Impacts of MgO waste:GGBS formulations on the performance of a stabilised natural high sulphate bearing soil

[1] *Adeleke, B.O., [2] Kinuthia, J.M., and [3] Oti, J.E.

[1-3] School of Engineering, Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd, CF37 1DL, UK

***Corresponding author.** Tel: +44 1443 482167, E-mail: blessing.adeleke@southwales.ac.uk

Abstract

Industrial and urban wastes have been generated overtime due to urban development with severe environmental and health implications. This paper reports the valorisation of waste and industrial by-product (magnesium oxide waste – MG1 and Ground Granulated Blastfurnace Slag – GGBS) to develop an alternative cementitious binder for suppressing swelling in high sulphate bearing soils, due to the formation of a highly expansive crystalline hydrate (ettringite) upon treatment with Portland Cement - PC or lime. Cylinder test specimens were developed using three MG1:GGBS proportions by weight (10:90, 20:80 and 30:70) to stabilise a natural Gypsum marl soil (GM) containing high levels of sulphate at varying stabiliser dosages (6, 8 and 10 wt.%), with PC as the control binder. UCS, Linear Expansion and SEM investigations were employed to assess the engineering suitability of the MG1:GGBS stabilised GM cylinder test specimen. Results suggest the viability of producing an alternative cementitious binder using up to 30 wt.% MgO-waste to successfully activate GGBS at stabiliser dosages of 6 - 10 wt.%. From a mechanical perspective, the MG1:GGBS stabilised GM soil was 1.5 – 3 times more than the control at 28 days moist curing age, while the resistance to linear expansion produced near zero swellings (0.13% – 0.2%) after 56 days, in comparison with the control of 3.2%. SEM micrographs showed a more compact structure with lesser voids and no morphology of ettringite. This new technology is expected to mitigate the environmental concerns of using PC and promote sustainable techniques of reusing industrial by-product materials for sulphate soils stabilisation.

Keywords: Sulphate bearing soil; Magnesium oxide waste; Soil stabilization; Mechanical strength; Linear expansion; Scanning electron microscopy; Ettringite.

1. INTRODUCTION

The choice of soil type on which various civil engineering structures are built is virtually impossible, whereby, requiring civil engineers to work with varied type of soils. However, with respect to civil engineering construction, some of the soil deposits in their natural form are suitable, others are suitable upon treatment (stabilisation), while some are unsuitable after treatment (problematic soil) due to their inherent composition that causes significant forms of swelling. Typical problematic soils are those containing certain levels of gypsum or calcium sulphates commonly known as sulphate-bearing soils (Kinuthia et al., 1999, Seco et al., 2011,

Seco et al., 2017, Diaz Caselles et al., 2020, Li et al., 2020). Pruška and Šedivý (2015) and Dang et al. (2016) described the swelling phenomenon in soils as a three-dimensional problem, which occurs when the fine particles of a soil material undergo a volumetric increase in size due to the absorption of water from its surrounding as a result of the incessant changes or fluctuation in moisture content caused by unstable seasonal weather conditions and flooding. This volumetric increase in size is of key importance to the civil engineering industry due to the generation of swelling and large magnitudes of swelling pressure, which leads to destruction and additional refurbishment cost to structures (building foundations, rail tracks, highway pavements, airports runways, tunnels, pipes, bridges, seaports etc) constructed in and on the soil (Jones and Jefferson, 2012, Pruška and Šedivý, 2015).

Stabilisation of soils has been found to be economically and technically effective in reducing swellings in expansive soils, by chemically altering the properties of the soil, which improves the geotechnical and engineering properties of the stabilised/treated soil, using Portland cement and Lime (Calcium based stabilisers) as activators, with various industrial by-products (Ground Granulated Blast Slag - GGBS, Pulverised Fuel Ash - PFA, Silica Fume - SF, limestone dust etc.) (Kinuthia and Oti, 2012, Miqueleiz et al., 2012, Phanikumar and Singla, 2016, Cheshomi et al., 2017, Seco et al., 2017). Seco et al. (2011); Cheng and Heidari (2018) and Schanz et al. (2018), all attributed this swelling tendency to the mineralogical composition/physiochemical properties of the soil, type of clay with respect to Base Exchange Capacity (or cation exchange capacity), quantity of clay, charge of exchangeable cations in the interlayer space, soil moisture content, plasticity and dry density and the type of material used in case of soil stabilisation. A number of studies have investigated and reported the reduction of this swelling tendency through the application of calcium-based materials (Lime and PC) for stabilisation purposes (Wang et al., 2003, Oti et al., 2009a, Oti et al., 2009b, Kinuthia and Oti, 2012). However, researchers also highlighted that sulphate-bearing soils are prone to strength loss, stability and durability risks due to the generation of expansive reactions, when treated or stabilised with calcium-based stabilisers (Kinuthia et al., 1999, Kinuthia and Wild, 2001, Wang et al., 2003, Rahmat and Kinuthia, 2011b, Nidzam and Kinuthia, 2010, Diaz Caselles et al., 2020). The increased expansion was believed to be partly caused by the formation of a highly expansive crystalline, and hydrated mineral from the hydration reaction of calcium (obtained from PC or Lime), alumina, silica, sulphate in the presence of water known as ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$] (Wild et al., 1999, Giliberto et al., 2008, Rahmat and Kinuthia, 2011a, Norman et al., 2013).

Apart from the negative impacts of calcium-based stabilisers (CBS) on sulphate bearing soils, the deleterious effects of their production on the environment with respect to high energy consumption (5240 MJ/ton for PC), increased emission of greenhouse gases and a large amount of carbon dioxide (CO_2) footprint (0.66 – 0.9t CO_2 per tonne for PC) cannot be overemphasized (Kinuthia and Wild, 2001, Juenger et al., 2011, Olivier et al., 2012, Behnood, 2018, Wang et al., 2019, Olivier and Peters, 2019). Furthermore, there is a current substantial growth in the amount of stored or landfilled wastes, which had considerably grown over the past years due to the reliance of the global economy on the development of materials (e.g. PC) with exhaustible natural resources (Górak et al., 2020). Taking the construction industry as a case study, there is a significant consumption of about 40 – 75% natural (virgin) materials, coupled with the generation of proportionate wastes during its extraction, and all through the stages of manufacture of the finished product; thus, the demand for the natural materials is growing and growing each year (John et al., 2011, El-Dieb and Kanaan, 2018, Górak et al., 2020). Therefore, current industrial organizations should endeavor to achieve sustainability through the effective

management of generated wastes (Gopinath et al., 2018). Goals nine and eleven of the United Nations sustainable development goals aimed at *''building resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" and to ''make cities and human settlements inclusive, safe, resilient and sustainable"* (United-Nations, 2015). Based on this understanding, we are now faced with a situation where the global construction industry is rediscovering large-scale interest in materials that, for decades, held largely niche or curiosity value (e.g. magnesium oxide - MgO) leading to an ongoing search for alternatives to PC (Juenger et al., 2011, Juenger and Siddique, 2015).

Recently, magnesium oxide (MgO) cementitious systems have been investigated by various researchers to mitigate the negative environmental impacts of PC, by employing it as an activator within a cementitious binder system (Jin et al., 2015, Yi et al., 2016, Wang et al., 2016), and demonstrated positive potentials to performing the expected functions of an activator within cementitious binder systems. Yi et al. (2015b) compared the use of MgO and PC for developing cementitious binder systems and found a 70 - 72% less energy consumption, 65 - 79% CO_2 emission reduction and 6 - 13% reduction in the cost of MgO production compared to PC. Generally, the principal cementitious hydrate from the hydration reaction of CBS (e.g PC) is the Calcium Silicate Hydrate gel (C-S-H). Hence, a cementitious binder system that is based on MgO as the primary alkaline activator results in the formation of a Magnesium Silicate Hydrate gel (M-S-H) gel that is similar to the C-S-H gel (Wu et al., 2018). The formation of the nanosized phyllosilicates gel cementitious hydrate (M-S-H gel) using MgO demonstrated its potentials within a $MgO\text{-}SiO_2\text{-}H_2O$ system using cement pastes (Li et al., 2014, Roosz et al., 2015, Bernard et al., 2019). MgO is produced majorly from Magnesite ($MgCO_3$), which is the magnesium end member of an isomorphous series of carbonates occurs naturally as a sedimentary rock (Jin and Al-Tabbaa, 2014). Magnesite mines remains the major source of raw material for the production of MgO, amounting to about 20 million tonnes per year (80% of which is produced in China) and other sources for MgO production are from brines and seawater (Gu et al., 2014). This claim was also corroborated by the United States geological survey, which estimated a total production of 6970 metric tonnes of magnesite in the world with China coming tops with a production of 4900 metric tonnes and Spain (the only European country with magnesite deposits) with a production of 280 metric tonnes (USGS, 2020). Therefore, the large production of magnesite with the sole aim of producing MgO provides a basis for the expected production and availability of MgO wastes.

MgO can be considered a more environmentally friendly stabiliser additive to PC because of its lower manufacturing impact/cost (Ruan and Unluer, 2016). Yi et al. (2014) demonstrated that after 28 days of moist curing, an appropriate proportion of MgO and GGBS enhanced the mechanical strength properties of a stabilised soil in comparison with PC. Several researchers corroborated this claim by suggesting that the enhancement of the physical and mechanical properties of a natural soil is due to the formation of the C-S-H gel and M-S-H gel (Jin et al., 2015, Yi et al., 2016, Goodarzi and Movahedrad, 2017). The reactivity and economic suitability of low-grade magnesium oxides obtained as by-products in the calcined magnesite manufacturing was demonstrated by del Valle-Zermeño et al. (2015) for environmental applications in remediation and/or wastewater treatment. Seco et al. (2017) also observed that magnesium-based additive enhanced the engineering properties of sulphate soils better than calcium-based ones. In that investigation, five sulphate soils with no clear sulphate content reached unconfined compressive strength above 10 MPa after 21 days, surpassing the requirements of a subbase layer (Ardah et al., 2017). Another beneficial effect of the magnesium stabilisation was the decrease of the soils' swell strain after prolonged exposure to

moisture. Li et al. (2020) demonstrated the advantage of a MgO-GGBS binder in a sulphate soil against swelling and better mechanical strength gain after test samples were soaked when compared to PC. These results suggest the potential of stabilisation of local sulphate soils with Mg based binders. Currently, experimental studies on soils stabilisation using MgO based binders are mainly focused on natural soils, with the suggestion of using about 10 - 20% stabiliser dosage (Gu et al., 2014, Yi et al., 2015a, Yi et al., 2016). In addition, recent investigations on sulphate soil stabilisation using MgO suggested a 4% stabiliser dosage for a natural sulphate-bearing soil with no clear indication of its sulphate content (Seco et al., 2017), while Li et al. (2020) also suggested a 10% stabiliser dosage for an artificially induced sulphate bearing Kaolinite clay with a 3.6wt.% bassanite (gypsum) content (2wt.% sulphate).

