

# Incorporation of reactive magnesia and quicklime in sustainable binders for soil stabilisation



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## ABSTRACT

The utilisation of reactive magnesia or quicklime as novel activators for slag offers a range of technical and environmental benefits over conventional caustic alkali activators and showed great potential in soil stabilisation. This paper investigates the mechanical and microstructural properties of two model soils, i.e., a clayey soil and a slightly silty clayey sand, stabilised by ground granulated blastfurnace slag (GGBS) using various techniques including unconfined compressive strength (UCS) test, thermogravimetric analysis (TGA) and scanning electron microscopy (SEM). A number of MgO and CaO mixtures with different MgO/CaO ratios were adopted for slag activation. The activator to GGBS ratio was 1:3 and the dosage of the binder (including MgO, CaO and GGBS) was 12% by weight of the dry soil. The result demonstrated that the increasing MgO/CaO ratio in the binder led to an increase in the UCS of the stabilised clayey soil up to 90 days, due to the increased homogeneity of C–S–H gel structure, the decreased Ca/Si ratio of C–S–H gel and the increased amount of voluminous hydrotalcite-like phases. On the other hand, slag activated with MgO–CaO mixtures showed poorer mechanical performance than slag activated with either MgO or CaO alone for sand stabilisation. In addition, strength enhancement was observed for the stabilised clayey soil upon different soaking conditions up to 7 days. After 28 days, although binders with higher MgO/CaO ratios showed slight strength degradation upon soaking, they still exhibited higher strength than those with lower MgO/CaO ratios.

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## 1. Introduction

Among many ground improvement methods, soil stabilisation with Portland cement (PC) or lime is most widely used in road, rail and airport construction, foundation construction, embankments and deep cement mixing. The introduction of such binder, slurry or powder into soil significantly improved the geotechnical properties of soils including strength, volume stability, durability and permeability. The primary mechanism of soil stabilisation with PC is through the hydration of PC which leads to the formation of cementitious calcium silicate hydrates (C–S–H), calcium aluminate hydrates (C–A–H) and calcium aluminium silicate hydrates (C–A–S–H). In case of the stabilisation with lime, the addition of lime into soils immediately results in the cation exchange between the metallic ions associated with the surface of the clay particles and the calcium ions of the hydrated lime, which leads to the flocculation process. In addition, pozzolanic reaction occurs between the silica and some alumina of the lattices of the clay minerals in the high alkaline environment produced by lime, forming secondary cementitious products as mentioned above (Bell, 1996; Lemaire et al., 2013).

Due to the calcination of limestone and the consumption of fossil fuels, the production of PC contributes approximately 5–8% of global man-made CO<sub>2</sub> emissions (Provis and van Deventer, 2014). Consequently, the search for more sustainable and environmental binders has led to the development of alkali-activated cements (AACs), which utilise a large portion of supplementary cementitious materials (SCMs) such as blastfurnace slag, fly ash, metakaolin and silica fume with the use of alkali activators (Demirboğa and Gül, 2006; Memon et al., 2007; Provis, 2013; Shi et al., 2006, 2011; Singhal et al., 2008). Among those SCMs, ground granulated blastfurnace slag (GGBS) has been demonstrated to be a promising option to partially replace PC or lime in soil stabilisation (Nidzam and Kinuthia, 2010; Obuzor et al., 2011a,b, 2012; Sargent et al., 2013; Tasong et al., 1999; Veith, 2000; Wild et al., 1998, 1999; Yi et al., 2014a), where PC or lime is used as an alkali activator for the slag to accelerate the hydration of slag. The benefits of using GGBS in soil stabilisation are not only in terms of low energy costs and positive environmental impact, but also in terms of enhanced mechanical properties and durability. The combination of GGBS and PC or lime is also very effective in reducing the expansion of the stabilised soil in the presence of sulfates or sulfides (Celik and Nalbantoglu, 2013; Tasong et al., 1999; Wild et al., 1999).

The benefits of incorporating reactive magnesia (MgO) in cementitious components for a number of applications have been investigated

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over the last 15 years or so and many promising applications have emerged (Al-Tabbaa, 2013). Reactive MgO is mainly produced from the processing of magnesite, magnesium chloride-rich brine or sea water at a much lower temperature (~700–1000 °C) than dead burned magnesia in PC (~1400 °C). Under those low temperatures, the MgO has high surface area, high reactivity, and low crystallinity (Shand, 2006). The use of reactive MgO with GGBS for soil stabilisation is a recent development offering a range of mechanical and durable advantages over PC or lime-slag blends (Jegandan et al., 2010; Yi et al., 2012, 2014b,c). Yi et al. (2014c) found that MgO–GGBS blend in the ratio of 1:9 by weight induced a higher unconfined compressive strength of stabilised sand and clayey silt than lime–GGBS blend at the same ratio at 7 days, although they obtained a similar strength range at 90 days. Additionally, the soil treated by GGBS–MgO mixture with proper ratio may achieve a strength ~1.3–4 times higher than the corresponding PC treated soil. Jegandan et al. (2010) and Yi et al. (2014b) found that the combination of MgO and GGBS in stabilisation produced higher resistance to sulfate and acid attack than PC stabilised soil, since no expansive phase ettringite formed in MgO–GGBS stabilised soil. In addition, the more effective ability of reactive MgO to immobilise heavy metals than PC has promoted the application of reactive MgO in land remediation technology (Al-Tabbaa et al., 2011).

An important obstacle to the wide application of MgO–GGBS in soil stabilisation should be related to the economic issue. Given the global production of MgO around 20 million tonnes per year, the price of MgO with potential in slag activation varies from US\$180 to US\$350 per ton in China (Beijing HL Consulting Company, 2009), higher than that of CaO (i.e., US\$30 to US\$80 per ton in China). In this context, the combination of MgO–CaO, as a way to cut down the cost of using MgO, is of worth being investigated, but with limited literature. Lu et al. (1957) investigated the use of calcitic lime [CaO, Ca(OH)<sub>2</sub>] and dolomitic lime [MgO–CaO, MgO–Ca(OH)<sub>2</sub>, Mg(OH)<sub>2</sub>–Ca(OH)<sub>2</sub>] in soil–lime stabilisation, but without using cementitious binders. The results indicated that the strengths of stabilised soils tended to be higher with dolomitic lime. Gu et al. (2014) studied the mechanical properties of GGBS paste activated with MgO–CaO mixtures and the result demonstrated that the use of CaO in MgO–GGBS blends can significantly accelerate the hydration rate in the early age while better long term mechanical performance was observed when the ratio of CaO to MgO was smaller than 1/19. So far, however, the utilisation of reactive MgO and CaO mixtures blended with slag in soil stabilisation has not been investigated yet.

