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Stabilization of highly expansive bentonite soil using polypropylene fiber and ground granulated blast furnace slag

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ABSTRACT

Expansive soils have been a significant problem in geotechnical engineering due to potential failures to various infrastructure such as buildings, bridges, roads, etc. The present study investigates the use of polypropylene fibre and Ground Granulated Blast-furnace Slag (GGBS) mixed separately with highly expansive commercially available sodium bentonite to reduce the expansivity index and other swelling & shrinkage parameters. The fibre content were 0, 0.25, 0.5, 0.75, and 1.0% and the GGBS contents were 0, 5, 10, and 15% mixed with bentonite by dry weight. The measured index properties included the Atterberg limits, specific gravity, and linear shrinkage and the engineering property test included compaction, expansivity index, and one-dimensional consolidation. Scanning Electronic Microscope (SEM), and Energy Dispersive X-Ray Spectroscopy (EDXS) tests were performed for microstructural analysis of the soil particle. Also surface charge has been measured using zeta potential analyser. The results show a significant reduction in the expansivity and swelling index of the bentonite when treated with either of the additives, i.e., fibre or GGBS. The results of this study show that polypropylene fibre and GGBS can be effective for stabilising highly expansive bentonite, utilizing industrial wastes such as GGBS can enhance sustainability.

Keywords: Bentonite, Ground Granulated Blast-furnace Slag (GGBS), Highly Expansive Soil, Polypropylene Fibre, Stabilization

1. INTRODUCTION

Expansive soils have damaged structures resulting in a loss of billions of dollars per year (Chen, 2012). Thus, stabilising expansive soils to prevent such problems is important. Traditional stabilising agents such as lime, cement, and primarily calcium-based fly ash, have been used for stabilising expansive soils. For example, Soltani et al. (2018) evaluated the use of these agents and found soil matrix enhancement in terms of swell reduction, shear strength improvement, and resistance to the influence of the wetting-drying cycles. The additives undergo both instant and prolonged time-dependent chemical reactions with the soil in the presence of water. The mechanisms include cation exchange, flocculation, agglomeration, pozzolanic reaction, and carbonate cementation involved in the stabilisation of soil with traditional agents (Firoozi et al., 2017).

Kolay & Ramesh (2015) studied the reduction of the expansive index, swelling, and compression behaviour of kaolinite clay and bentonite with sand and class C fly ash. Ottawa sand and fly ash were used in the proportion of 0-50% by weight, which reduced the expansivity index (EI) from approximately 10 to 50% and 4 to 49% for kaolinite clay and bentonite, respectively. Liquid limit and plasticity index also decreased significantly with the addition of sand and fly ash. While the dry density of the mixes decreased with the addition of fly ash and increased with the addition of sand, the optimum moisture content (OMC) increased with the addition of fly ash and decreased with the addition of sand. Fly ash addition resulted in a more significant reduction in linear shrinkage than the sand addition. Swelling index values for soil mixed with sand and fly ash ranged from 7.84 to 73.39%. The maximum swelling pressure decreased significantly by 93% and 64% for kaolinite clay and bentonite, respectively.

Dayalan (2016) conducted a comparative study on soil stabilisation with GGBS and fly ash, mixing fly ash and GGBS in proportions of 5, 10, 15, and 20% by dry weight and found that the OMC for both mixes was 10%. He noticed a significant improvement in strength and concluded that the optimum value of fly ash and GGBS was 15% and 20%, respectively, based on California Bearing Ratio (CBR) results for stabilization.

Non-traditional stabilising agents are referred to primarily as industrial by-products. Industrial by-products influence the physico-chemical interactions in the soil matrix by the chemical reaction with soil in the presence of water. Some common industrial by-products used for soil stabilization are cement kiln dust, lime kiln dust, ground granulated blast furnace slag (GGBS), pulverised coal bottom ash, steel slag, mine tailings, and others and calcium oxide-rich products like wastepaper sludge ash, sulphonated oils, ionic compounds, and polymers (Petry & Little, 2002; Alazigha et al., 2016; Estabragh et al., 2020; Bhusal et al., 2022). The mechanism involved in soil stabilisation by such additives differs from traditional stabilisers. Onyejekwe & Ghatora (2015) studied the influence of sulphonated oils and polymers and found that the alignment of clay particles and changes in clay surface charge polarity increased the inter-particle cohesive strength.

This study evaluated the use of fibre and GGBS to stabilise highly expansive bentonite. Commercially available bentonite was stabilised with different separate percentages of polypropylene fibre and GGBS. The fibre percentages were varied from 0.25 to 1.0%, in increments of 0.25%. Similarly, the GGBS percentages were varied from 5 to 15%, in increments of 5%. Index properties and engineering properties of the bentonite and treated mixes were determined following standard test procedures.