Due to the lack/insufficient amount of knowledge on the appropriate MgO based stabiliser dosage for stabilising natural high sulphate soils, possibility of developing cementitious binder systems using MgO waste as an activator as opposed to previous studies that employed the use of commercial MgO binders and experimental simulation of a sulphate soil system, and potential application of the developed cementitious binder to reduce swelling in natural high sulphate soil using the technique of chemical stabilisation, this paper presents an evaluation of the engineering performance and microstructural properties of a stabilised natural high sulphate soil using MgO-waste activated GGBS binder. It is expected that the use of reactive MgO wastes could become an additional environmental advantage by reducing the manufacturing or reliance on commercial MgO products (which could be expensive) rather than utilising its waste streams that was obtained during the manufacturing process. In addition, there will be a reduction in the production of CBS that are deleterious to the environment with respect to high energy consumption, increased emission of greenhouse gases, large amount of CO_2 footprint (Juenger et al., 2011, Olivier et al., 2012) and the potential reduction of swelling in high sulphate-bearing soils (Kinuthia and Wild, 2001, Seco et al., 2017, Behnood, 2018).

2. METHODOLOGY

2.1 Materials

The materials used in this study were Gypsum marl clay (GM), Portland cement - PC (CEM I-42.5N), Magnesium oxide waste (MG1), Ground Granulated Blast-furnace Slag (GGBS) and De-ionized water. GM was a natural soil with approximately 22 wt.% sulphate (SO_3) content that was obtained from the Ebro's Valley in Navarra, Northern Spain. PC was manufactured in compliance with BS EN 197-1:2011 and supplied by Lafarge Cement UK, while GGBS as a latent hydraulic material was supplied and used in accordance with BS EN 15167-1:2006 by Civil and Marine Ltd, Llanwern, Newport, UK. MG1 is a waste product obtained as a bye-product during the mining activities of magnesite ($MgCO_3$) by Magnesitas Navarras, Navarra, Spain. Table 1 shows the corresponding chemical compositions and other relevant properties for the raw materials. The chemical compositions were obtained using a portable benchtop TXRF X-ray Fluorescence spectrometer, which is comprised of an air-cooled low power X-ray metal-ceramic tube with a molybdenum target. It runs at a max power of 50 W with a liquid nitrogen-free Silicon Drift Detector (SSD)(BS EN 15309:2007, BS ISO 18227:2014).

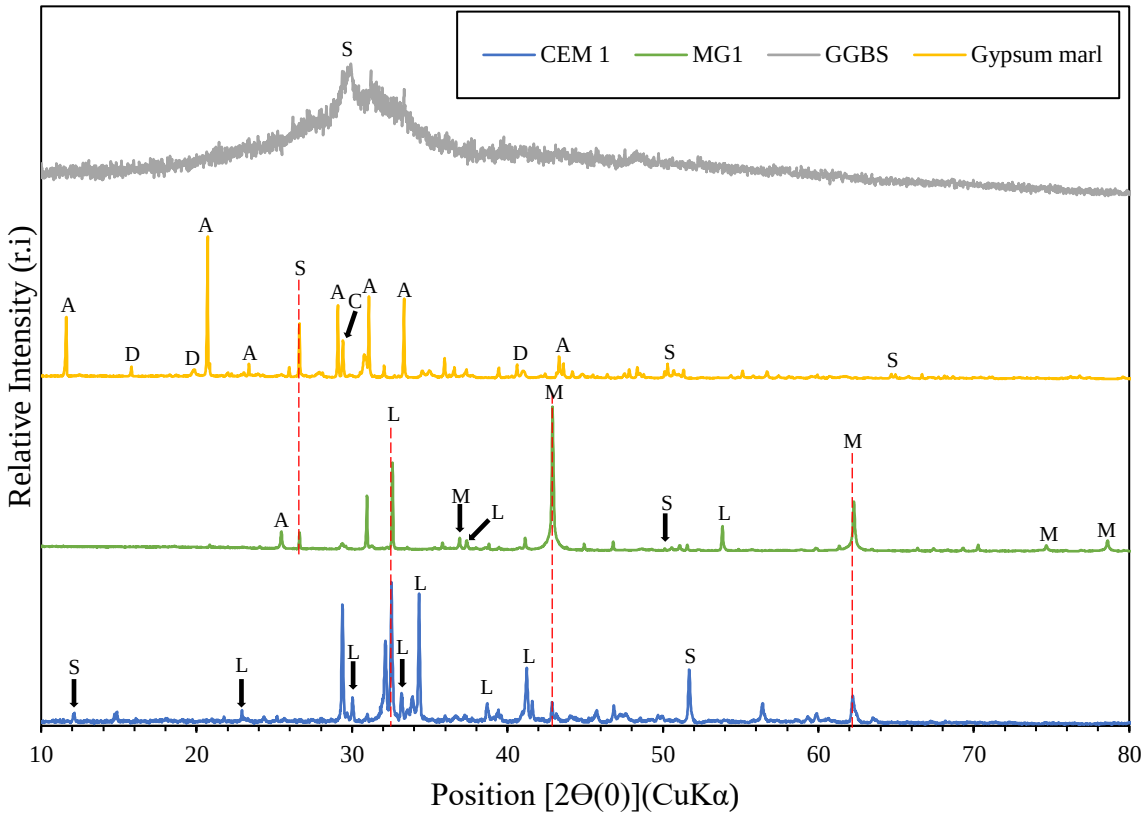
186 **Table 1:** Chemical composition of Kaolinite clay, CEM I and GP

Oxides	Composition (wt%)			
	CEM I	**MG1**	**GGBS**	**Gypsum marl**
CaO	61.49	9.39	37.99	23.16
SiO_2	18.84	2.51	35.54	16.97
Al_2O_3	4.77	0.52	11.46	6.70
MgO	3.54	56.26	8.78	3.21
Fe_2O_3	2.87	2.13	0.42	2.03
Mn_2O_3	0.05	0.15	0.43	0.04
SO_3	3.12	6.22	1.54	22.39
TiO_2	0.26	0.01	0.70	0.21
K_2O	0.57	0.18	0.43	1.39
Na_2O	0.02	0.09	0.37	0.77
P_2O_5	0.10	0.06	0.02	0.07
V_2O_5	0.06	0.10	0.04	0.02
BaO	0.05	0.01	0.09	0.02
L.O.I.	4.30	22.30	2.00	23.00
Physical Properties				
Colour	Grey	Light-Brown	Off-white	Grey
Specific gravity	3.16	2.86	2.90	2.33
Reactivity (m)	-	30	-	-

187

188

189 The X – ray diffractograms in Figure 1 showed the crystallized forms for the primary materials
190 (CEM I, MG1, GGBS and GM) used in this study as periclase, lime, quartz, gypsum
191 (anhydrite), dolomite and calcite. However, observation showed a glassy phase for GGBS. The
192 particle distribution curves for the raw materials are shown in Figure 2 and indicates a rather
193 higher proportions of fine particles for MG1 in relation to CEM I. The reactivity of MG1 was
194 carried as described by Shand (2006) to determine the rate of acid neutralization and
195 established as a reactive MgO.



Periclase (MgO) - M, Lime (CaO) – L, Quartz (SiO_2) – S, Gypsum (Anhydrite - $CaSO_4$) – A, Dolomite ($CaMg(O_6)_2$) – D, Calcite ($CaCO_3$) - C

Figure 1: X-ray diffractograms for the materials

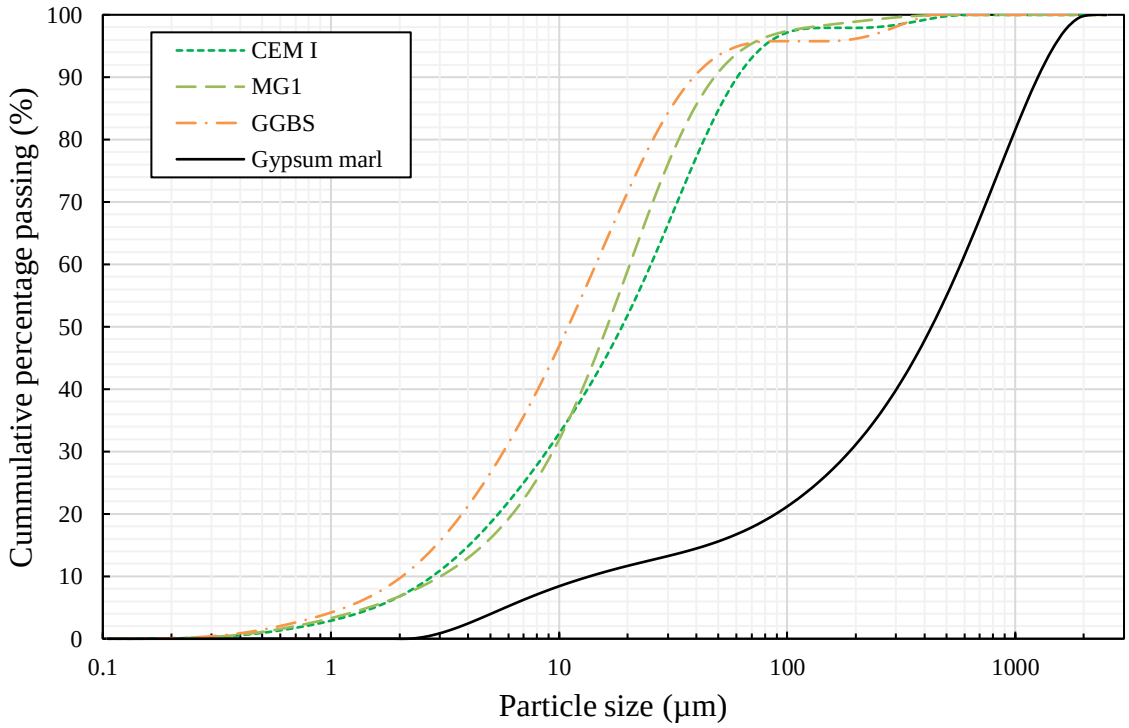


Figure 2: Particle size distribution curves for the raw materials

2.2 Mix design, test sample preparation and experimental testing

Tables 2 shows the mix compositions that were developed and used in this study to produce cylindrical test specimens. In accordance with the findings of Adeleke et al. (2020), an 8 wt.% optimum stabilizer dosage using CEM I for a simulated high sulphate bearing soil was used as the control for the current study. The MG1:GGBS binder compositions were developed at three MG1:GGBS proportions by weight of 10 : 90, 20 : 80 and 30 : 70 to stabilise GM at varying stabiliser dosages of 6, 8 and 10 wt.%. The MG1 content within the MG1:GGBS binder compositions corresponds to 10, 20 and 30wt.%. It is imperative to note that the mix code of 1M, 2M and 3M which denotes 10wt.%, 20wt.% and 30wt.% of MG1, while 7G, 8G and 9G which denotes 70wt.%, 80wt.% and 90wt.% of GGBS will be used all throughout this study.