This paper presents the experimental study on the stabilisation of two model soils, a clayey soil and a slightly clayey silty sand, using reactive MgO, CaO and GGBS blends, with CaO/MgO ratio at 3/0, 1.5/1.5, 0.2/2.8 and 0/3. The mechanical properties and microstructure characteristics of the stabilised soils were explored by a range of tests including unconfined compressive strength (UCS), water content measurement, scanning electron microscopy (SEM) and thermogravimetric analysis (TGA). In addition, the durability of stabilised clayey soil subjected to different soaking conditions was also studied.

## 2. Materials

### 2.1. Model soils

Two model soils: a clayey soil and a slightly clayey silty sand, were used. The clayey soil consists of 40 wt.% kaolin clay, 35 wt.% silica flour and 25 wt.% sand. The sand consists of 5 wt.% kaolin clay, 5 wt.% silica flour and 90 wt.% sand. The kaolin clay, with a liquid limit of 51% and plastic limit of 30%, was obtained from Richard Baker Harrison, UK. The silica flour, 87% particle of which passes 75 µm sieve, was obtained from David Ball Group, UK. Its specific gravity was between 2.64 and 2.66. The sharp sand, with D<sub>50</sub> of 0.8 mm and coefficient of uniformity of 4.3, was obtained from Ridgeons, UK. The chemical compositions of kaolin clay and silica flour are included in Table 1. The compaction test

**Table 1**

Chemical compositions and physical properties of raw materials (from suppliers' datasheets).

	Kaolin	Silica flour	MgO	CaO	GGBS
<i>Chemical composition</i>					
SiO <sub>2</sub>	45–55	99.2	0.9	0.9	37.0
Al <sub>2</sub> O <sub>3</sub>	30–39	0.3	0.22	0.13	13.0
CaO	0–0.3	0.01	0.9	94.0	40.0
MgO	0–0.6	<0.02	>93.2	0.5	8.0
K <sub>2</sub> O	0–5	0.04	–	–	0.6
Na <sub>2</sub> O	0–0.3	<0.03	–	–	0.3
SO <sub>3</sub>	–	–	–	0.06	1.0
Fe <sub>2</sub> O <sub>3</sub>	0–2	–	0.5	0.08	–
CaCO <sub>3</sub>	–	–	–	3.7	–
<i>Physical properties</i>					
Specific surface area (m <sup>2</sup> /kg)	–	–	9000	–	493
Bulk density (kg/m <sup>3</sup> )	–	–	–	1020	1050

indicated that the optimal water content of the clayey soil and the maximum dry density are 24% and 1.54 g/cm<sup>3</sup>, respectively.

The kaolin clay, silica flour and sand were first oven dried at 105 °C for 24 h, then left to cool to room temperature in sealed plastic bags. The model soils were prepared by homogeneously mixing these materials in a mixer for 5 min.

### 2.2. Binders

Reactive MgO (from Richard Baker Harrison) or quicklime (CaO, from Tarmac and Buxton Lime and Cement, UK) blended with GGBS (from Hanson, UK) is used as binder for soil stabilisation. Their chemical compositions and physical properties are also shown in Table 1. The reactivity of the reactive MgO is ~100 s determined by the acetic acid test according to Shand (2006) and is categorised as a medium reactive MgO (Jin and Al-Tabbaa, 2013). This type of reactive MgO is selected for its proper reactivity and cost, and it has been reported to be able to effectively activate the slag, with the long term compressive strength outperforming CaO activated slag (Gu et al., 2014; Jin et al., 2015).

## 3. Methodology

### 3.1. Sample preparation

The total content of the binders was fixed at 12% by weight of the stabilised soil, and the activator (MgO, CaO or their combinations) to GGBS ratio was set as 1:3. Four binder compositions were used in this study by varying the ratio of MgO to CaO (Table 2).

The binders were mixed homogeneously with the model soils in dry powder form in a mixer for 5 min, and then predetermined amount of distilled water was added. For the clayey soil, the initial water content was 26%, slightly higher than the optimal water content (i.e., 24%) since the hydration heat of binders may cause the evaporation of water during mixing, especially in the presence of CaO. For the sand, the initial water content was 10%. After homogeneously mixed with water, the wet stabilised soils were cast into cylindrical plastic moulds and statically compacted to  $\Phi 50 \times 100$  mm in two layers. The dry density of stabilised clayey soil was controlled at 1.54 g/cm<sup>3</sup> and that of stabilised sand was 1.70 g/cm<sup>3</sup>. Without demoulding, the samples

**Table 2**

Compositions of binders for soil stabilisation.

Binder nomenclature	Binder composition	Ratio
C3S9	CaO:GGBS	3:9
M1.5C1.5S9	MgO:CaO:GGBS	1.5:1.5:9
M2.8C0.2S9	MgO:CaO:GGBS	2.8:0.2:9
M3S9	MgO:GGBS	3:9

were then wrapped with cling film to eliminate the water loss and cured at  $20 \pm 2^\circ\text{C}$  and  $99 \pm 1\%$  humidity in sealed plastic boxes until ready for testing.

### 3.2. Testing procedure

The unconfined compressive strength (UCS) was tested in triplicate using a CONTROLS Uniframe test machine with the vertical load applied at a constant displacement rate of 1.14 mm/min according to ASTM standard D1633-00 (ASTM, 2007) after 7, 28, 56 and 90 days of curing. The water contents of the crushed samples were determined after the test. The elastic stiffness ( $E_{50}$ ) and the failure strain of samples were calculated from the stress–strain curves obtained from the strength test. A portion of the crushed soil sample was immersed in excess acetone for 3 days to arrest the hydration of binder, and then the samples were vacuum dried for at least 3 days and oven dried for 1 day at  $35^\circ\text{C}$ . To determine the amount of cementitious products in stabilised clayey soil, thermogravimetric analysis (TGA) was performed on selected samples using a PerkinElmer STA 6000 by heating samples from  $40^\circ\text{C}$  to  $1000^\circ\text{C}$  in air with the rate of  $10^\circ\text{C}/\text{min}$ . Scanning electron microscope (SEM) imaging analysis using JEOL 820 machine was also employed on selected samples to investigate the microstructure of the stabilised soil.

The durability of stabilised soil was evaluated by soaking unwrapped, demoulded samples in tap water for 4 days at  $20 \pm 2^\circ\text{C}$  in sealed plastic boxes (the samples were prepared and cured in the same way as the ordinary ones before soaking). This method was similar to the assessment of durability of stabilised soil in flood events by Obuzor et al. (2012). Two soaking regimes were applied: (1) partially soaked (i.e., half of the sample soaked in water) and (2) completely soaked. It should be noted that the samples were subjected to soaking at the last 4 days of each curing period rather than an extended 4 days period used by Obuzor et al. (2012). Because in this case, the effect of longer hydration time on the strength of the soaked samples can be eliminated. At the lapse of each curing period, the UCS of the samples was determined in duplicate by the same method on the unsoaked samples.