2. MATERIALS AND METHODOLOGY

For the stabilisation of bentonite, polypropylene fibre (supplied by FORTA Corporation, USA), and GGBS were used as the additives. Bentonite was mixed with the different proportions of fibre and GGBS by dry weight of bentonite. Due to the moisture in bentonite and GGBS, the samples were oven dried for 24 hours before mixing them. Bentonite was combined with 0.25, 0.5, 0.75, and 1.0% fibre by dry weight or with 5, 10, and 15% GGBS by dry weight. Various soil sample mixes were prepared at the OMC using distilled water. The index and engineering property tests were performed according to ASTM or BS standards to determine the soil properties mixed at different combinations. The Atterberg limits tests were performed to measure the liquid limit (BS 1377: Part 2:1990) and the plastic limit (ASTM D 4318 – 10) of the soil. A linear shrinkage test was conducted to estimate the shrinkage limit of the soil mix. A 5.5-inch (139.7 mm) long linear metallic mould with 0.5-inch (12.7 mm) depth and 1.0-inch (25.4 mm) diameter was fabricated to measure the linear shrinkage limit. A helium gas pycnometer was used to measure the specific gravity of untreated and mixed soils (ASTM D5550-14). The study on fine-grained soil with particle size smaller than 2 mm by Sridharan & Sivapullaiah (2005) asserted the use of a miniature Proctor test for compaction test since it agreed with the test results of the standard Proctor test. The OMC and MDD were determined through a miniature Proctor test for all the mixes. An expansivity index test (ASTM D 4829-08) was performed. 1-D consolidation test (ASTM D2435-96 Method B) was performed. The SEM and EDX tests were performed by SEM/EDX scanning instrument, and the electrokinetic test was performed by a Zetasizer nano ZS machine (Malvern Zetasizer Pro).

3. RESULTS AND DISCUSSION

3.1 Index properties tests

3.1.1 Atterberg Limits

Preliminary tests conducted on fibre and GGBS mixes by Casagrande's apparatus showed inconsistent results, so the liquid limit test was performed using a cone penetrometer (BS 1377: Part 2:1990). The test result of soil mixed with fibre and GGBS are shown in Figures 1 & 2.

The original bentonite had a measured liquid limit of 343 and a plastic limit of 46. When the fibre proportion was increased, the liquid limit was increased to 378 at 1.0% fibre, whereas the plastic limit decreased to 36. Since the fibre is a hydrophobic and chemically inert material, it does not absorb or react with soil moisture (Miller & Rifai, 2004).

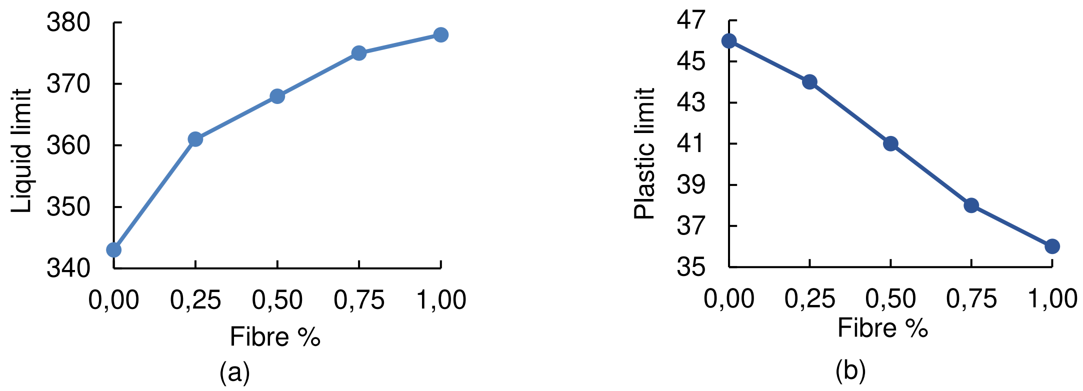


Figure 1. *Liquid limit (a) and plastic limit (b) values for bentonite mixed with fibre.*