Table 2: Mix design using Gypsum marl soil

Mix code	Stabiliser dosage (wt.%)	Mix composition	Binders (g)			Target Material (g)	Water (g)	Total weight (g)
			M	G	CEM I	GM		
BG1a	8	8CEM I - GM	-	-	26.2	374.4	51.9	452.5
BG6-1	6	1M:9G - GM	2.3	20.4	-	377.9	47.6	448.2
BG6-2		2M:8G - GM	4.5	18.1	-	377.9	47.6	448.2
BG6-3		3M:7G - GM	6.8	15.9	-	377.9	47.6	448.2
BG8-1	8	1M:9G - GM	3.0	26.7	-	370.9	47.6	448.2
BG8-2		2M:8G - GM	5.9	23.7	-	370.9	47.6	448.2
BG8-3		3M:7G - GM	8.9	20.8	-	370.9	47.6	448.2
BG10-1	10	1M:9G - GM	3.6	32.8	-	364.2	47.6	448.2
BG10-2		2M:8G - GM	7.3	29.1	-	364.2	47.6	448.2
BG10-3		3M:7G - GM	10.9	25.5	-	364.2	47.6	448.2

M – MG1; CEM I - Portland cement; G - Ground Granulated Blastfurnace slag; GM - Gypsum marl soil

Dry materials capable of producing three compacted cylindrical test specimens from each binder composition, each of dimensions 50 mm in diameter and 100 mm in length, were thoroughly mixed in a mechanical mixer for 2 minutes before slowly introducing the predetermined amount of water. Intermittent hand mixing with a palette knife was accomplished for another 2 minutes to achieve a homogeneous mix, and to ensure that the full potential of stabilisation was achieved. Each compacted cylindrical test specimen was made by placing the wet material of each sample in a steel mould fitted with a collar (Figure 3), so as to accommodate all the materials. This material was then subjected to a static compression using a hydraulic jack to achieve the desired maximum dry density (MDD) in a loading frame, while the volume was kept constant. Afterwards, the cylindrical test specimen was wiped of any

clinging soil particles or oil stains, weighed, labelled, and wrapped with a cling film to ensure minimal loss of moisture. Thereafter, the specimens were placed in a sealed plastic box, stored for moist curing at a temperature of 20 ± 2^0C for a duration of 7, 28 and 56 days prior to testing. The plastic container helped in the regulation of the humidity at which they are cured, and prevent any deleterious carbonation effect which is common to stabilised soil systems.

The mechanical performance of the cylindrical test specimen was investigated using the Unconfined Compression Strength (UCS) test in compliance with BS 1924 - 2:2018, using an Instron 8502 mechanical testing machine, which is capable of loading over 10kN (Figure 4). Three test samples per mix composition were tested for compressive strength at the end of the moist curing period of 7, 28 and 56 days until failure occurs at a compression strain rate of 1 mm/minute. The maximum load at the point of failure for each cylindrical test specimen was recorded and the mean of three strength values are used as the representative UCS value for the mix composition. The swelling/shrinkage performance (%) of the cylindrical test specimen was achieved by utilising a Linear expansion test. This was carried out in accordance with BS EN 13286-49:2004 by measuring the amount of expansion using a Perspex cell, which was equipped with a digital dial gauge (Figure 5). The linear expansion measurements were monitored and recorded during the moist curing and partial soaking period in water for every 24 hours, until no further significant swelling was detected.

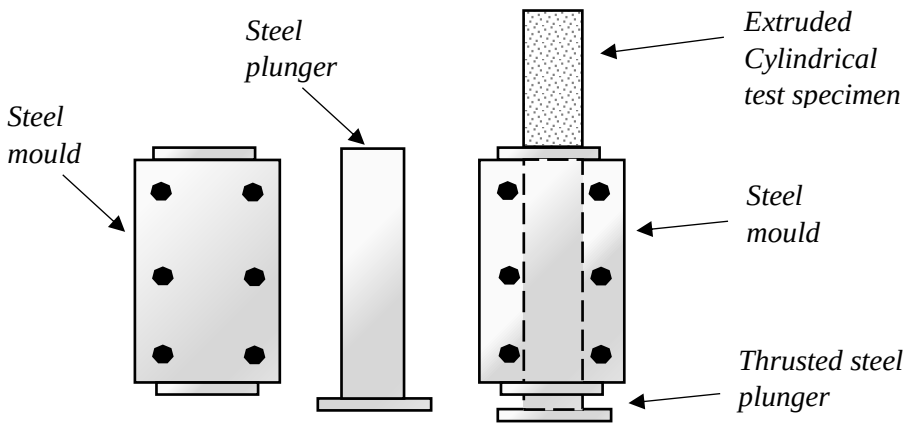


Figure 3: Steel mould with the extruded cylindrical test specimen

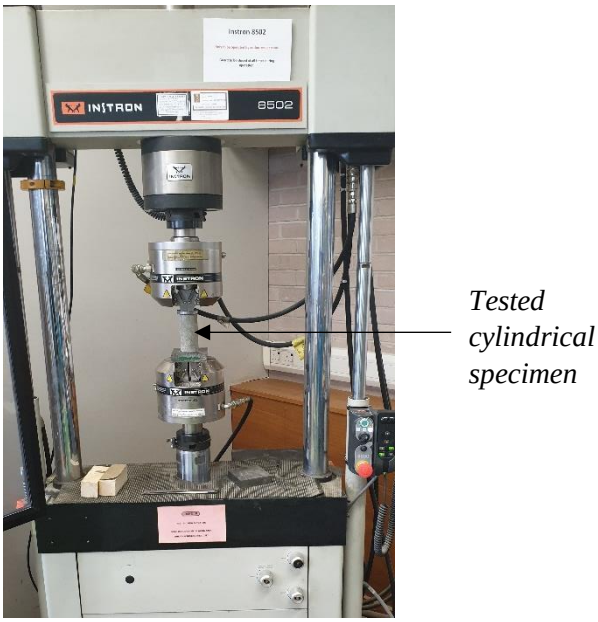


Figure 4: An Instron 8502 mechanical testing machine

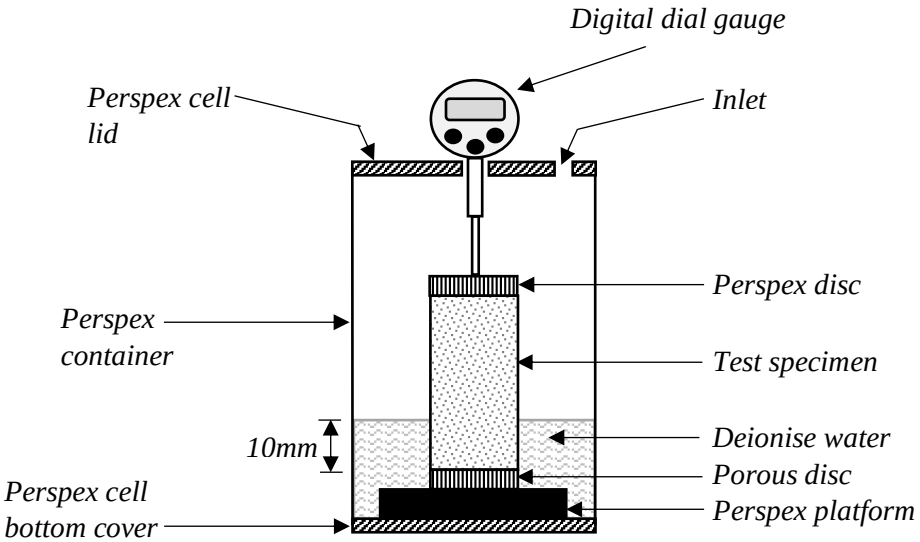


Figure 5: Schematic diagram of a Perspex cell test set-up

A microstructural investigation was employed to analyse the morphology of each hydrated dried specimen using a MIRA3 TESCAN Scanning Electron Microscope (SEM), which was fitted with a Solid-state Backscattered (electron) Detector (SBD). Initial sample preparation was carried out by placing the cylindrical test specimen in a desiccator cabinet, and at a low temperature of 40^0C containing silica gel for accelerated drying of the specimen. Thereafter, a diamond wheel tile cutter was used to produce small slices (5mm thickness) of the dried cylindrical specimen. Each slice from the sample was initially polished, gold coated and infused on a stub made up of carbon tapings to make the specimen electrically conductive. Afterwards, the stub was mounted on the sample stand in the SEM chamber before the commencement of the SEM analysis.

3. RESULTS

3.1 Unconfined Compressive Strength (UCS) test

Figure 6 presents the Unconfined Compressive Strength (UCS) results of GM cylinder test specimens (10wt.% MG1:90wt.% GGBS – 1M:9G; 20wt.% MG1:80wt.% GGBS – 2M:8G; 30wt.% MG1:70wt.% GGBS – 3M:7G proportions), which were stabilised with 6, 8 and 10 wt.% of MG1:GGBS binder compositions at both 7, 28 and 56 days moist curing periods. A steady increase in strength development was observed for all the GM cylinder test specimens in all cases of stabiliser dosages (6, 8 and 10 wt.%) at every moist curing age of 7, 28 and 56 days. However, an average rate of strength development was more pronounced at the 28 days moist curing age in comparison with 7 and 56 days for all the binder compositions at varying stabiliser dosages (6 – 10wt.%).

At 7 days moist curing age, a gradual trend of strength increase was experienced by all the GM cylinder test specimens with increasing MG1 content within the varying MG1:GGBS binder compositions (1M:9G; 2M:8G and 3M:7G) for all stabiliser dosages (6 – 10 wt.%). This trend was not the case for other moist curing ages as there was a staggered strength development for the binder compositions at 28 days, with blend composition 2M:8G attaining the highest UCS strength across the stabiliser dosages. However, a reduction or slow increase in UCS was observed at 56 days moist curing for every increase in MG1 content within the MG1:GGBS binder compositions at all stabiliser dosages (6 – 10 wt.%). The lowest magnitude of UCS value was produced by the control mix cylinder test specimen composed of 8wt.% CEM I at 28 days moist curing age at all cases of stabiliser dosage (6, 8 and 10 wt.%), while the largest strength magnitude was experienced by cylinder specimens stabilised with 20wt.% MG1:80wt.% GGBS composition. At later moist curing age (56 days), this trend changed in favour of the cylinder test specimens stabilised with 10wt.% MG1:90wt.% GGBS composition to achieve the maximum UCS value of 6769, 9320 and 14626 kN/m^2 at 6, 8 and 10wt.% stabiliser dosages, respectively. An average strength increase was observed within the range of 11 – 48%, 20 – 45% and 12 – 47% at every increase in stabiliser dosage (6, 8 and 10wt.%) for all the GM cylinder test specimens stabilised with 1M:9G, 2M:8G and 3M:7G binder compositions respectively.