## 4. Results

### 4.1. Mechanical performance

#### 4.1.1. Unconfined compressive strength

Fig. 1 shows the UCS results of the stabilised soils using different binders. A clear trend of continuous strength development of stabilised soils with time was observed. Fig. 1a demonstrates that the replacement of CaO by MgO induced an increase in strength of the treated clayey soil at each time. After 7 days, C3S9 stabilised soil showed strength of 0.30 MPa. With the increasing content of MgO in the binder, the strength linearly increased to 0.91 MPa of M3S9 treated soil. There is a significant strength development by 28 days for all samples and the strengths meet the strength requirement for general soil mixing applications, typically 0.1–5.0 MPa (Bruce, 2001). Thereafter, M3S9 treated soil still showed significant strength development by 56 days and 90 days, while binders with CaO (C3S9, M1.5C1.5S9 and M2.8C0.2S9) stabilised soil showed relatively smaller increases. Additionally, the latter three binders treated soil still had a more or less linear relationship in strength.

Different strength development pattern was observed in the stabilisation of sand (Fig. 1b). After 7 days, M3S9 treated sand still exhibited the highest strength, followed by the C3S9 treated sand. The utilisation of MgO–CaO mixtures in the binder resulted in lower strength than both of binders using CaO or MgO alone. By 28 days, all samples showed a significant strength development, with slower development in the later ages, meanwhile the strength development patterns with binder composition remain the same as 7 days. After 90 days, C3S9

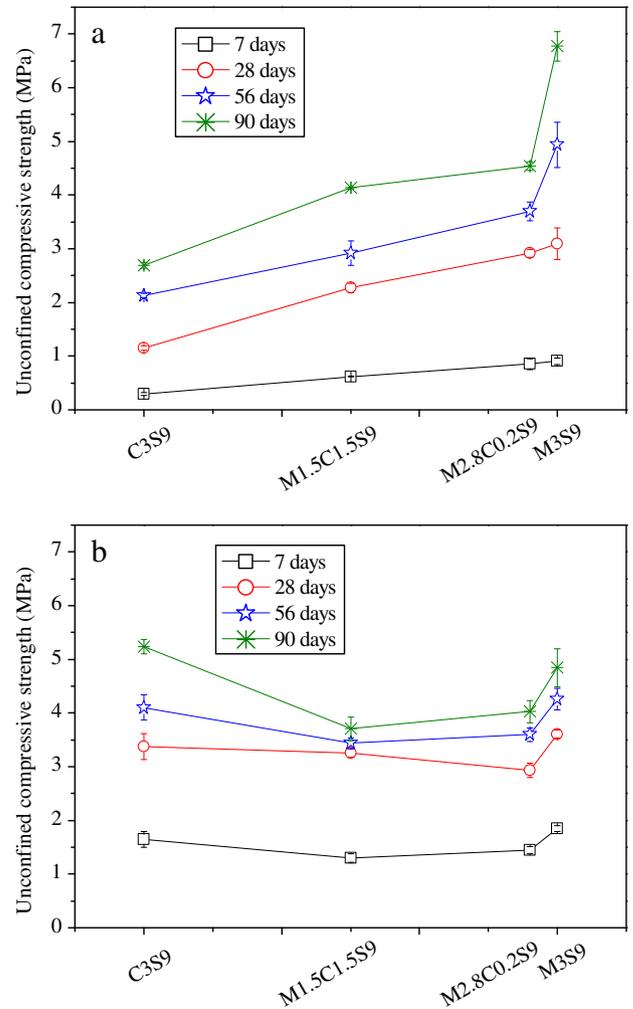


Fig. 1. Unconfined compressive strength of stabilised soils. (a) Clayey soil, (b) sand.

treated sand showed the highest strength of 5.24 MPa, followed by M3S9 treated sand with 4.84 MPa.

#### 4.1.2. Elastic stiffness

The modulus of elasticity ( $E_{50}$ ) is an important parameter for deformation analysis and design. Fig. 2 shows that the  $E_{50}$  values of treated soils increased with time. Additionally,  $E_{50}$  of clayey soil samples generally increases with increasing content of MgO in the binder (Fig. 2a) while no significant trend can be observed on the sand samples (Fig. 2b). The elasticity modulus of stabilised sand is mainly in the range of 100–400 MPa.

The correlation of the elastic stiffness with the unconfined compressive strength is shown in Fig. 3. For the clayey soil, a range of  $40\text{UCS} < E_{50} < 125\text{UCS}$  was calculated while the stabilised sand had a slightly narrower range of  $50\text{UCS} < E_{50} < 120\text{UCS}$ . In general, the correlation of  $E_{50}$  and UCS varies significantly with the type of soils (whose physico-chemical properties differ with the geological processes and stress history during the origin), the type and the amount of the binder used, according to the investigations on the relationship between  $E_{50}$  and UCS for different soils using different binders as summarised in Table 3. The ranges were usually wider than that observed in this study, which may be attributed to the fact that only one binder content (i.e., 12%) was used in this study. Additionally, Table 3 reveals that soils stabilised with GGBS based binders tend to have relatively lower and narrower ranges than soils treated with cement based binders.

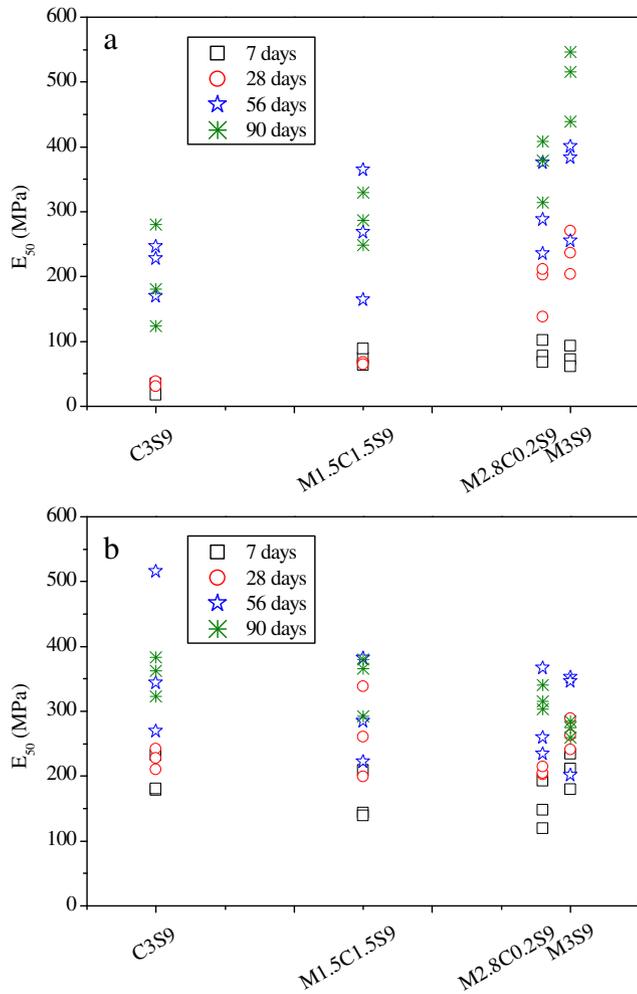


Fig. 2. Relationship between  $E_{50}$  and binder composition. (a) Clayey soil, (b) sand.