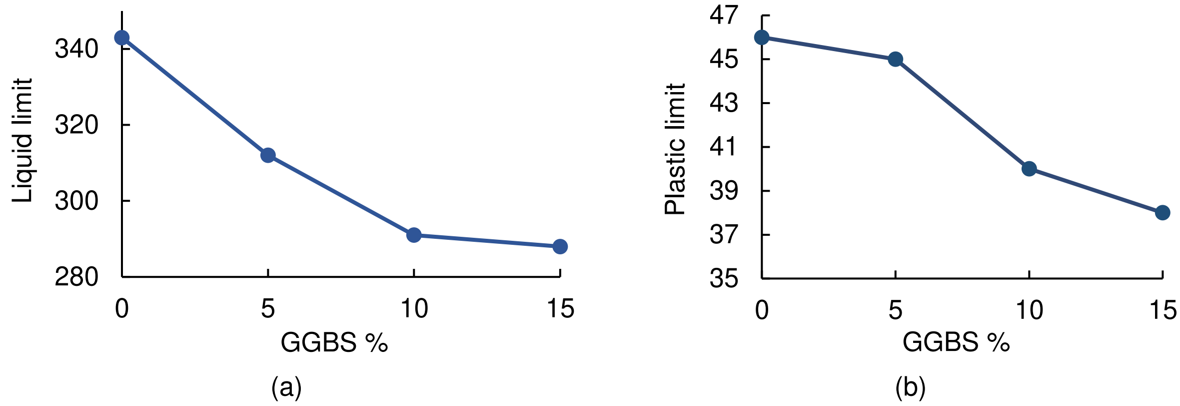


Figure 2. *Liquid limit (a) and plastic limit (b) values for bentonite mixed with GGBS.*

The addition of GGBS slag decreased both the liquid limit and plastic limit. This trend is expected because adding the slag powder to the soil fills the soil voids with slag fines, which increases the dry density and reduces the pore space available for moisture movement. The addition of pozzolanic materials such as GGBS causes considerable changes in the index properties of the soil by reducing the diffuse double layer thickness and causing the flocculation of the clay particles (Sivapullaiah et al., 1996). A lower plasticity index corresponds to a smaller swell potential (Herzog & Mitchell, 1963).

3.1.2 Specific Gravity Test

The measured specific gravity values for the untreated samples of bentonite, fibre, and GGBS were 2.67, 0.89, and 3.20, respectively. Since the specific gravity of fibre is much lower than the bentonite, adding fibre to the bentonite decreases the specific gravity of the mixes, as is evident from the data illustrated in Figure 3 (a). Similarly, the specific gravity of the GGBS is higher than the bentonite, so the addition of GGBS increases the specific gravity of mixes, as shown in Figure 3 (b).

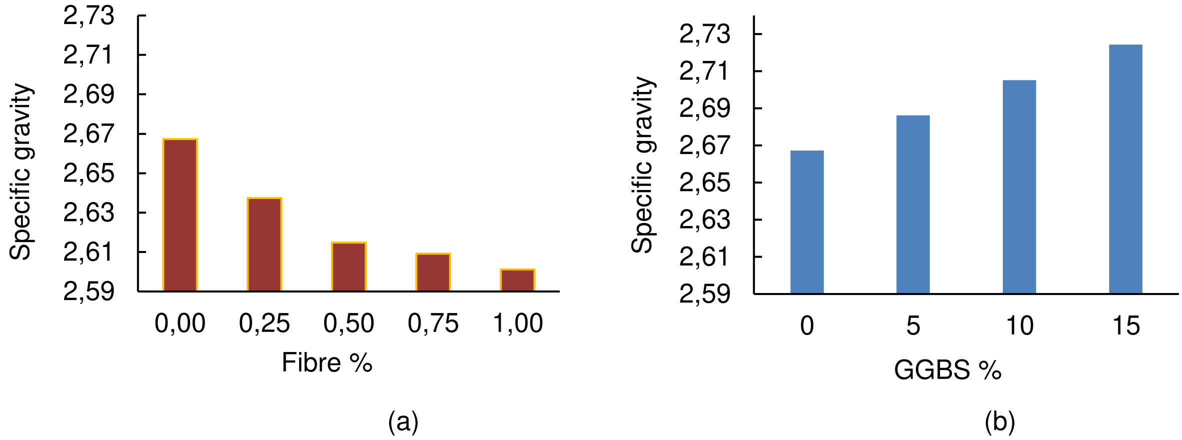


Figure 3. *Specific gravity of bentonite mixed with (a) fibre and (b) GGBS.*

3.1.3 Linear Shrinkage Test

The results of the linear shrinkage tests performed to determine soil shrinkage percentage by adding fibre and GGBS to the untreated bentonite are shown in Figure 4.

The linear shrinkage decreased with the addition of fibre because the inclusion of fibres caused less desiccation and the reinforced sample experienced less volumetric changes. The availability of more fibres in the mix increased surface contact with the soil, leading to more resistance to volume change upon desiccation. This means that the addition of fibre effectively improved the soil tensile strength, thus resisting shrinkage on desiccation, as shown in Figure 5. A similar observation was also reported by Mahmood et al. (2008). Taleb & Unsever (2022) also studied strength and swell behavioural change and properties of the clay-fibre mixes and found a similar result. The increment of soil stiffness with the addition of fibre content can be attributed to the bonding effect that enhances cohesion between soil particles through the fibres.