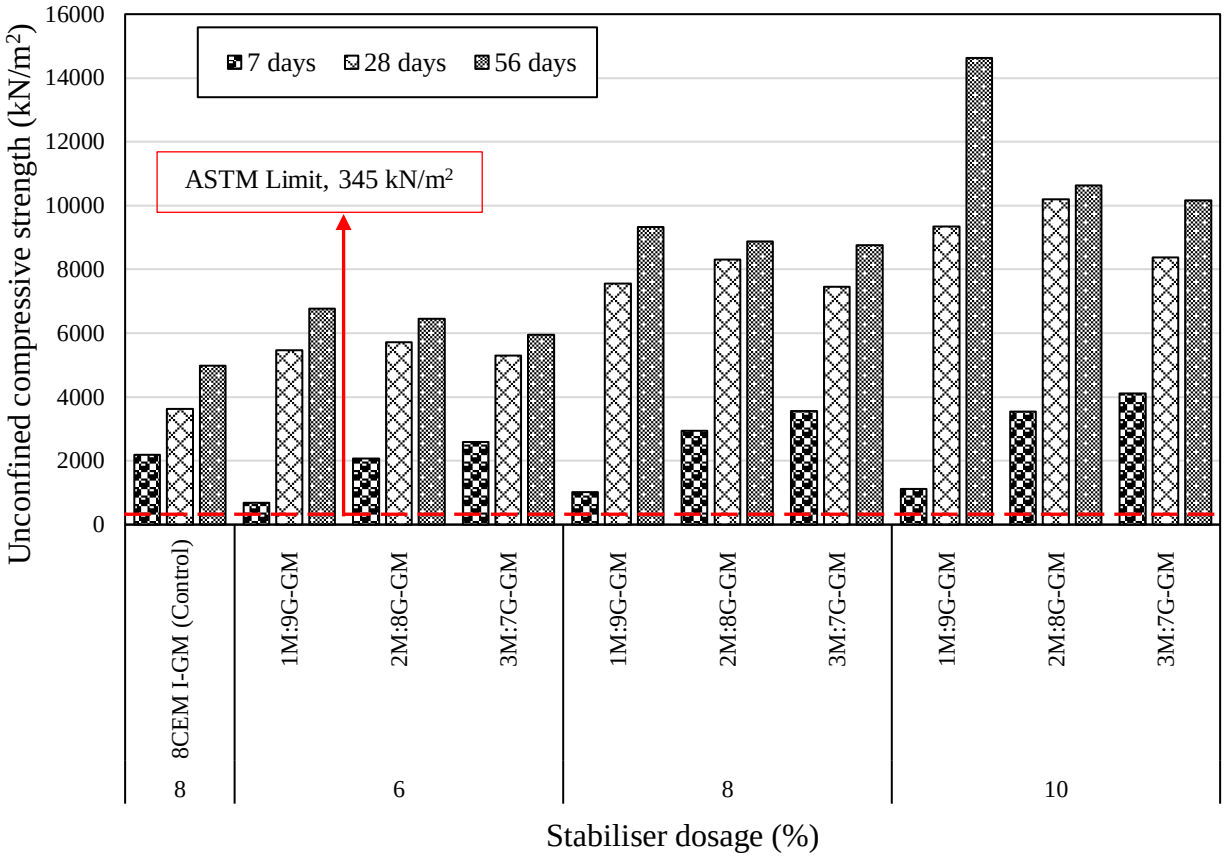


Figure 6: Combined UCS test results at 7, 28 and 56 days curing age for GM cylinder test specimens stabilised with varying stabiliser dosages **(6, 8 & 10 wt.%)** of MgO-waste activated GGBS binder compositions

Generally, all the cylinder specimens that were produced using the MG1:GGBS binder compositions (1M:9G; 2M:8G and 3M:7G) produced superior strength performances at all the investigated stabiliser dosages in comparison with the control cylinder specimen, at the standardised curing age of 28 days.

3.2 Linear expansion test

The typical linear expansion plots for GM cylinder test specimens, that were stabilised with 6, 8 and 10 wt.% of MG1:GGBS binder contents during a moist curing and subsequent partial soaking conditions is shown in Figure 7 – 9.

A marginal increase in linear expansion can be seen for the GM cylinder test specimens produced for the three MG1:GGBS binder contents (6, 8 and 10 wt.%) after 7 days of moist curing. A maximum linear expansion of 9% was experienced by cylinder specimens stabilised with 6 wt.% of 10wt.% MG1:90wt.% GGBS blend composition, while the control cylinder specimen with 8 wt.% CEM I experienced a maximum expansion of 3.2% at both 8 and 10 wt.% binder dosage. It was also observed that there was a reduction in linear expansion for every increase in the MG1 waste content within the MG1:GGBS blend compositions. This observation suggests why the lowest linear expansion of 0.13, 0.04 and 0.20% were detected for the GM cylinder test specimens containing 30wt.% MG1:70wt.% GGBS blend composition at 6, 8 and 10 wt.% binder dosage after 49 days of partial soaking in deionised water.

Furthermore, a reduction in the linear expansion was evident in the GM cylinder test specimens containing 10wt.% MG1:90wt.% GGBS and 20wt.% MG1:80wt.% GGBS blend composition with every increase in the amount of binder dosage. However, this was not the case for cylinder test specimens with 30wt.% MG1:70%wt.GGBS blend composition, as they already exhibited stability in linear expansion using a range of 6 – 8wt.% stabiliser dosage. A trend of potential propagation of further linear expansion at increased stabiliser content for cylinder specimen with increased level of MG1 content is evident in Figure 9. This suggests that stabiliser dosages above 10 wt.% could result in the propagation of further linear expansion. Observation also showed that the GM cylinder test specimens that were produced using the control blend mix (8 wt.% CEM I) and 10wt.% MG1:90wt.% GGBS blend at 6 wt.% binder content, exceeded both expansion benchmarks as established in the American standard of measurement (ASTM) – 1.5% (ASTM D4829 - 11) and the legal limit of 3% in Spain as reported by Seco et al. (2011).for stabilised soil systems. Furthermore, the GM cylinder test specimen with 10wt.% MG1:90wt.% GGBS blend slightly went over the ASTM limit (1.5%) at an increased binder dosage of 8 wt.%, after 17 days of been partially soaked in deionised water.

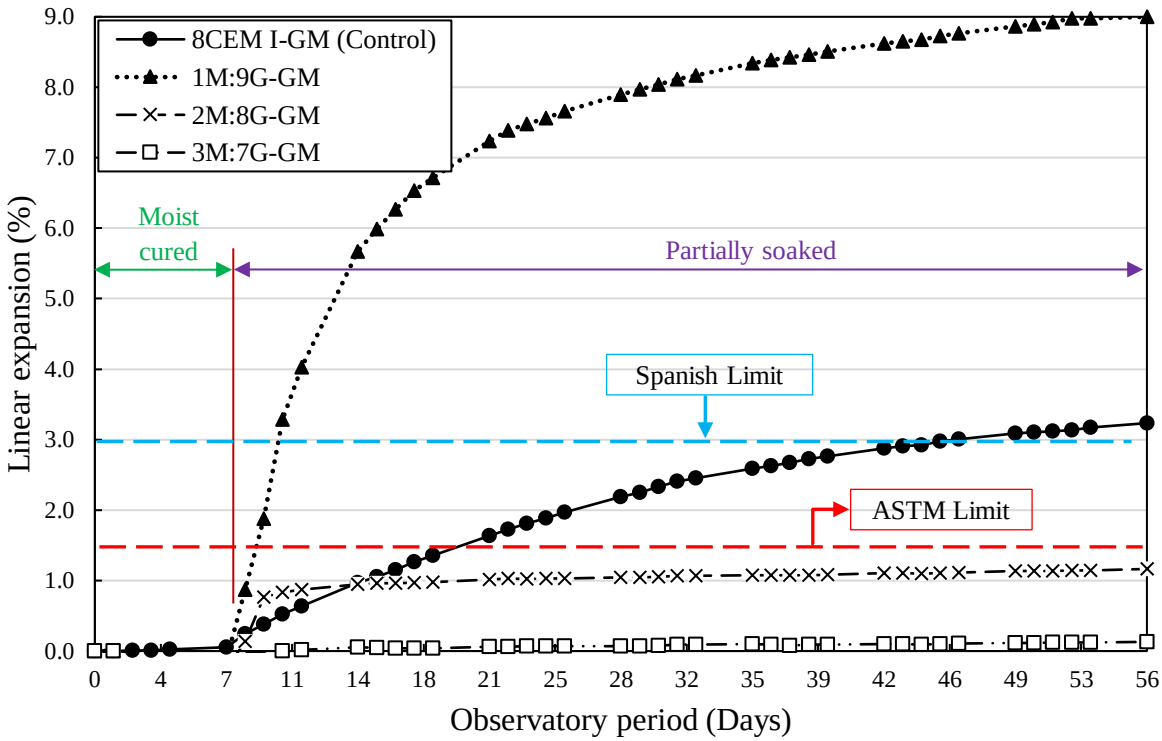


Figure 7: Typical plots of linear expansion against observatory period for GM cylinder test specimens containing varying levels of MG1:GGBS content and stabilised with **6 wt.%** binder dosage at both moist and partially soaked curing conditions

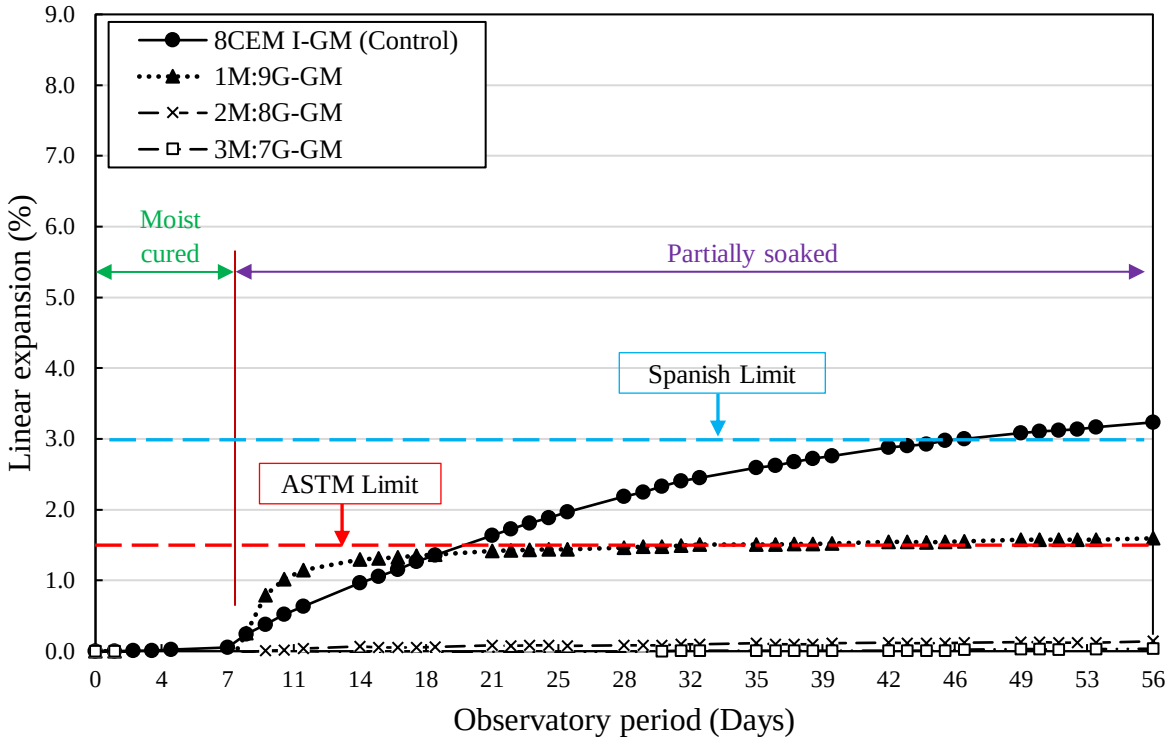


Figure 8: Typical plots of linear expansion against observatory period for GM cylinder test specimens containing varying levels of MG1:GGBS content and stabilised with **8 wt.%** binder dosage at both moist and partially soaked curing conditions