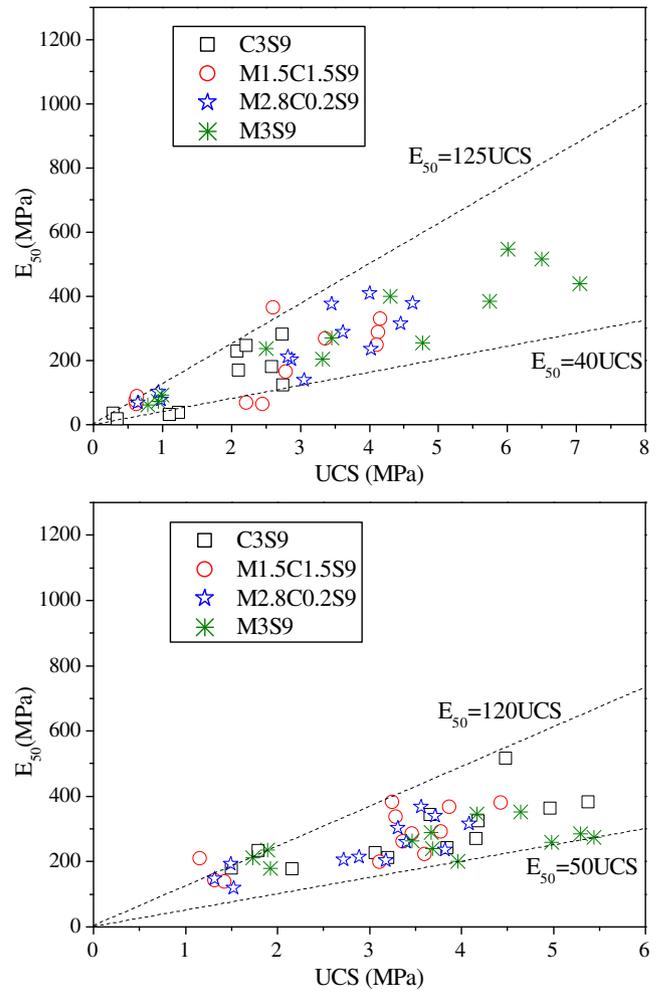


Fig. 3.  $E_{50}$  plotted against UCS for different binders. (a) Clayey soil, (b) sand.

#### 4.1.3. Failure strain

Fig. 4 shows the failure strain ( $\varepsilon_f$ ) for the stabilised clayey soil and sand. The trend that the failure strain of the stabilised clayey soil decreased with increasing strength agrees well with the results reported by others (Åhnberg et al., 2003). At 7 days, when the strength of samples is lower than 1.0 MPa, the failure strain decreased with the increasing content of MgO used in the binder, thereafter no significant relationship of the failure strain and the binder composition was observed. A scatter in measured failure strain can be seen, especially when the compressive strength is lower than 2.5 MPa. In addition, the plots of C3S9 and M1.5C1.5S9 are more scattered while the plots of M2.8C0.2S9 and M3S9 tend to be along with the fitting line. The scatter can be explained by the lower homogeneity of the C3S9 and M1.5C1.5S9 treated samples, in which the presence of CaO can cause high hydration heat release and induced the evaporation of water in some areas. In general, the relationship between UCS and failure strain of treated clayey soil can be represented by a power function expressed by:

$$\varepsilon_f = 1.81562 \times \text{UCS}^{-0.23781}, \quad R^2 = 0.30. \quad (1)$$

The relatively small correlation coefficient ( $R$ ), however, suggests that more data is required to build a fair relationship.

For the stabilised sand, no significant dependence of the relationship between failure strain and strength on the binder was obtained. In addition, small variation of the failure strain with increasing strength was observed.

As can be seen, the failure strain of stabilised clayey soil was in the range of 0.8%–3.1%. The cohesion of the clayey soil allowed relatively more ductile behaviour of stabilised soil when the strength was lower than 2.5 MPa. At higher UCS, the failure strain tended to remain in the range of 1.0%–1.8%, agreed well by the increase in stiffness (Fig. 2a). On the other hand, the observed failure strain of sand was in a narrower range of 0.7%–1.5%. The failure strain of sand was largely dependent on the hydrated binder, which results in increased brittle behaviour of the treated sand (Hamidi and Hooresfand, 2013).

#### 4.2. Water content

Since soil samples were cured in cling film sealed moulds, the decrease in water content of stabilised soils was mainly caused by the hydration process of binders. Fig. 5 illustrates the variation of water content of the samples. Due to the evaporation of water, which was caused by the exothermic hydration of the binders, the measured initial water contents of sample (at 0 day) were all smaller than the predetermined water content (i.e., 26% for the clayey soil and 10% for the sand). Additionally, the measured initial water content increased with the amount of MgO used in the binders, due to the slower hydration rate of MgO than CaO and lower hydration heat of MgO,  $-37.11$  kJ/mol (Shand, 2006) than CaO,  $-65.27$  kJ/mol (Obuzor et al., 2012). For the clayey soil, the water content decreased most significantly in the first 7 days, while smaller decreases were observed thereafter. Due to the latent hydration of MgO activated slag (Gu et al., 2014; Jin et al., 2015), the measured water content, in general, increased with the increasing content of

**Table 3**  
Relationships between modulus and UCS.

Soil type	Binder	Binder content (%)	Relationship	Reference
Model clayey soil	CaO:GGBS, MgO:CaO:GGBS, MgO:GGBS	12	$40UCS < E_{50} < 125UCS$	This study
Model sand	CaO:GGBS, MgO:CaO:GGBS, MgO:GGBS	12	$50UCS < E_{50} < 120UCS$	This study
Model gravelly sand	PC:GGBS, PC:PFA, PC:CKD	2.5–10	$55UCS < E_{50} < 160UCS$ (UCS up to 2.5 MPa), $220UCS < E_{50} < 360UCS$	Jegandan et al. (2010)
Model clayey silt	PC:GGBS, PC:PFA, PC:CKD	2.5–10	$15UCS < E_{50} < 130UCS$ (UCS up to 0.25 MPa), $121UCS-23 < E_{50} < 132UCS$	Jegandan et al. (2010)
Bangkok clay	Type I PC	5–20	$115UCS < E_{50} < 150UCS$	Lorenzo and Bergado (2006)
Lianyungang marine clay in NaCl solution	Type I PC	10–20	$150UCS < E_{50} < 275UCS$	Zhang et al. (2013)
Dried-pulverized Singapore marine clay	PC	20–70	$45UCS < E_{50} < 130UCS$	Lee et al. (2005)
Slurry Singapore marine clay	PC	20–70	$80UCS < E_{50} < 200UCS$	Lee et al. (2005)
Silty clay, silt and laterite	PC	0–13	$100UCS < E_{50} < 326UCS$	Rashid et al. (2014)
Shinagawa clay	PC	5–15	$350UCS < E_{50} < 1000UCS$	Saitoh et al. (1980)