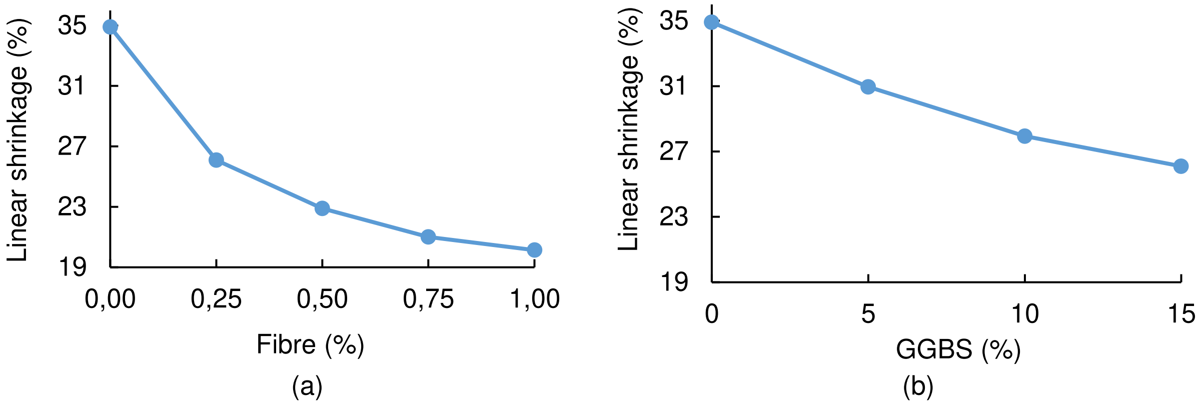


Figure 4. *Linear shrinkage of bentonite when mixed with (a) fibre and (b) GGBS.*

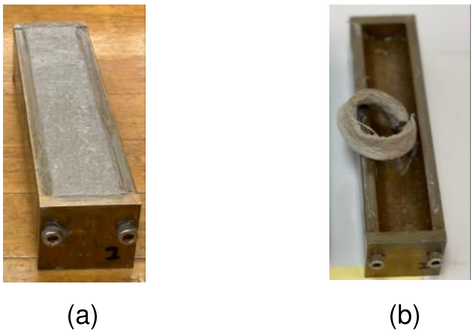


Figure 5. *Linear shrinkage test sample mixed with 99% bentonite and 1.0% fibre (a) before oven drying, and (b) after oven drying*

The reduction of linear shrinkage of various mixes with the addition of GGBS can be attributed to the chemical reactions between the GGBS and bentonite clay particles. The flocculation and agglomeration process between the GGBS-clay interactions reduced the soil plasticity, and therefore the sensitivity toward shrinkage with less moisture in the mixes, as evident from Figure 6. Furthermore, the aggregation of soil caused by GGBS-clay reactions may have resulted in smaller and disconnected pore voids such that water migration was restricted, thereby reducing the shrinkage.

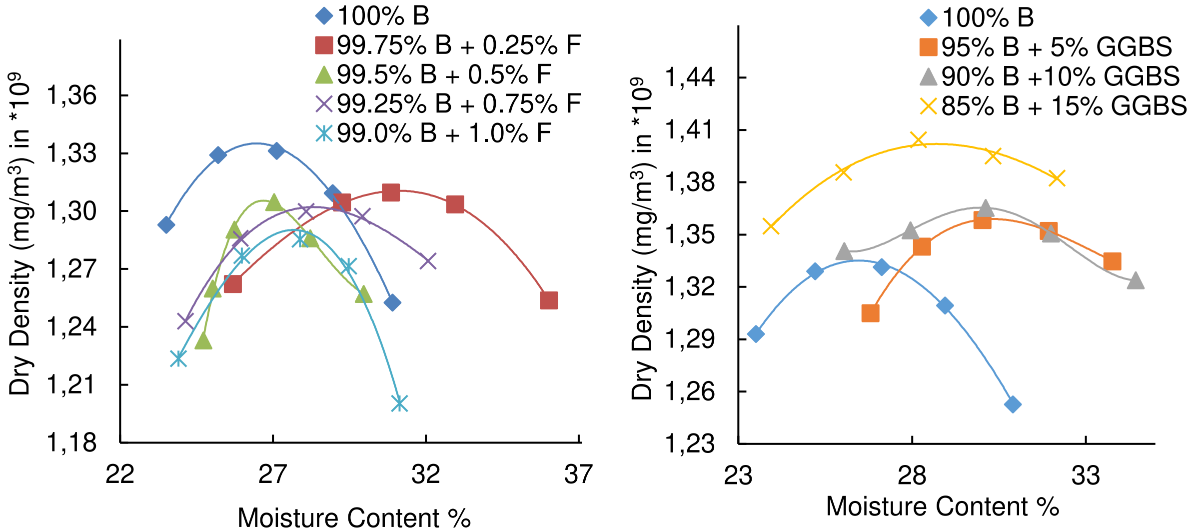
(a) (b)

Figure 6. *Linear shrinkage test sample mixed with 85% bentonite and 15% GGBS (a) before oven drying, and (b) after oven drying*

3.2 Engineering Properties

3.2.1 Compaction

The effect of polypropylene fibre, and GGBS, on the optimum moisture content and maximum dry density of the bentonite, is shown in Figure 7. The compaction curve as shown in Figure 7 fits with 3rd order polynomial, which was also used by Howell et al. (1997). The addition of fibre or GGBS resulted in no consistent trend in the optimum moisture content, which is similar to the result, reported by Khosrowshahi & Senol (2014), Nataraj & McManis (2001), Abdi & Ebrahimi (2005), and Miller & Rifai (2004).