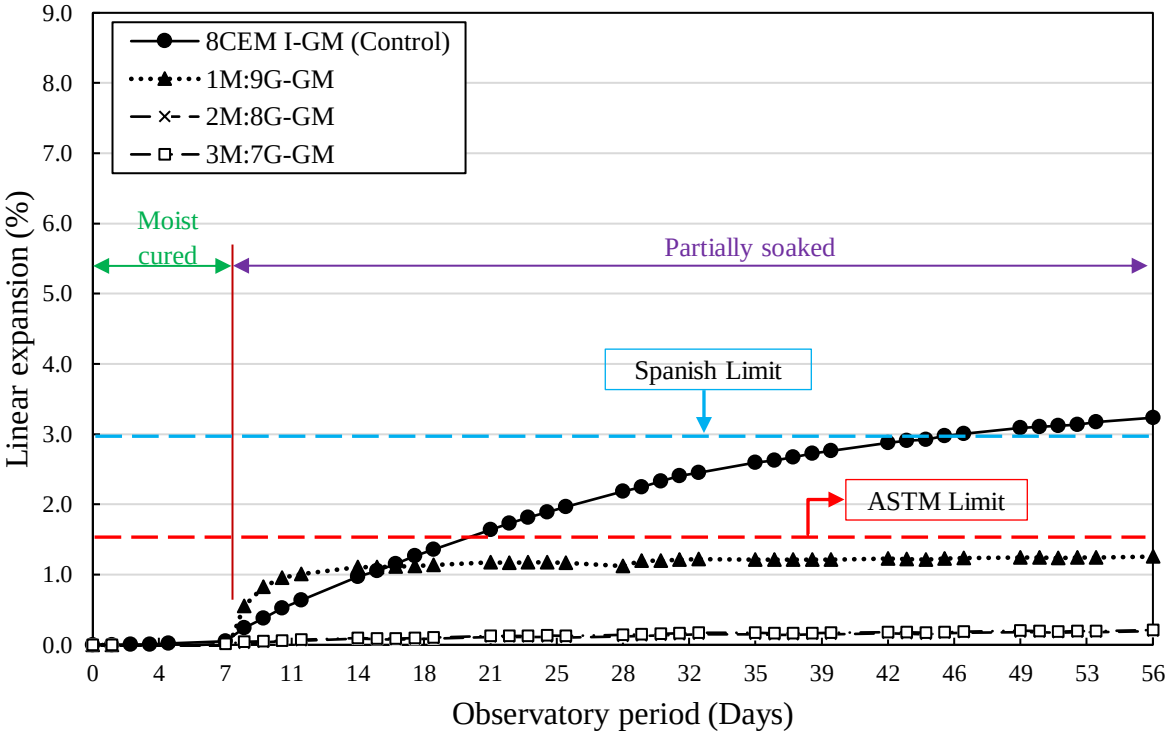


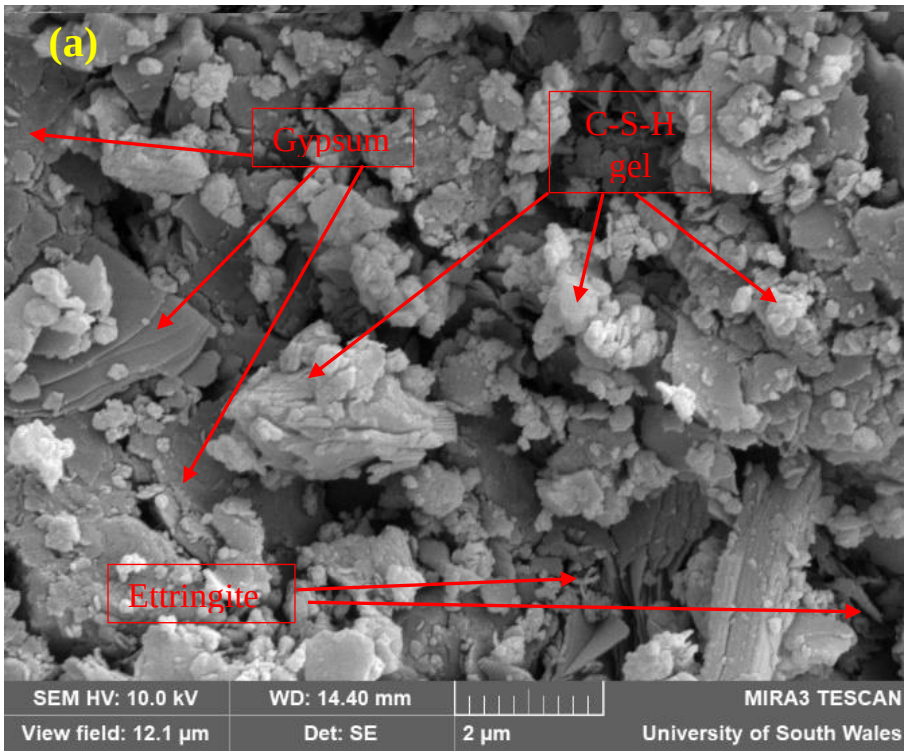
Figure 9: Typical plots of linear expansion against observatory period for GM cylinder test specimens containing varying levels of MG1:GGBS content and stabilised with **10 wt.%** binder dosage at both moist and partially soaked curing conditions

3.3 Microstructural investigation

Figures 10 and 11 present the SEM micrographs from the fragments obtained from stabilised samples of GM cylinder test specimen using 8wt.% CEM I (Control) and 6 wt.% binder dosage of 30wt.% MG1:70wt.% GGBS composition (3M:7G), at 28days for different curing conditions (moist curing and partial soaked).

It was observed that the morphology of the stabilised GM using 8wt.% CEM I (Control) in Figure 10(a) is very different to that of the MG1-activated GGBS binders in Figure 10(b), which confirms the formation of a different type of microstructure after 28 days of moist curing condition. This trend was also similar to the SEM images that were obtained in Figure 11 for both stabilised Gypsum marl soil using CEM I and MG1-activated GGBS binders after 28 days of partial soaking in deionised water.

It was also seen from the SEM micrographs in Figure 10 that the Control GM stabilised sample under moist curing condition produced a hydration compound which consists of small globular-like particles clumped together with no definite shape known as C-S-H gel. Additionally, flat sheets of gypsum (sulphate) and ettringite crystal precipitates were also visually identified as some of the hydration compounds (Li et al., 2020, Diaz Caselles et al., 2020). However, a visual inspection of the GM samples that were stabilised with 6wt.% MG1-activated GGBS binder showed a relatively flocculated structure of the soil particles. The SEM micrographs in Figure 11(a) shows the formation of large quantities of ettringite structures, hydration compound (C-S-H gel) and gypsum in the GM soil that was stabilised with CEM I after partial soaking conditions for 28 days. However, Figure 11(b) still showed a more compact structure with almost little voids even after partial soaking for 28 days.



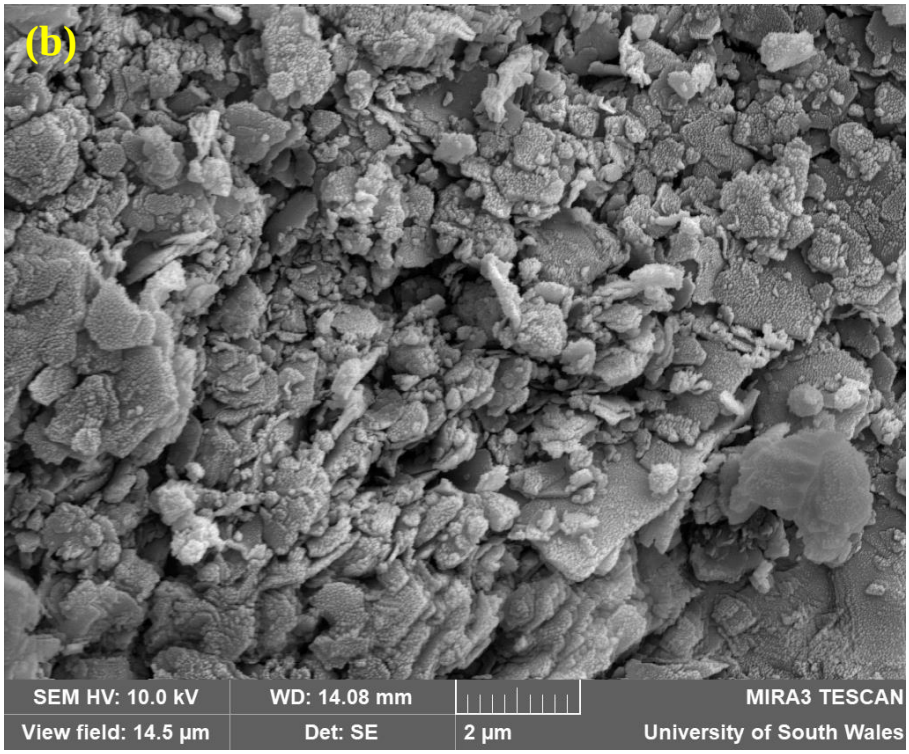
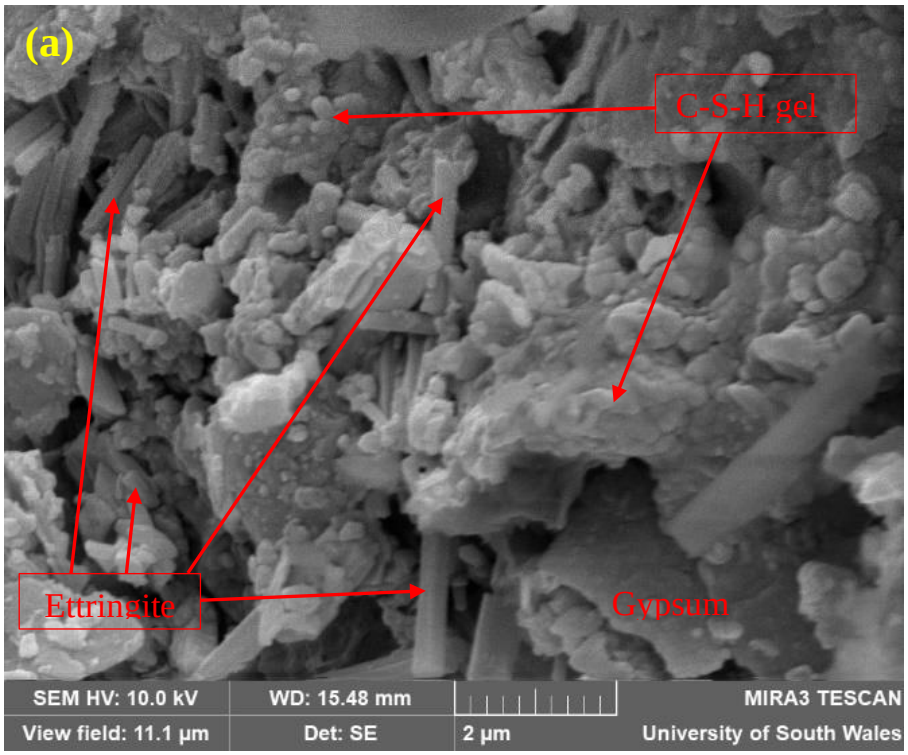


Figure 10: SEM micrographs of stabilised Gypsum marl soil after **28 days moist curing condition** using (a) 8 **wt.% CEM I binder dosage at 2**µm resolution, and (b) **6 wt.% binder dosage** of 3M:7G composition **at 20**µm resolution.



