. and Little, D.N. (2002), "Review of stabilization of clays and expansive soils in pavements and lightly loaded structures—history, practice, and future", *J. Mater. Civ. Eng.*, **14**(6), 447-460. https://doi.org/10.1061/(ASCE)0899-1561(2002)14:6(447).

Punthutaecha, K, Puppala, A.J., Vanapalli, S.K. and Inyang, H. (2006), "Volume change behaviors of expansive soils stabilized with recycled ashes and fibers", *J. Mater. Civ. Eng.*, **18**(2), 295-306. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:2(295).

Puppala, A.J., Griffin, J.A., Hoyos, L.R. and Chomtid, S. (2004), "Studies on sulfate-resistant cement stabilization methods to address sulfate-induced soil heave", *J. Geotech. Geoenviron. Eng.*, **130**(4), 391-402. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:4(391).

Puppala, A.J., Intharasombat, N. and Vempati, R.K. (2005), "Experimental studies on ettringite induced heaving in soils", *J. Geotech. Geoenviron. Eng.*, **131**(3), 325-337. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:3(325).

Rafique, U., Nasreen, S., Naveed, R. and Ashraf, M.A. (2016), "Application of bioenzymatic soil stabilization in comparison to macadam in the construction of transport infrastructure", *J. Environ. Biol.*, **37**(5), 1209-1215.

Rashad, A.M. and Sadek, D.M. (2016), "An investigation on Portland cement replaced by high-volume GGBS pastes modified with micro-sized metakaolin subjected to elevated temperatures", *Int. J. Sustain. Built Environ.*, **6**(1), 91-101.