(a) (b)

Figure 7. *Compaction curves of bentonite (B) when mixed with (a) fibre (F) and (b) GGBS.*

In the present study, the MDD increased with the addition of GGBS and decreased with fibre, as shown in Table 1 and Table 2. The increment in MDD with the addition of GGBS is imperative as the GGBS replaces the soil in the mixes, which has a relatively higher specific gravity of 3.20 compared to untreated bentonite, which is 2.67. The other reason could be that the presence of GGBS in the soil decreased the proportion of coarse material, making it difficult to attain good compaction. Similarly, the decrement in MDD with the addition of fibre can be attributed to the replacement of soil by the fibre added, which has a relatively lower specific gravity of 0.894 compared to untreated bentonite, i.e., 2.67.

Table 1*: OMC and MDD of bentonite (B) when mixed with fibre (F)*

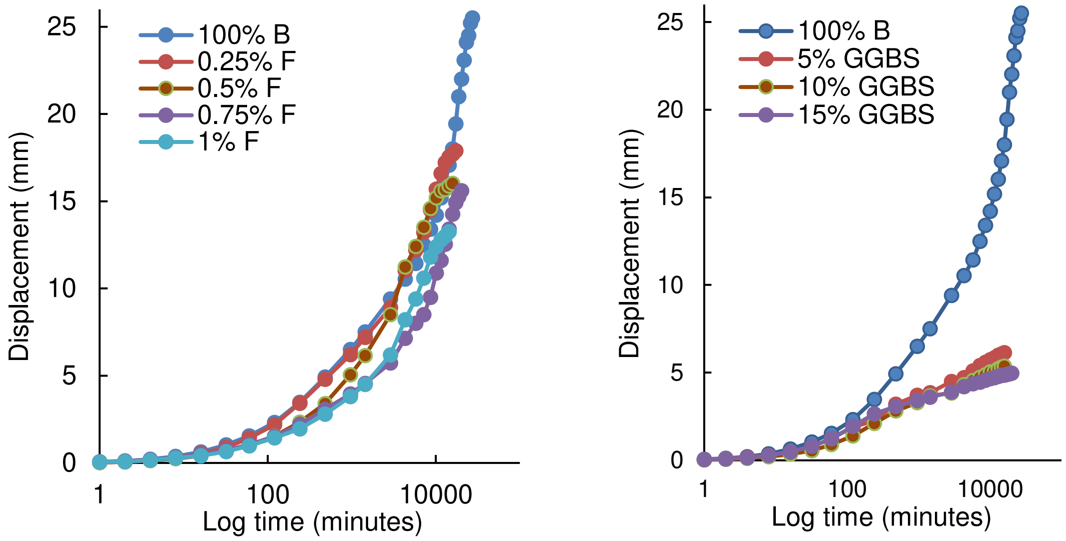
Mixes	100% B	99.75% B + 0.25% F	99.5% B + 0.5% F	99.25% B + 0.75% F	99.0% B + 1.0% F
OMC (%)	26	30.86	27	28.2	27.8
MDD (mg/m^3) in $*10^9$	1.328	1.310	1.306	1.300	1.286

Table 2: *OMC and MDD of bentonite (B) when mixed with GGBS*

Mixes	100% B	95% B + 5% GGBS	90% B +10% GGBS	85% B + 15% GGBS
OMC (%)	26	30.1	30.12	28.2
MDD (mg/m^3) in *10^9	1.328	1.359	1.365	1.404

3.2.2 Expansivity Index

According to the classification of potential expansion of soils using Expansion Index (EI) (ASTM D 4829-08), the soil is classified as “Very High” potential expansion for EI > 130. The EI of untreated bentonite was 988, which indicates very highly expansive soil. Figure 8 shows the EI test results in logarithmic time vs displacement graph of bentonite (B) when mixed with (a) fibre (F) and (b) GGBS. When treated with fibre, there was a significant reduction in the expansivity of the soil. As shown in Table 3, while increasing the fibre percentage in the mix, the expansivity index kept reducing, and at 1.0% fibre, the expansivity decreased by 47%. The reduction of the expansivity index with the addition of the fibre can be attributed to the strong interlocking mechanism between the fibre and bentonite clay particles, which prevented the bentonite sample from swelling. The other reason may be the friction generated between the bentonite and the fibre.