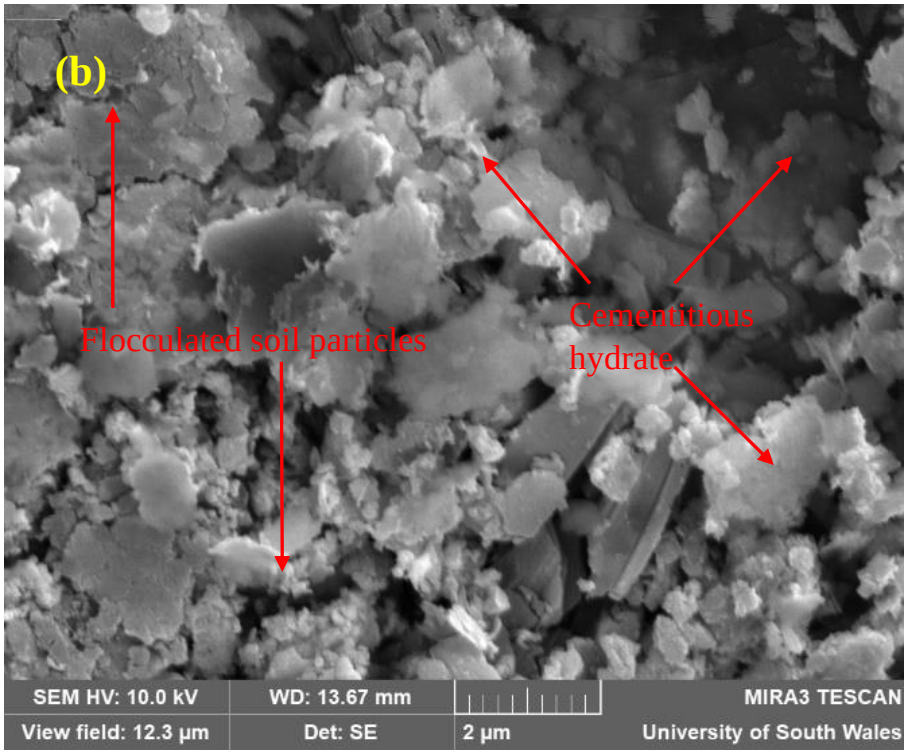


Figure 11: SEM micrographs of stabilised Gypsum marl soil after **28 days partially soaking condition** using (a) 8 **wt.% CEM I binder dosage at 2**µm resolution, and (b) **6 wt.% binder dosage** of 3M:7G composition **at 2**µm resolution.

4. DISCUSSIONS

4.1 Mechanical performance of stabilised GM soil with MgO-waste binders

An effective stabilisation effort on soils requires that a certain UCS value is achieved at either 7 or 28 days of moist curing age, as it will be a direct indicator of the efficacy of the MgO-waste's potential at activating GGBS. The display of strength gain by all the stabilised GM cylinder test specimens in all cases of stabiliser dosage (6, 8 and 10 wt.%) could be attributed to the hydration reaction caused by the successful activation of GGBS by MG1 (MgO waste material) over the curing period. Goodarzi and Movahedrad (2017) corroborated this claim and suggested that the gain in strength could as well be the formation of more cementing hydrate/phases which fills up the colloidal spaces, and subsequently lead to interlocking of the clay particles. The main cementing hydrate/phases that are formed during a pozzolanic reaction (hydration) within the stabilised cylinder specimen using the MG1:GGBS blend composition are Magnesium Silicate Hydrate (M-S-H gel) or Hydrotalcite – Ht (Zhang et al., 2014, Yi et al., 2015b, Abdalqader et al., 2015, Li et al., 2020). The activation process of GGBS by MG1 begins with an initial destruction of the bonds within the GGBS composition e.g., Mg – O, Ca – O, Si – O – Si, Al – O -Si and Al – O – Al, which is subsequently followed by the development of a Si – Al inter-surface layer over the grains of the GGBS material. Thereafter, Mg^{2+} either reacts with Si–O or Al–O to produce a cementing hydrate mainly as C-S-H gel and M-S-H gel or Hydrotalcite/Magnesium Aluminate Hydrate – M-A-H (Darko and Branislav, 2002, Jin et al., 2015). Therefore, an overall hydration reaction for the MG1:GGBS binder composition can be summarized in Equation 1.

$$MgO + (CaO - MgO - Al_2O_3 - SiO_2)\ GGBS + H_2O \rightarrow \mathbf{C-S-H} + \mathbf{M-S-H} + \mathbf{M-A-H(Ht)} + \mathbf{C-A-S-H} \quad \textit{Equation 1}$$

The formation of C-S-H and C-A-S-H within the stabilised system using MG1:GGBS binder composition is as a result of the available Ca content within the elemental composition of each material (MG1 and GGBS). However, this is not of major concern as the hydration products are of very minute quantity with no substantial negative impact on the UCS of the stabilised system during the moist curing period. It is also important to note that the presence of brucite ($Mg(OH)_2$) within the first stage of hydration could be deleterious to the overall stabilised matrix, if there are not enough hydration conditions (adequate alkalinity level, water content and temperature) for complete dissolution of brucite to form the cementitious M-S-H gel (Jin and Al-Tabbaa, 2013, Gomes and de Oliveira, 2018). Another obvious justification for the increase in UCS performances at 28 days curing age, could be due to the increase in curing age for each mix compositions that allows for the production of more cementing gel (M-S-H) as a result of the pozzolanic reaction.

The initial slow development of UCS strength that was observed for the MG1:GGBS binder with 10 wt.% MG1 in the stabilised GM cylinder specimens in comparison with the control at 7 days, could be ascribed to the higher reactivity of Ca during the initial stage of hydration, which produces faster cementing gels (only C-S-H) necessary for strength gain. However, this was not the case at 28 days as the pozzolanic reaction set in to form different types of cementing hydrates (some amount of C-S-H but more of M-S-H gels) necessary for further strength gain. This finding agrees with that of Wang et al. (2016) and Goodarzi and Movahedrad (2017), who also suggested that the M-S-H gel or Ht compounds are very large compared with C-S-H and can increase the level of long-range structural efficiency of the hydration elements, which provides the necessary binding capacity that will lead to greater strength in the stabilised soil. It is worthy to note that the presence of sulphate within the GM soil system did not pose any reduction to UCS of the stabilised cylinder specimens. This observation could be credited to the reduced presence of available Ca within the stabilised system that would have reacted with the available sulphate to form the needle-like ettringite crystals that could have been detrimental to the overall stabilised system. Hence, the sulphate content was coated with the cementing gel that was produced, remained dormant within the stabilised system, and could have contributed to the overall compressive strength of the stabilised cylinder specimen due to its crystalline nature. The UCS performance also showed that high MG1 contents within the range of 20 to 30wt.% of the MG1:GGBS composition can accelerate the strength development of GGBS stabilised sulphate soils at 7 and 28 days moist curing age. However, some reduction and slow increase in strength gain was observed at 56 days curing. This showed that high amounts of MG1 content can act as a negative impact on the UCS performance at later stages. Yi et al. (2016) also attributed this reduction in UCS performance to the type of MgO (reactive) that was used within the MG1:GGBS composition. Therefore, lower amounts of reactive MG1 contents (10 wt.%) with large GGBS content (90 wt.%) is suggested for a continuous pozzolanic activity, as it will result in further strength development within the investigated sulphate stabilised system. In addition, the application of an acceptable UCS threshold of 345 kN/m^2 for stabilised products using waste materials was established, as all the investigated mix combinations are in compliance with the ASTM (American Society for Testing and Materials)

and Environmental Protection Agency manual (EPA) strength threshold at 7 days moist curing age (Goodarzi and Movahedrad, 2017).

4.2 Linear expansion of stabilised GM soil with MgO-waste binders

The swelling phenomenon in soils is of key interest as it dictates the overall suitability and stability of the soil after stabilisation in preparation for its application for various civil engineering works (subgrades, light building foundations etc). However, the extent of the swelling occurrence is reliant on certain factors such as the particle size distribution, type and amount of mineral present within the soil/clay and any variance in moisture content (Oti et al., 2009a, Oti et al., 2009b). Hafez et al. (2008) and Tran et al. (2014) also reported the deleterious impact of the swelling phenomena as the settlement attributes of the soils when subjected to alternating variations in moisture. Therefore, the variance in the results from the linear expansion tests in the current research, can be used to hypothesize the expected swelling/shrinkage tendencies of GM soil using both calcium based (CEM I) and MgO-waste activated GGBS binders. Hence, a maximum expansion limit of 1.5% as stipulated in the American standard of measurement (ASTM) and a Spanish limit of 3% for stabilised soil systems will be employed as a benchmark in the current investigation (ASTM D4829 - 11, Seco et al., 2011, Diaz Caselles et al., 2020). The magnitude of linear expansion for the control cylinder specimens will also be employed as the secondary benchmark.

The stabilised GM soil containing CEM I (Control) demonstrated an astronomical increase in linear expansion as soon as water was introduced into the cylindrical set up after 7-days of most curing. One significant factor that could have caused the linear expansion could be due to the presence of ettringite crystals which absorbs water upon contact with water (Adeleke et al., 2020, Li et al., 2020). Furthermore, the significant linear expansion exhibited by cylinder specimens that were stabilised with 6 wt.% of 10wt.% MG1:90wt.% GGBS blend composition could be due to the presence of ettringite formation amongst other hydration compounds in the presence of sulphate. This is possible due to the corresponding high amounts of available Ca from increased GGBS content within the blend composition. The reduction in linear expansion that was observed for every increase in the MG1 content within the MG1:GGBS blend compositions at successive stabiliser dosages (6, 8 and 10 wt.%) can be attributed to the increase in the activator content (in this case MgO waste) necessary for improved hydration reaction with the production of more cementitious hydrate compounds. This cementing gel was able to effectively bind and fill up the colloidal spaces within the GM soil particles. In addition, the cementing gel (M-S-H) that was produced coated the available sulphate (gypsum crystals) within the GM soil. This occurrence prevented the gypsum from any further reaction with the available Ca within the hydrating system, that could cause any deleterious impact on the stabilised Gypsum marl soil in the long term. Research works by Jin et al. (2015) and Wang et al. (2016) are in agreement with the earlier hypothesis and suggested that the increased amount of activator (reactive MgO) effectively increases the pH level within a stabilised system, which is essential to activate GGBS for a more active and improved pozzolanic reaction.

The significant linear expansion of 9, 1.6 and 1.3% that was observed for Gypsum marl clay cylinder specimens containing 10 wt.% MG1:90 wt.% GGBS (see Figures 6 – 8) seem to reduce with each increasing stabiliser dosage of 6, 8 and 10 wt.%. This could be attributed to the decrease in the activation of the GGBS by the reduced quantity of MG1 within the stabilised system. However, as the stabiliser dosage increased (as seen for blend compositions with 20 wt.% and 30wt.% MG1 wastes), there was an increased activity in the hydration reaction to

produce more cementing compound (M-S-H gel). Generally, the GM cylinder test specimen with 20 wt.% MG1:80 wt.% GGBS blend composition and 30 wt.% MG1:70 wt.% GGBS blend composition with stabiliser dosages of 6 – 10 wt.% all achieved linear expansion limits within the range of 0.04 – 1.17%, which are well below the established benchmark of 1.5% (ASTM limit), 3% (Spanish limit) and the control cylinder specimen with calcium-based binder (8 wt.% CEM I). This exceptional performance in linear expansion has demonstrated the viability of using MgO-waste activated GGBS binders to stabilise natural soils with high sulphate content.

4.3 Microstructural investigation of stabilised GM soil with MgO-waste binders

Microstructural investigation is key to unravelling the mechanism behind the behaviour of stabilised materials by providing visual images of the morphology, and structure of the components of the stabilised cylinder specimen and any cementitious hydrate compound that might have been formed during the hydration reaction (Goldstein et al., 2017). Generally, the flocculated structure observed in the SEM micrographs for the investigated GM test cylinders using both calcium based (Control) and MG1-waste activated GGBS binders after 28 days of moist curing can be attributed to the ion-exchange process, resulting in the replacement of multivalent ions (Ca and Mg) from the activators (CEM I and MG1) with the monovalent cations in the surface of the clay particles (Du et al. (2013) and Goodarzi and Salimi (2015)).