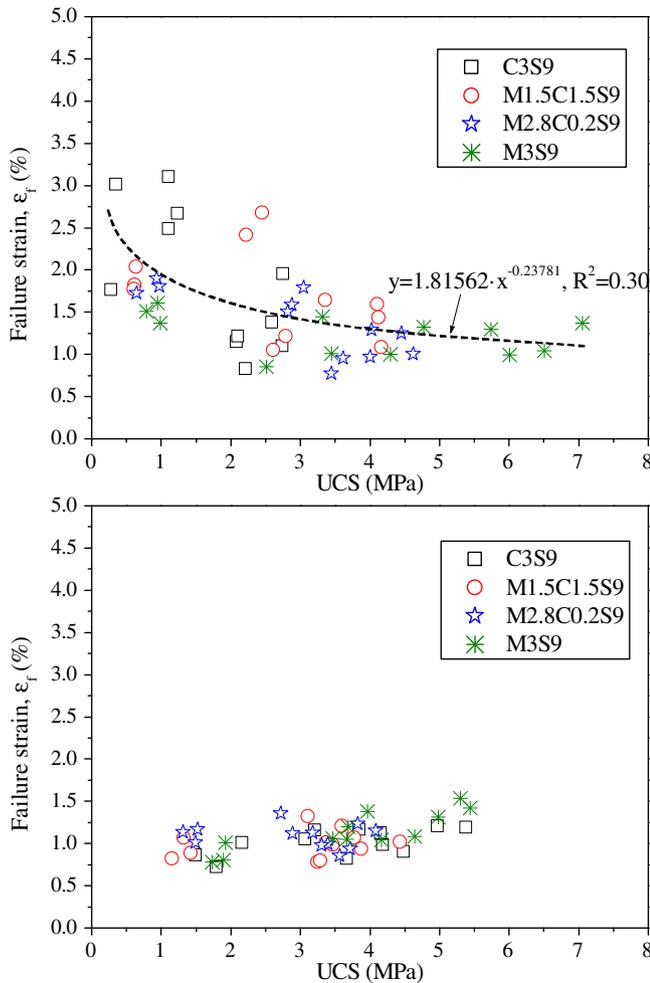
MgO in the binder, by which the binder may hydrate more sufficiently. After 56 days and 90 days, it should be noted, the water content of M3S9 stabilised soil dropped rapidly, due to the accelerated hydration degree of slag and hence accelerated demand of water, according to the previous work (Gu et al., 2014). As for the sand, the decrease in water content due to the hydration of the binders with time was also observed, with a similar pattern of water content development to the clayey soil. The reason should be the same as mentioned in the clayey soil.

The stable water content of the stabilised soil could be estimated by the following equation (Åhnberg et al., 2003):

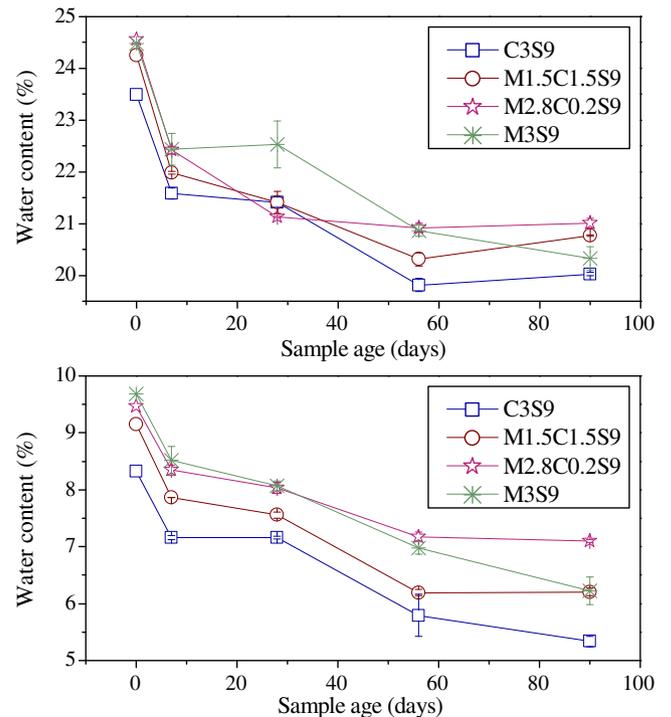
$$w_{\text{stab}} = \frac{\rho_{\text{soil}} \left( \frac{w_i}{w_i + 1} \right) - nx}{\rho_{\text{soil}} \left( \frac{w_i}{w_i + 1} \right) + (1 + n)x} \quad (2)$$

In which  $\rho_{\text{soil}}$  is the bulk density of the unstabilised soil ( $\text{g}/\text{cm}^3$ );  $w_i$  is the initial water content of the untreated soil;  $x$  is the amount of dry binder added to the soil ( $\text{g}/\text{cm}^3$ ); and  $n$  is the content of non-evaporable water of the hydration product with respect to dry binder weight. Here, the parameter  $n$  was selected to be 0.2 for the hydrated slag (Åhnberg et al., 2003), which is a smaller  $n$  than used in hydrated cement (i.e., 0.23) (Taylor, 1997).