(a) (b)

Figure 8. *Expansivity index test results of bentonite (B) when mixed with (a) fibre (F) and (b) GGBS.*

Table 3: *Final deformation, EI, and reduced % of bentonite (B) when mixed with fibre and GGBS*

Mixes with Fibre %	Final Deformation (mm)	EI = ΔH * 1000 /H	Reduced %	Mixes with GGBS %	Final Deformation (mm)	EI = ΔH * 1000 /H	Reduced %
0.00	25.22	988	0	0	25.22	988	0
0.25	17.89	701	29	5	6.15	241	76
0.50	16.03	628	36	10	5.38	211	79
0.75	15.60	611	38	15	4.98	195	80
1.00	13.26	520	47				

The addition of GGBS resulted in a significant reduction in the expansivity of bentonite, as represented in Table 3. The expansivity was reduced with the increment of GGBS percentage, and decreased by 80% at 15% GGBS by dry weight. This trend may be attributed to the flocculation and agglomeration between the clay particles and GGBS. The results also illustrate the greater effectiveness of GGBS over fibre with the overall expansivity of bentonite decreased by 80% with GGBS relative to only 47% with the fibre. The expansion in bentonite was continuous and lasted for several days. For both the fibre and

GGBS, the swelling lasted for at least nine days. The test was terminated when the swelling rate was less than 0.0005 mm/hr. The results showed that the primary swelling occurred a faster rate between 10 to 100 minutes due to the inter-crystalline swelling and voids, whereas secondary swelling can be attributed to the double-layer repulsion in the clay particles (Kolay & Ramesh, 2015).

3.2.3 One-dimensional Consolidation

The consolidation parameters: compression index (C_c), swelling index (C_s), and pre-consolidation pressure (P_c) were calculated using the test results plotted on e – log p graph, illustrated in Figure 9. C_c, C_s and P_c for bentonite mixed with different percentages of fibre and GGBS is represented in Table 4. C_s for untreated bentonite was 0.0249 but decreased continuously to 0.0083 with 1.0% fibre, which represents a 66.4% reduction. A similar trend was observed for bentonite with GGBS, with C_s decreasing continuously with the addition of GGBS to 0.0134 at 15.0% GGBS, which represents a 46.07% reduction. This concludes that the addition of fibre and GGBS to the bentonite caused a decrease in the C_s. This reduction is because of the decline in the number of clay particles replaced by additives: fibre and GGBS; another reason is the robust tensile strength and strong compression strength of fibre, which reduces C_c. The reduction of C_s could also be attributed to the reason both fibre and GGBS play an influential role in developing additional bonding between the particle until the reinforcing was 0.75% with fibre or 10% with GGBS. Similar results were also reported by Taleb & Unsever (2022), Maheshwari et al. (2013), Yang et al. (2017), and Sharma & Rohin (2019).

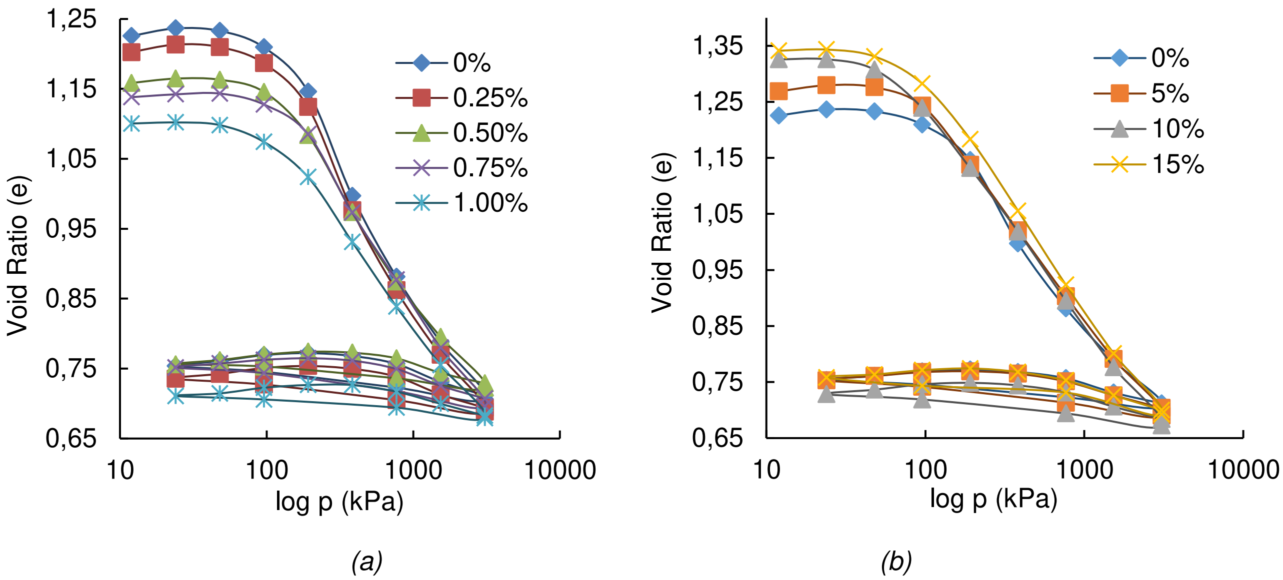


Figure 9. *e - log p graph for bentonite mixed with (a) different % of fibre, and (b) GGBS*