The microstructure of both CEM I and MG1:GGBS stabilised GM soil consists of an agglomeration of phases, with a typical morphology of sulphate-bearing minerals such as ettringite and gypsum. Small globular particles clumped together with no definite shape thought to be C-S-H gel and flat sheets of gypsum and ettringite crystal precipitates were visually identified as some of the hydration compounds in the Control cylinder test specimen (Li et al., 2020). Several researchers (Rahmat and Kinuthia, 2011b, Adeleke et al., 2020, Li et al., 2020) have reported that when soils containing some levels of sulphate content react with calcium-based binders (such as PC and lime), which produces Calcium Aluminate Sulphate Hydrate (C-A-S-H) minerals. An example of such mineral is the formation of a needle-like structure known as ettringite, which has a large expansive potential due to its ability to absorb large volumes of water but can remain dormant with no contact with water. Upon partial soaking for 28 days, the ettringite structure caused very high swelling pressure during its formation resulting in a disruptive increase in volume. Furthermore, the ettringite occupied a greater volume than the original constituent reactants (C-S-H gel), which can also have a negative impact on the compressive strength property and binding capacity of the cementing gel (Yi et al., 2015a). However, GM soil that was stabilised with the MG1:GGBS binder indicated no trace of the needle-like ettringite crystal and showed a rather compact structure (flocculated soil articles) composed of the cementitious hydrate (M-S-H gel). This explains the low linear expansion that was observed in Figure 6 - 8 for the GM soil stabilised with MG1:GGBS binders. In addition, the M-S-H gel that was formed during the hydration reaction of MG1-activated-GGBS binder formed a coating around the sheets of gypsum, hereby hindering the expected reaction of any available Ca to react with the gypsum and form ettringite crystals.

The presence of voids were more prominently noticed in the micrographs for CEM I stabilised GM soil which indicates a rather weak bonding between the soil particles (Yi et al., 2015a, Gomes and de Oliveira, 2018). However, the presence of voids were almost absent in the case of the MG1:GGBS stabilised GM soil as the soil structure was well integrated with the soil grains and well surrounded by the cementitious hydrate (M-S-H gel).This explains the

improved compressive strength of MG1:GGBS stabilised cylinder specimen compared to the CEM I stabilised GM cylinder test specimen (Goodarzi and Movahedrad, 2017). Generally, ettringite was not definite during moist curing, but clearly evident after soaking of the GM cylinders that were stabilised with CEM I.

CONCLUSION

The outcomes from the current study suggest the viability of producing an alternative cementitious binder (MG1:GGBS) by using up to 30 wt.% MgO-waste (MG1) to successfully activate GGBS for stabilising natural soils containing high sulphate content. The following conclusions can be drawn as follows:

1. The compressive strength of the MG1:GGBS stabilised GM soil was significantly improved above the acceptable limits as set by the ASTM (American Society for Testing and Materials), Environmental Protection Agency manual (EPA) for the use of industrial waste materials using stabiliser dosages within the range of 6 - 10 wt.%. In all mix compositions, the compressive strength resistance was more pronounced using the 10wt.% than for the 6wt.% stabiliser dosage. The UCS of MG1:GGBS stabilised GM soils were 1.5 – 3 times more than the control at the standardised 28 days moist curing age.

2. The MG1:GGBS binder demonstrated resistance to linear expansion as low as 0.13% – 0.2% using 30wt.% MG1:70wt.% GGBS mix proportion at all stabiliser dosages (6 - 10 wt.%) after 56 days of observation compared with the control blend mix of 3.2%, which is more than the benchmarks as set by the American standard of measurement (ASTM) – 1.5% and Spanish limits – 3% for stabilised soil systems. In addition, the linear expansion reduces with an increase in the stabiliser dosage (6 – 10wt.%) for all mix proportions. However, stabilizer dosage below 6wt.% is not advisable for stabilising high sulphate soils due to the potential for more expansion that is suspected to be caused by ettringite formation.

3. The SEM micrographs for the MG1:GGBS binder stabilised GM soil showed a more compact and dense microstructure compared with the control at 28 day moist cured and soaking conditions. The enhanced microstructure justifies the significant compressive strength increase for the MG1:GGBS stabilised soils. The presence of holes were clearly evident in the SEM micrographs for the control with a morphology of small globular particles clumped together with no definite shape known as C-S-H gel, flat sheets of gypsum and needle-like ettringite prisms after 28 days moist curing. In addition, the flocculated structure produced larger holes when subjected to the partially soaking conditions, which could be due to the increased production of the needle-like ettringite prism upon contact with water and recrystallisation of the gypsum crystals which exerts pressure on the developing cementitious hydrate and causes the stabilised product to disintegrate.
4. The limitations to this study that could impact on the authenticity of the experimental results are the use of a single soil type with a specific sulphate content (22 wt.%) for the experimentations and the level of technical expertise during the sample preparation.

AUTHOR CONTRIBUTIONS

Adeleke B. O. and Kinuthia J. M. : Conceptualization, Methodology, Software. **Adeleke B. O.**: Data curation, Writing- Original draft preparation. **Adeleke B. O.**: Visualization, Investigation. **Kinuthia J. M. and Oti J. E.**: *Supervision*. **Adeleke B. O., Kinuthia J. M. and Oti J. E**: Software, Validation.: **Kinuthia J. M. and Oti J. E.:** Writing- Reviewing and Editing,

CONFLICT OF INTEREST

None

REFERENCES

ASTM D4829 - 11. Standard Test Method for Expansion Index of Soils *Annual Book of ASTM Standards.* West Conshohocken PA, 2010: ASTM International.

BS 1924 - 2:2018. Hydraulically bound and stabilized materials for civil engineering purposes. *Sample preparation and testing of materials during and after treatment.* BSI Standard Limited.

BS EN 197-1:2011. Cement. *Part 1: Composition, specifications and conformity criteria for common cements.* BSI Standards Limited.

BS EN 13286-49:2004. Unbound and hydraulically bound mixtures. *Accelerated swelling test for soil treated by lime and/or hydraulic binder.* BSI Standards Limited.

BS EN 15167-1:2006. Ground granulated blast furnace slag for use in concrete, mortar and grout —. *Part 1: Definitions, specifications and conformity criteria.* BSI Standards Limited.

BS EN 15309:2007. Characterization of waste and soil. *Determination of elemental composition by X-ray fluorescence.* BSI Standards Limited.

BS ISO 18227:2014. Soil quality. *Determination of elemental composition by X-ray fluorescence.* BSI Standards Limited.

ABDALQADER, A., F., JIN, F. & AL-TABBAA, A. 2015. Characterisation of reactive magnesia and sodium carbonate-activated fly ash/slag paste blends. *Construction and Building Materials,* 93**,** 506-513**,** doi: 10.1016/j.conbuildmat.2015.06.015.

ADELEKE, B. O., KINUTHIA, J. M. & OTI, J. E. 2020. Strength and Swell Performance of High-Sulphate Kaolinite Clay Soil. *Sustainability,* 12**,** 10164 - 10168.

ARDAH, A., CHEN, Q. & ABU-FARSAKH, M. 2017. Evaluating the performance of very weak subgrade soils treated/stabilized with cementitious materials for sustainable pavements. *Transportation Geotechnics,* 11**,** 107–119.

644 BEHNOOD, A. 2018. Soil and clay stabilization with calcium- and non-calcium-based
645 additives: A state-of-the-art review of challenges, approaches and techniques.
646 *Transportation Geotechnics,* 17**,** 14-32**,** doi: 10.1016/j.trgeo.2018.08.002.

647 BERNARD, E., LOTHENBACH, B., CHLIQUE, C., WYRZYKOWSKI, M., DAUZÈRES,
648 A., POCHARD, I. & CAU-DIT-COUMES, C. 2019. Characterization of magnesium
649 silicate hydrate (M-S-H). *Cement and Concrete Research,* 116**,** 309-330**,** doi:
650 10.1016/j.cemconres.2018.09.007.

651 CHENG, K. & HEIDARI, Z. 2018. A new method for quantifying cation exchange capacity
652 in clay minerals. *Applied Clay Science,* 161**,** 444-455.

653 CHESHOMI, A., ESHAGHI, A. & HASSANPOUR, J. 2017. Effect of lime and fly ash on
654 swelling percentage and Atterberg limits of sulfate-bearing clay. *Applied Clay*
655 *Science,* 135**,** 190-198**,** doi: 10.1016/j.clay.2016.09.019.

656 DANG, L. C., FATAHI, B. & KHABBAZ, H. 2016. Behaviour of expansive clay stabilized
657 with hydrated lime and Bagasse Fibres. *Procedia Engineering* 143**,** 658-665.

658 DARKO, K. & BRANISLAV, Z. 2002. Effects of dosage and modulus of water glass on
659 early hydration of alkali–slag cements. *Cement and Concrete Research,* 32**,** 1181–
660 1188.

661 DEL VALLE-ZERMEÑO, R., GIRO-PALOMAA, J. & CHIMENOSA, J., M. 2015. Low-
662 grade magnesium oxide by-products for environmental solutions: characterization and
663 geochemical performance. *Journal of Geochemical Exploration,* 152**,** 134–144.

664 DIAZ CASELLES, L., HOT, J., ROOSZ, C. & CYR, M. 2020. Stabilization of soils
665 containing sulfates by using alternative hydraulic binders. *Applied Geochemistry,* 113**,**
666 doi: 10.1016/j.apgeochem.2019.104494.

667 DU, Y. J., JIANG, N. J., LIU, S. Y., JIN, F., SINGH, D. N. & PUPPALA, A. J. 2013.
668 Engineering properties and microstructural characteristics of cement-stabilized zinc
669 contaminated kaolin. *Geotech,* 51**,** 289 - 302.

670 EL-DIEB, A. S. & KANAAN, D. M. 2018. Ceramic waste powder an alternative cement
671 replacement – Characterization and evaluation. *Sustainable Materials and*
672 *Technologies,* 17**,** doi: 10.1016/j.susmat.2018.e00063.

673 GILIBERTO, E., IOPPOLO, S. & MANUELLA, F. 2008. Ettringite and thaumasite: a
674 chemical route for their removal from cementious artefacts. *Journal of Cultural*
675 *Heritage,* 9**,** 30–37.

676 GOLDSTEIN, J. I., NEWBURY, D. E., ECHLIN, P., JOY, D. C., FIORI, C. & LIFSHIN, E.
677 2017. *Scanning Electron Microscopy and X-Ray Microanalysis,* New York, Springer
678 Nature.

679 GOMES, C. M. & DE OLIVEIRA, A. D. S. 2018. Chemical phases and microstructural
680 analysis of pastes based on magnesia cement. *Construction and Building Materials,*
681 188**,** 615-620**,** doi: 10.1016/j.conbuildmat.2018.08.083.

GOODARZI, A. & SALIMI, M. 2015. Stabilization treatment of a dispersive clayey soil using granulated blast furnace slag and basic oxygen furnace slag. *Applied Clay Science,* 108**,** 61-69.

GOODARZI, A. R. & MOVAHEDRAD, M. 2017. Stabilization/solidification of zinc-contaminated kaolin clay using ground granulated blast-furnace slag and different types of activators. *Applied Geochemistry,* 81**,** 155-165**,** doi: 10.1016/j.apgeochem.2017.04.014.

GOPINATH, A., BAHURUDEEN, A., APPARI, S. & NANTHAGOPALAN, P. 2018. A circular framework for the valorisation of sugar industry wastes: Review on the industrial symbiosis between sugar, construction and energy industries. *Journal of Cleaner Production,* 203**,** 89-108**,** doi: 10.1016/j.jclepro.2018.08.252.