As can be seen, the measured water contents of clayey soil are slightly higher than the estimated water contents (Fig. 6), implying the presence of inaccessible free water in the soil. The migration of water in clayey soil could be affected by the kaolin clay particles, which can easily



**Fig. 4.** Failure strain plotted against UCS for different binders. (a) Clayey soil, (b) sand.



**Fig. 5.** Variation of measured water contents over time. (a) Clayey soil, (b) sand.

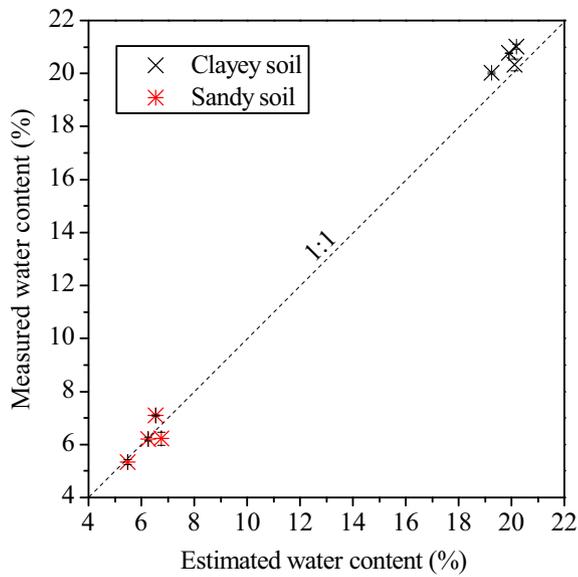


Fig. 6. Estimated water content of stabilised soils against measured plots after 90 days.

absorb water and produce small pores; therefore some water was difficult to react with the binder. On the other hand, the estimated water contents of sand had better correlations with the measured values. The water in the sand sample participated in the hydration process of the binders in a higher proportion than in the clayey soil.

#### 4.3. Microstructure

The model soils used in this study were prepared by mixing different materials, and thus the structural strength between the particles was

relatively weak. The hydrated binder combined the soil particles together, with physical (i.e., binding, bridging) and/or chemical (i.e., pozzolanic reaction) processes. Fig. 7 illustrates the change of the microstructure of M1.5C1.5S9 stabilised clayey soil with time. As can be seen, the structure of the soil was relatively loose with many pores developed after 28 days (Fig. 7a). The binding of the plate-like clay particles by hydration products (mainly cementitious C–S–H gel) was observed in a magnified scale (Fig. 7b). After 90 days, with the hydration of the binder and probably the pozzolanic reaction, significantly more cementitious C–S–H gel made contribution to the strength development by forming a much denser matrix in Fig. 7c and d than observed in Fig. 7a and b. The soil particles exhibited close interconnection and the pores were well filled by the hydration products, explaining the high strength and small failure strain of the soil.

The hydrated binder connected the sand particles mainly by physical processes such as bridging, binding and pore filling effect. The microstructure analysis on the same stabilised model sand carried out by Yi et al. (2014c) indicated the good interconnection between soil particles by hydrated binders. But the relatively coarse surface morphology made it difficult to identify the microstructural change over time.

The effect of binder composition on the microstructure was difficult to be determined due to (1) the presence of the soil particles, especially soft kaolin clay particles, which induced a complex microstructure with specific mineral difficult to be identified; (2) the amorphous nature of the gels formed, which intermixed together and has no specific morphology (Jin et al., 2015, in press).

#### 4.4. Thermogravimetric analysis

TGA was performed to identify the main phases in the stabilised soils. Fig. 8 shows the TG/DTG curves of M1.5C1.5S9 and M3S9 treated clayey soil after 28 days. For both samples, two main weight losses can be seen. The weight loss from 40 °C to 200 °C was mainly due to the dehydration of C–S–H gel (Ben Haha et al., 2011; Michel et al.,

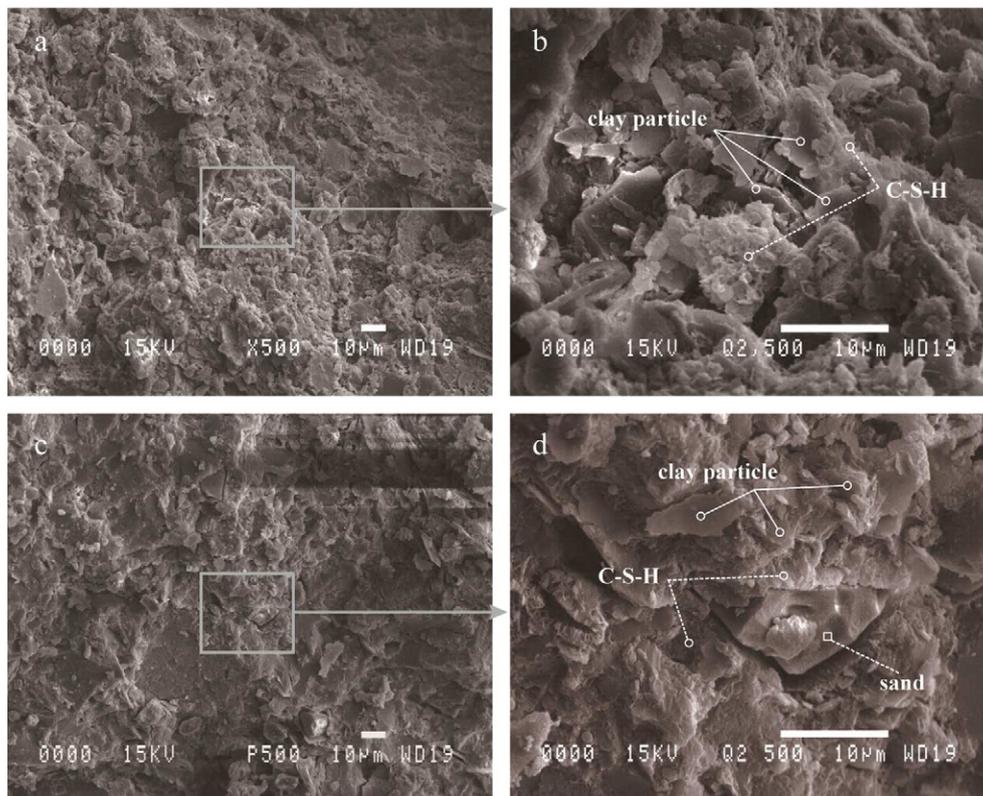


Fig. 7. SEM images of M1.5C1.5S9 stabilised clayey soil. (a) and (b) 28 days, (c) and (d) 90 days.

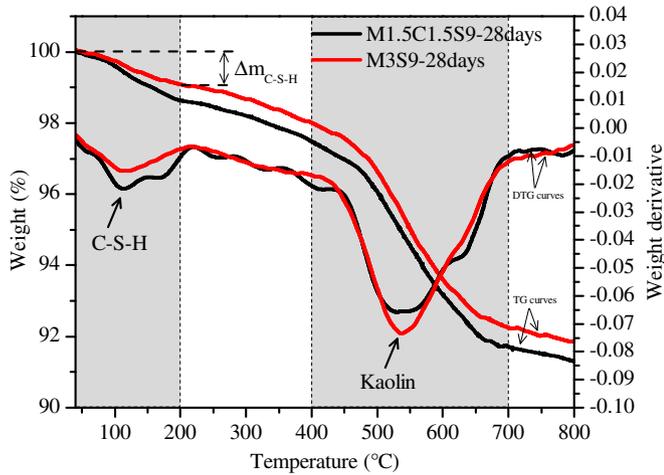


Fig. 8. TG/DTG curves of selected stabilised clayey soil samples.