Table 4. *Compression index, swelling index, and pre-consolidation pressure for bentonite mixed with different % of fibre and GGBS*

Fibre %	Compression Index (C_c)	Swelling Index (C_s)	Pre-Consolidation Pressure (P_c) (kPa)	GGBS %	Compression Index (C_c)	Swelling Index (C_s)	Pre-Consolidation Pressure (P_c) (kPa)
0	0.495	0.0249	140	0	0.495	0.0249	140
0.25	0.490	0.0246	145	5	0.390	0.0194	97
0.50	0.366	0.0186	150	10	0.376	0.0158	81
0.75	0.276	0.0131	165	15	0.425	0.0134	88
1.00	0.307	0.0083	210				

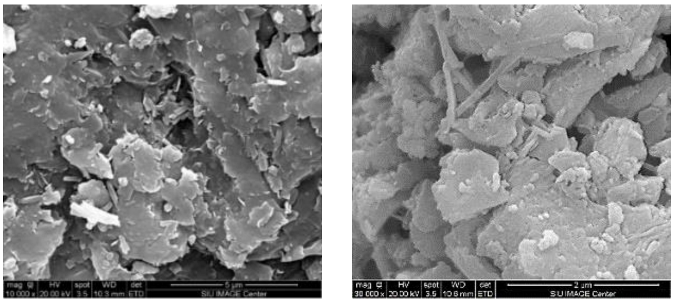
3.3 Microstructural Analysis

3.3.1 SEM and EDX Results

SEM and EDX tests were performed on bentonite, GGBS, and bentonite mixed with 5, 10, and 15% of GGBS. The SEM result shows that the clay particle of bentonite has a plate-like structure, where the particles were conglomerations and randomly oriented, as shown in Figure 10(a), at 10,000 times magnification. The EDX test results indicate that the significant constituents of bentonite are oxygen (36%), silica (43%), and alumina (9%). Iron (4%), calcium (3%), manganese (2%) and sodium (1%) were also present in a small percentage. This result matches with the research conducted by Arita et al. (2013).

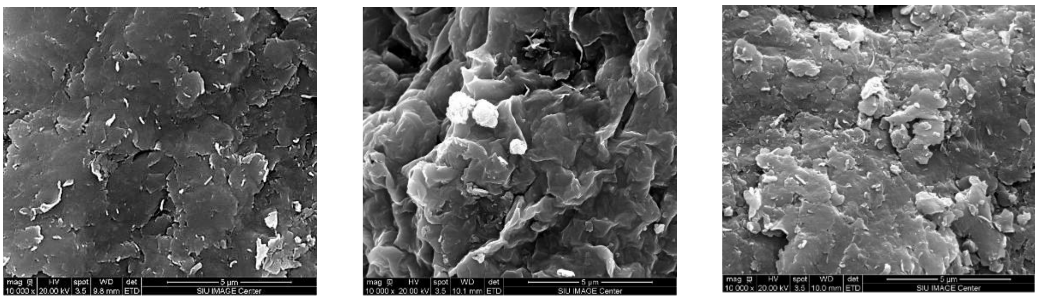
The SEM image of GGBS as shown in Figure 10(a) indicates GGBS consists of dense and bulky prismatic particles, clearly visible in the 10,000 times magnified SEM image. The presence of oxygen (48%), calcium (30%), and silica (11%) as significant constituents in the GGBS is confirmed by the EDX analysis, whereas manganese (3%), chromium (3%), and fluorine (3%) were also present in small amount. The significant presence of calcium signifies that the increase in GGBS substantially increases the presence of calcium content in the mix, which results in the formation of calcium silicate hydrate (CSH) gel (Rajini et al., 2021), which contributes to control the swelling and shrinkage of the expansive nature of bentonite by increasing the bonding among the particles.

The SEM image at 10,000 times magnification of bentonite mixed with the 5, 10 and 15% proportions of GGBS is shown in Figure 11. The EDX result shows that most elements are oxygen (47%), silica (32%), and alumina (12%) in the bentonite with 15% GGBS. This is evidence of the improvement in the compactness of the mixes with the increment of percentages of GGBS, which may enhance the compressive strength and reduce the porosity (Rajini et al., 2021). Rajini et al. (2021) also performed a micro-level study of fly ash and GGBS-based geopolymer and reported that the presence of calcium in the GGBS enables the formation of a compact gel structure and improves mechanical properties.