GÓRAK, P., POSTAWA, P., TRUSILEWICZ, L. N. & KALWIK, A. 2020. Cementitious eco-composites and their physicochemical/mechanical properties in Portland cement-based mortars with a lightweight aggregate manufactured by upcycling waste by-products. *Journal of Cleaner Production***,** doi: 10.1016/j.jclepro.2020.125156.

GU, K., JIN, F., AL-TABBAA, A., SHI, B. & LIU, J. 2014. Mechanical and hydration properties of ground granulated blastfurnace slag pastes activated with MgO–CaO mixtures. *Construction and Building Materials,* 69**,** 101-108**,** doi: 10.1016/j.conbuildmat.2014.07.032.

HAFEZ, M. A., SIDEK, N. & NOOR, M. J. 2008. Effect of pozzolanic process on the strength of stabilized lime clay. *Electronic Journal of Geotechnical Engineering,* 13.

JIN, F. & AL-TABBAA, A. 2013. Thermogravimetric study on the hydration of reactive magnesia and silica mixture at room temperature. *Thermochimica Acta,* 566**,** 162-168**,** doi: 10.1016/j.tca.2013.05.036.

JIN, F. & AL-TABBAA, A. 2014. Characterisation of different commercial reactive magnesia. *Advances in Cement Research,* 26**,** 101-113**,** doi: 10.1680/adcr.13.00004.

JIN, F., GU, K. & AL-TABBAA, A. 2015. Strength and hydration properties of reactive MgO-activated ground granulated blastfurnace slag paste. *Cement and Concrete Composites,* 57**,** 8-16.

JOHN, U. E., JEFFERSON, I., BOARDMAN, D. I., GHATAORA, G. S. & HILLS, C. D. 2011. Leaching evaluation of cement stabilisation / solidification treated kaolin clay. *Engineering Geology,* 123**,** 315-323**,** doi: 10.1016/j.enggeo.2011.09.004.

JONES, L. D. & JEFFERSON, I. 2012. Expansive soils. *ICE Manual of geotechnical engineering***,** 413–41.

JUENGER, M. C. G. & SIDDIQUE, R. 2015. Recent advances in understanding the role of supplementary cementitious materials in concrete. *Cement and Concrete Research,* 78**,** 71-80**,** doi: 10.1016/j.cemconres.2015.03.018.

JUENGER, M. C. G., WINNEFELD, F., PROVIS, J. L. & IDEKER, J. H. 2011. Advances in alternative cementitious binders. *Cement and Concrete Research,* 41**,** 1232-1243**,** doi: 10.1016/j.cemconres.2010.11.012.

KINUTHIA, J. M. & OTI, J. E. 2012. Designed non-fired clay mixes for sustainable and low carbon use. *Applied Clay Science,* 59–60**,** 131–139.

KINUTHIA, J. M. & WILD, S. 2001. Effects of some metal sulphates on the strength and swelling properties of lime-stabilised kaolinite. *International Jornal on Pavement Engineering,* 2**,** 103–120.

KINUTHIA, J. M., WILD, S. & JONES, G. I. 1999. Effects of monovalent and divalent metal sulphates on consistency and compaction of lime-stabilised kaolinite. *Applied clay science,* 14**,** 27-25.

LI, W., YI, Y. & PUPPALA, A. J. 2020. Suppressing Ettringite-Induced Swelling of Gypseous Soil by Using Magnesia-Activated Ground Granulated Blast-Furnace Slag. *Journal of Geotechnical and Geoenvironmental Engineering,* 146**,** doi: 10.1061/(asce)gt.1943-5606.0002292.

LI, Y., SUN, J. & CHEN, B. 2014. Experimental study of magnesia and M/ P ratio influencing properties of magnesium phosphate cement. *Construction and Building Materials,* 671**,** 741-753.

MIQUELEIZ, L., RAMÍREZ, F., SECO, A., NIDZAM, R., KINUTHIA, J., TAIR, A. & GARCIA, R. 2012. The use of stabilised Spanish clay soil for sustainable construction materials. *Engineering Geology,* 133-134**,** 9-15.

NIDZAM, R., M. & KINUTHIA, J., M. 2010. Sustainable soil stabilisation with blastfurnace slag – a review. *Proceedings of the Institution of Civil Engineers - Construction Materials,* 163**,** 157-165.

NORMAN, R., DANN, S., HOGG, S. & KIRK, C. 2013. Synthesis and structural characterisation of new ettringite and thaumasite type phases: $Ca_6[Ga(OH)_6{\cdot}12H_2O]2(SO_4)_3{\cdot}2H_2O$ and $Ca_6[M(OH)_6{\cdot}12H_2O]2(SO_4)_2(CO_3)_2$, M = Mn, Sn. *Solid State Sciences,* 25**,** 110-117.

OLIVIER, J., G., J., & PETERS, J., A., H., W. 2019. Trends In Global CO_2 And Total Greenhouse Gas Emissions. The Hague.

OLIVIER, J. G. J., JANSSENS-MAENHOUT, G. & PETERS, J. A. H. W. 2012. Trends in Global CO2 Emissions. *Report; PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands***,** 40.

OTI, J. E., KINUTHIA, J. M. & BAI, J. 2009a. Compressive strength and microstructural analysis of unfired clay masonry bricks. *Engineering Geology,* 109**,** 230-240**,** doi: 10.1016/j.enggeo.2009.08.010.

OTI, J. E., KINUTHIA, J. M. & BAI, J. 2009b. Engineering properties of unfired clay masonry bricks. *Engineering Geology,* 107**,** 130-139**,** doi: https://doi.org/10.1016/j.enggeo.2009.05.002.

PHANIKUMAR, B. & SINGLA, R. 2016. Swell-consolidation characteristics of fibre-reinforced expansive soils. *Soils and Foundations,* 56**,** 138-143.

PRUŠKA, J. & ŠEDIVÝ, M. 2015. Prediction of Soil Swelling Parameters. *Procedia Earth and Planetary Science,* 15**,** 219-224**,** doi: 10.1016/j.proeps.2015.08.052.

RAHMAT, M. & KINUTHIA, J. 2011a. Effects of mellowing sulfate-bearing clay soil stabilized with wastepaper sludge ash for road construction. *Engineering Geology,* 117**,** 170-179.

RAHMAT, M. N. & KINUTHIA, J. M. 2011b. Effects of mellowing sulfate-bearing clay soil stabilized with wastepaper sludge ash for road construction. *Engineering Geology,* 117**,** 170-179**,** doi: 10.1016/j.enggeo.2010.10.015.

ROOSZ, C., GRANGEON, S., BLANC, P., MONTOUILLOUT, V., LOTHENBACH, B., HENOCQ, P., GIFFAUT, E., VIEILLARD, P. & GABOREAU, S. 2015. Crystal structure of magnesium silicate hydrates (M-S-H): The relation with 2:1 Mg-Si phyllosilicates. *Cement and Concrete Research,* 73**,** 228–237.

RUAN, S. & UNLUER, C. 2016. Comparative life cycle assessment of reactive MgO and Portland cement production. *Journal of Cleaner Production,* 137**,** 258–273.

SCHANZ, T., TRIPATHY, S. & SRIDHARAN, A. 2018. Volume change behaviour of swelling and non-swelling clays upon inundation with water and a low dielectric constant fluid. *Applied Clay Science,* 158**,** 219-225.

SECO, A., MIQUELEIZ, L., PRIETO, E., MARCELINO, S., GARCÍA, B. & URMENETA, P. 2017. Sulfate soils stabilization with magnesium-based binders. *Applied Clay Science,* 135**,** 457-464**,** doi: 10.1016/j.clay.2016.10.033.

SECO, A., RAMÍREZ, F., MIQUELEIZ, L. & GARCÍA, B. 2011. Stabilization of expansive soils for use in construction. *Applied Clay Science,* 51**,** 348-352**,** doi: 10.1016/j.clay.2010.12.027.

SHAND, M. A. 2006. *The Chemistry and Technology of Magnesia,* New York, John Wiley& Sons.

TRAN, T. D., CUI, Y.-J., TANG, A. M., AUDIGUIER, M. & COJEAN, R. 2014. Effects of lime treatment on the microstructure and hydraulic conductivity of Héricourt clay. *Journal of Rock Mechanics and Geotechnical Engineering,* 6**,** 399-404**,** doi: 10.1016/j.jrmge.2014.07.001.

UNITED-NATIONS. 2015. *Transforming our World: The 2030 Agenda for Sustainable Development,* [Online]. Available: https://doi.org/10.1080/02513625.2015.1038080 [Accessed April 2020].

USGS 2020. Mineral Commodity Summaries. *In:* INTERIOR, U. S. D. O. T. (ed.). White house - USA: DOI Inspector General.

WANG, F., JIN, F., SHEN, Z. & AL-TABBAA, A. 2016. Three-year performance of in-situ mass stabilised contaminated site soils using MgO-bearing binders. *J Hazard Mater,* 318**,** 302-307**,** doi: 10.1016/j.jhazmat.2016.07.018.

WANG, L., CHEN, L., CHO, D. W., TSANG, D. C. W., YANG, J., HOU, D., BAEK, K., KUA, H. W. & POON, C. S. 2019. Novel synergy of Si-rich minerals and reactive

MgO for stabilisation/solidification of contaminated sediment. *J Hazard Mater,* 365**,** 695-706**,** doi: 10.1016/j.jhazmat.2018.11.067.

WANG, L., ROY, A., SEALS, R. K. & METCALF, J. B. 2003. Stabilization of Sulfate-Containing Soil by Cementitious Mixtures Mechanical Properties. *Geomaterials,* 3724**,** 12-19.

WILD, S., KINUTHIA, J., JONES, G. & HIGGINS, 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 (GGBS). *Engineering Geology,* 51**,** 257-277.

WU, H.-L., JIN, F., BO, Y.-L., DU, Y.-J. & ZHENG, J.-X. 2018. Leaching and microstructural properties of lead contaminated kaolin stabilized by GGBS-MgO in semi-dynamic leaching tests. *Construction and Building Materials,* 172**,** 626-634**,** doi: 10.1016/j.conbuildmat.2018.03.164.

YI, Y., GU, L. & LIU, S. 2015a. Microstructural and mechanical properties of marine soft clay stabilized by lime-activated ground granulated blastfurnace slag. *Applied Clay Science,* 103**,** 71-76**,** doi: 10.1016/j.clay.2014.11.005.

YI, Y., GU, L., LIU, S. & JIN, F. 2016. Magnesia reactivity on activating efficacy for ground granulated blastfurnace slag for soft clay stabilisation. *Applied Clay Science,* 126**,** 57-62**,** doi: 10.1016/j.clay.2016.02.033.

YI, Y., LISKA, M. & AL-TABBAA, A. 2014. Properties and microstructure of GGBS-MgO pastes. *Advances in Cement Research,* 26**,** 114–122.

YI, Y., ZHENG, X., LIU, S. & AL-TABBAA, A. 2015b. Comparison of reactive magnesia- and carbide slag-activated ground granulated blastfurnace slag and Portland cement for stabilisation of a natural soil. *Applied Clay Science,* 111**,** 21-26**,** doi: 10.1016/j.clay.2015.03.023.

ZHANG, T., VANDEPERRE, L. J. & CHEESEMAN, C. R. 2014. Formation of magnesium silicate hydrate (M-S-H) cement pastes using sodium hexametaphosphate. *Cement and Concrete Research,* 65**,** 8-14**,** doi: 10.1016/j.cemconres.2014.07.001.