https://doi.org/10.1016/j.ijsbe.2016.10.002.
Rauch, A.F., Katz, L.E. and Liljestrand, H.M. (2003), "An analysis of the mechanisms and efficacy of three liquid chemical soil stabilizers", Research Report 1993-1, Center for Transportation Research, University of Texas at Austin, Texas, U.S.A.
Rollings, R.S., Burkes, J.P. and Rollings, M.P. (1999), "Sulfate attack on cement-stabilized sand", *J. Geotech. Geoenviron. Eng*., **125**(5), 364-372. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:5(364).
Sargent, P. (2015), *The Development of Alkali Activated Mixtures for Soil Stabilisation*, in *Handbook of Alkali-activated Cements, Mortars and Concretes*, AECOM, U.K.
Sargent, P., Hughes, P.N., Rouainia, M. and Glendinning, S. (2012), "Soil stabilisation using sustainable industrial by-product binders and Alkali activation", *Proceedings of the GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering*, Oakland, California, U.S.A.
Scholen, D.E. (1992), "Nonstandard stabilizers", Report FHWA-FLP-92-011, FHWA.
Scrivener, K.L. and Kirkpatrick, R.J. (2008), "Innovation in use and research on cementitious material", *Cement Concrere Res*., **38**(2), 128-136. https://doi.org/10.1016/j.cemconres.2007.09.025.
Seco, A., Miqueleiz, L., Prieto, E., Marcelino, S., García, B. and Urmeneta P. (2017) "Sulfate soils stabilization with magnesium-based binders", *Appl. Clay Sci*., **135**, 457-464. https://doi.org/10.1016/j.clay.2016.10.033.
Solanki, P., Khoury, N. and Zaman, M. (2009), "A comparative evaluation of various additives used in the stabilisation of sulfate bearing lean clay", *J. ASTM Int*., **6**(8), 1-18. https://doi.org/10.1520/JAI101826.
Song, S., Sohn, D., Jennings, H.M. and Mason, T.O. (2000), "Hydration of alkali-activated ground granulated blastfurnace slag", *J. Mater. Sci*., **35**(1), 249-257. https://doi.org/10.1023/A:1004742027117.
Talluri, N. (2013), "Stabilization of high sulfate soils", Ph.D. Dissertation, The University of Texas at Arlington, Texas, U.S.A.
Tasong, W.A., Wild, S. and Tilley, R.J.D. (1999), "Mechanisms by which ground granulated blastfurnace slag prevents sulphate attack of lime-stabilised kaolinite", *Cement Concrete Res*., **29**(7), 975-982. https://doi.org/10.1016/S0008-8846(99)00007-1.
Terrazyme, (2016), <http://terrazyme.com/howtzworks.htm>.
Tingle, J.S., Newman, J.K., Larson, S.L., Weiss, C.A. and Rushing, J.F. (2007), "Stabilisation mechanisms of nontraditional additives", *J. Transport. Res. Board*, Transportation Research Record, No. 1989, **2,** 59-67. https://doi.org/10.3141%2F1989-49.
Velasquez, R., Marasteanu, O.M., Hozalski, R. and Clyne T. (2005), "Preliminary laboratory investigation of enzyme solutions as a soil stabilizer", Report No. MN/RC–2005-25, Department of Civil Engineering, Minnesota Department of Transportation Research, Minneapolis, U.S.A.
Wang, L., Roy, A., Seals, R.K. and Byerley, Z., (2005), "Suppression of sulfate attack on a stabilized soil", *J. Amer. Ceramic Soc*., **88**(6), 1600-1606. https://doi.org/10.1111/j.1551-2916.2005.00304.x.
Wang, S. and Scrivener, K.L. (1995), "Hydration products of alkali activated slag cement", *Cement Concrete Res*., **25**(3), 561-571. https://doi.org/10.1016/0008-8846(95)00045-E.
Wild, S., Kinuthia, J.M., Jones, G.I. and Higgins, D.D. (1998), "Effects of partial substitution of lime with ground granulated blast furnace slag (GGBS) on the strength properties of lime stabilised sulphate-bearing clay soils", *Eng. Geol*., **51**(1), 37-53. https://doi.org/10.1016/S0013-7952(98)00039-8.
Wild, S., Kinuthia, J.M., Jones, G.I. and Higgins, D.D. (1999), "Suppression of swelling associated with ettringite formation in lime stabilized sulphate bearing clay soils by partial substitution of lime with ground granulated blastfurnace slag", *Eng. Geol*., **51**(4), 257-277. https://doi.org/10.1016/S0013-7952(98)00069-6.
Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L.O. (2001), "Carbon dioxide emissions from the global cement industry", *Ann. Rev. Energy Environ*., **26**(1), 303-329. https://doi.org/10.1146/annurev.energy.26.1.303.
Wu, X., Jiang, W. and Roy, D.M. (1990), "Early activation and properties of slag cement", *Cement Concrete Res*., **20**(6), 961-974. https://doi.org/10.1016/0008-8846(90)90060-B.
Yi, Y., Gu, L., Liu, S. and Jin, F. (2016), "Magnesia reactivity on activating efficacy for ground granulated blastfurnace slag for soft clay stabilisation", *Appl. Clay Sci*., **126**, 57-62. https://doi.org/10.1016/j.clay.2016.02.033.
Yi, Y., Li, C. and Liu, S. (2014), "Alkali-activated ground-granulated blast furnace slag for stabilization of marine soft clay", *J. Mater. Civ. Eng*., **27**(4), 04014146. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001100.
Yu, B., Du, Y., Jin, F. and Liu, C. (2016), "Multiscale study of sodium sulfate soaking durability of low plastic clay stabilized by reactive magnesia-activated ground granulated blast-furnace slag", *J. Mater. Civ. Eng*., **28**(6), 04016016.
Zhang, M., Zhao, M., Zhang, G., Nowak, P., Coen, A. and Tao, M. (2015), "Calcium-free geopolymer as a stabilizer for sulfate-rich soils", *Appl. Clay Sci*., **108**, 199-207. https://doi.org/10.1016/j.clay.2015.02.029.

CC