2012) and the weight loss between 400 °C and 700 °C represented the decomposition of kaolin (Ptáček et al., 2014).

The binding capacity of the hydrated binder is mainly dependent on the amount of cementitious C–S–H gel, whose amount in different samples can be estimated by the weight loss from 40 °C to 200 °C (Ben Haha et al., 2011). Fig. 9 illustrates the amount of C–S–H gel of M1.5C1.5S9, M2.8C0.2S9 and M3S9 treated clayey soil after 28 days and 90 days according to the TGA results. It is clear that the amount of C–S–H gel in stabilised soil increased with the hydration time and, it should be noted, the amount of C–S–H gel decreased with the increasing content of MgO in the binder. According to the compressive strength results (Fig. 1), however, higher MgO content in the binder induced higher strength at each time. The explanation will be given in the Discussion section.

#### 4.5. Durability in different soaking conditions

Fig. 10 illustrates the effect of soaking on the strength of the stabilised clayey soil using the four binders. The grey plots represent the percentages of strength variation upon soaking conditions to the strength of unsoaked samples. In the early age (7 days), both partially soaked and completely soaking conditions resulted in an increase in strength of stabilised soil with all four binders. The soaked samples had 16%–43% higher strength than the unsoaked samples. At later

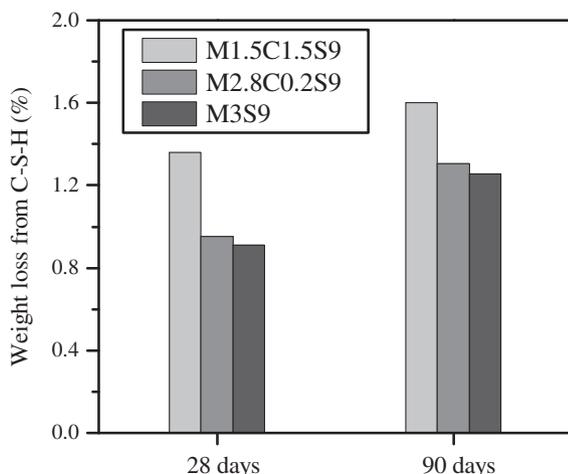


Fig. 9. Calculated amount of C–S–H gel formed in stabilised samples from TGA results.

ages, relatively smaller variations in strength upon soaking conditions were seen, which can be explained by the decreased hydration rate with time. Apparently, after being subjected to different soaking conditions, continuous strength increase with increasing MgO/CaO ratio of the binder was still observed. That is, clayey soil stabilised with binders of higher MgO/CaO ratio always exhibited higher strength. The effect of MgO and CaO on the soil behaviour upon soaking conditions is different. On the one hand, MgO alone activated slag (M3S9) treated soil appears to have poor durability upon different soaking conditions after 28 days and thereafter, in spite of its highest strengths upon ordinary curing condition. On the other hand, the presence of CaO in the binder to some extent improves the durability of stabilised soil in waterish conditions through additional pozzolanic reaction and slag hydration until 56 days. Nevertheless, the soil samples treated with MgO containing binders still showed higher strengths than CaO alone activated slag (i.e., C3S9) stabilised soil, demonstrating the better mechanical performance of MgO or MgO–CaO mixtures activated slag stabilised soils than quicklime (lime) activated slag stabilised soils in waterish conditions such as intense fall, flood and rising of groundwater level.

## 5. Discussions

CaO can produce a relatively high pH environment (i.e., 12.5) of pore solution than MgO (i.e., 10.5), hence the hydration of the binder usually proceeded more rapidly in the presence of CaO than using MgO alone in the activation. The faster reaction of the slag leads to a fast precipitation of relatively dense C–S–H layer, in which case further hydration of slag almost developed entirely in the place of the original slag particles, with very little hydrates formed between slag particles (Ben Haha et al., 2011). Consequently, C–S–H gel was less homogeneously distributed in the matrix and presented lower strength. The increase in MgO content reduced the hydration rate of the binders and the amount of C–S–H gel (Gu et al., 2014), but enhanced the uniformity of distribution of hydrates. Additionally, a decrease in Ca/Si ratio of the C–S–H in MgO–CaO mixtures activated GGBS paste with increased MgO/CaO ratio was observed on the same raw materials by Gu et al. (2014). According to Provis and van Deventer (2014), the cohesion and strength of C–S–H gel tend to decrease with its Ca/Si ratio, and thus the relatively lower Ca/Si ratio of the C–S–H formed in MgO–GGBS may give higher strength of the stabilised soil. On the other hand, the activation of slag with MgO can induce the formation of hydrotalcite-like phases, which are more voluminous than C–S–H gel that had formed in lime activated slag (Jin et al., 2015), and its pore filling effect will compact the structure therefore strengthen the soil (Yi et al., 2014c). Consequently, the compressive strength of clayey soil increased with the increasing content of MgO in the binder (Fig. 1a), but with decreasing amount of formed C–S–H gel (Fig. 9). In case of the sand stabilisation, the high void ratio and the coarse sand particles may lead to a loose structure of the treated sand, which to some extent eliminated the influence of C–S–H homogeneity, C–S–H cohesion and voluminous hydrotalcite-like phases on the strength. Therefore similar strength was achieved by C3S9 and M3S9 treated sand. The combination use of MgO and CaO seems to have poor potential, in terms of mechanical performance, in sand stabilisation since smaller strength was observed than soil treated by CaO or MgO alone activated slag at each time.

Another issue on the application of MgO in soil stabilisation, either alone or blended with other powder, should be related to MgO itself. Dead burned MgO in PC, which is manufactured at temperatures ~1450 °C, is recognised as a problematic impurity which leads to expansion and cracking of cement and concrete through the delayed hydration. Reactive MgOs have much higher reactivity than dead burned MgO and hence faster hydration rate. On the other hand, given the different origins and production process, reactive MgOs show a great variety in reactivity, specific surface area and crystallinity (Shand, 2006) and present significantly different performance in slag activation (Jin et al., in press). Generally, increasing the reactivity of MgO and/or the