(a) (b)

Figure 10. *SEM image of (a) bentonite and (b) GGBS*



(a) (b) (c)

Figure 11. *(a) SEM image of (a) 95% bentonite + 5% GGBS, (b) 90% bentonite + 10% GGBS and (c) 85% bentonite + 15% GGBS*

3.3.2 Electrokinetic Results

The zeta-potential (ZP) test was performed for the suspensions of the samples of the bentonite, the GGBS and their mixes at the proportions of 5, 10 and 15% GGBS by dry weight. The temperature of the samples was 25°C at the time of measurement. Darrow et al. (2020) studied the zeta-potential of cation-treated soils and suggested that the influence of pH in zeta-potential is negligible, whereas changes in zeta potential depend moreover on temperature and montmorillonite sample.

Table 5. *Electrokinetic results*

Samples	Z-potential (mV)
100% Bentonite (B)	-30.9
100% GGBS	-12.3
95% B + 5% GGBS	-38.2
90% B + 10% GGBS	-40.7
85% B + 15% GGBS	-37.3

The electrokinetic test results are summarized in Table 5. The ZP for all the samples were negative with no charge reversal observed at any stage. The ZP calculation of untreated bentonite and GGBS particles in distilled water are -30.9 mV and -12.3 mV, and electrical conductivity is 0.462 and 0.376 mS/cm, respectively. The EDX test results of bentonite and GGBS shows the presence of the same cations such as Si^{4+} and Ca^{2+}, and anions, such as O^{2-}. With addition of 5% and 10% of GGBS to the bentonite, the ZP kept decreased and reached -40.7 mV, and with the addition of 15% of GGBS, the ZP increased slightly reaching -37.3 mV. This difference could be due to the development of charges at the edges by the transfer of ions in between the clay particles. The major presence and high negative charges of SiO_2 in the multiparticle mixes with bentonite control the charges in zeta potential (Otsuki & Hayagen, 2020). Akbulut & Arasan (2010) studied the influence of fly ash on the zeta potential of high-plasticity clay and found a decrement in zeta potential. The increase in electrolyte concentration and cation valency reduced the zeta-potential, and the response was due to the decrease in DDL thickness in both cases (Yukselen & Kaya, 2008). Their study also showed that the hydrated ionic radius significantly affects the zeta potential.

4. CONCLUSIONS

The use of polypropylene fibre and ground granulated blast furnace slag (GGBS) to stabilize the highly expansive commercial sodium bentonite was found to be effective via improved index and engineering properties. For the Atterberg limits, the liquid limits increased gradual, with the increment in fibre percentage in bentonite, due to the capillary characteristics of the fibre, while the plastic limit decreased as fibre is hydrophobic and chemically inert. For the bentonite treated with GGBS, the liquid and plastic limits decreased gradually, as the air voids and pore spaces available for moisture movement were filled with slag fines. Adding fibre to the bentonite reduced the specific gravity while adding GGBS increased the specific gravity. The specific gravity of fibre is lower, whereas that for the GGBS is higher than the untreated bentonite. The percentage of linear shrinkage for untreated bentonite decreased with treatment by fibre or GGBS, because the addition of fibre increased its surface contact with the soil causing excellent resistance to shrinkage and lesser desiccation, while the GGBS addition caused the flocculation and agglomeration process, reducing the sensitivity toward shrinkage with less moisture in the mix and disconnected pore voids restricting the inflow and outflow of water.

With the addition of fibre and GGBS, there were no noticeable changes in the optimum moisture content (OMC), but maximum dry density (MDD) decreased with the addition of fibre and increased with the addition of GGBS. This trend is attributed to the difference in specific gravity among the additives, which changes the density of the mix. In the expansivity index test, 25.5 mm of final heaving of untreated bentonite was reduced from 17.9 mm (29% of reduction) to 13.2 mm (47% of reduction) when mixed with 0.25% to 1.0% fibre, respectively. The addition of fibre creates a strong interlocking mechanism with the bentonite particles and generates friction, which prevents the mix from heaving. The reduction in Expansivity Index (EI) is more significant with the addition of GGBS relative to that of the fibre. The final heaving ranged from 6.1 mm (76% of reduction) to 5.0 mm (80% of reduction) when mixed with 5% to 15% of GGBS, respectively. This reduction may be because of flocculation and agglomeration between the GGBS and bentonite. With the addition of fibre, the swelling index reduced because of the robust tensile strength and strong compression strength, while the reduction in swelling index with the addition of GGBS resulted because of the replacement of clay particles by GGBS. SEM-EDX test results revealed that adding GGBS to the bentonite increased the calcium content in the soil by forming the CSA gel in the mix which helps to improve compactness, decreases porosity, and prevents the bentonite's swelling and shrinkage behaviour. The electrokinetic test results performed for the analysis of Zeta-potential (ZP) in the bentonite, GGBS and their mixes provided insight into the phenomenon of the diffused double layer in the mix.

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