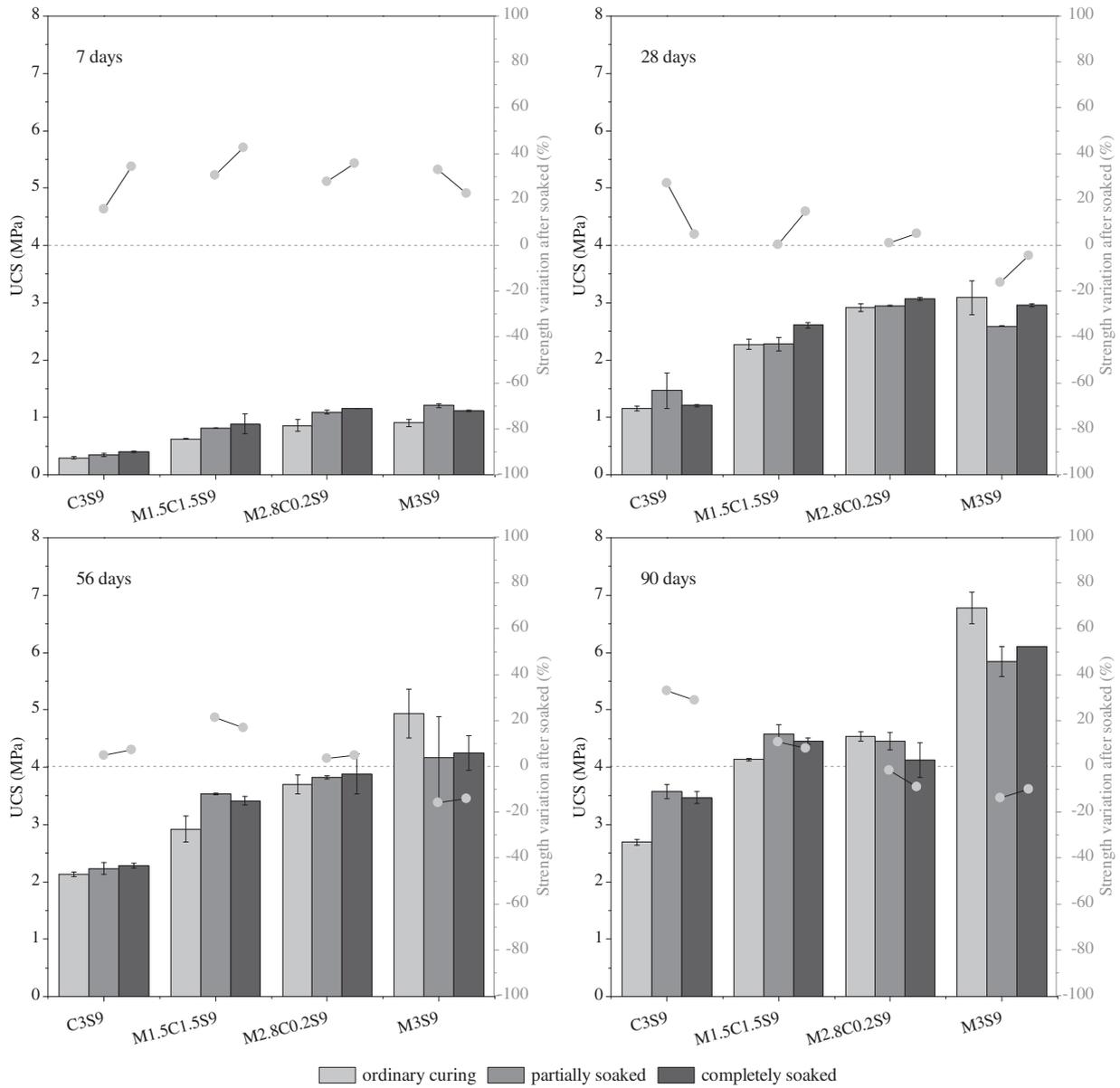


Fig. 10. Variation of strength upon partially and completely soaked conditions.

amount of MgO can induce higher early age strength of slag paste and stabilised soil. The MgO used in this work was of lower reactivity than that used in the study reported by Yi et al. (2014c) on a same model sand. The strength of M3S9 treated sand was 1.8 MPa at 7 days (Fig. 1b) and was much smaller than 5.0 MPa reported by the authors, even though the authors used a slightly smaller MgO to slag ratio (i.e., 1/4) with the total binder content of 10%. In addition, despite the superior performance of stabilised soils with more MgO in the binder, arbitrarily increasing the amount of MgO should not be encouraged, not only due to the economic issue, but also due to the fact that the hydration of residue MgO may cause cracks in the stabilised soil and reduce the long term strength, which has been reported by Yi et al. (2014c). The hydration of MgO forming brucite [ $\text{Mg}(\text{OH})_2$ ] can cause 118% volume growth, which is the reason of MgO with proper reactivity used as expansive agent in expansive concrete (Xu and Deng, 2005). Additionally, excess CaO may also lead to excess hydroxalite-like phases, which may also cause cracks in the matrix and be detrimental to the strength (Jin et al., in press). These two mentioned potential detrimental effects of excess MgO on the stabilised soil may explain the

decrease in strength of stabilised clayey soil when subjected to soaking conditions.

## 6. Conclusions

The utilisation of MgO–CaO–GGBS blends in stabilising two model soils, a clayey soil and a clayey silty sand, was investigated in this paper. The binder content was 12 wt.% with 9 wt.% slag and 3 wt.% MgO, CaO or their mixtures. Four MgO/CaO ratios [i.e., 0/3 (CaO alone), 1.5/1.5, 2.8/0.2 and 3/0 (MgO alone)] were used.

The unconfined compressive strength of stabilised clayey soil increased with the increasing MgO/CaO ratio up to 90 days. MgO alone activated slag stabilised soil had significantly higher strength after 56 days and longer than the other three binders. However, the amount of cementitious C–S–H gel, which provides the binding capacity of stabilised soil, decreased with the increasing MgO/CaO ratio of the binder due to the decreased reaction rate. This can be attributed to (1) the slower hydration rate led to more homogeneous formation of the C–S–H gel, (2) lower Ca/Si ratio of the C–S–H gel formed, which

could give higher strength and (3) the amount of hydrotalcite-like phases, which compacted the structure of C–S–H gel, increased with the increasing MgO/CaO ratio. Additionally, the increase in elasticity modulus ( $E_{50}$ ) of stabilised clayey soil with increasing MgO/CaO ratio at all ages and the decrease in failure strain of clayey soil with increasing MgO/CaO ratio in the early age was observed.

The combination of MgO and CaO in slag activation for sand stabilisation, however, led to poorer mechanical performance than MgO or CaO alone activated slag stabilised sand. No significant dependence of  $E_{50}$  and failure strain on the MgO/CaO ratio was observed in this study. The relatively loose structure of sand to some extent eliminated the influence of MgO/CaO ratio on the hydrated binder therefore on the mechanical performance.

The result on the durability of stabilised clayey soil demonstrated the enhanced mechanical performance of soil with the increasing MgO/CaO ratio in the binder under different soaking conditions, therefore better resistance of stabilised soil to extreme or particular conditions such as intense fall, flood and rising of groundwater. But care should be taken on the reactivity and amount of reactive MgO used, which may reduce the long term strength of soil by the formation of expansive brucite and hydrotalcite-like phases through the delayed hydration with additional water. In this context, further investigation on the optimisation of the content of MgOs with varied reactivity and the MgO/CaO ratio should be performed.

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