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Sustainable cementitious blends for strength enhancement of dredged mud in Queensland, Australia

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Cement is commonly used as a stabilisation material in soft soil stabilisation. However, the use of cement can cause environmental issues, as the production of cement results in high emission of carbon dioxide (CO₂). Hence, it is essential to develop other suitable stabilisation materials to reduce the amount of cement used in the stabilisation of soft soil. Fly ash and DuraCrete (blended cement) were investigated in this study to be used as partial replacements for traditional cement-only mixes. The behaviour of specimens stabilised using cement, fly ash and DuraCrete under both unconfined compressive and consolidated isotropic undrained conditions was investigated in this study. The experimental results proved that both fly ash and DuraCrete can be used as partial replacements for cement. Fly ash can provide the highest reduction in terms of percentage of cement. Meanwhile, DuraCrete is more cost effective, as a relatively smaller quantity of DuraCrete can replace a correspondingly larger amount of cement for a similar strength gain. The contribution of this research can provide engineers with alternative, more sustainable design mixes for soft soil stabilisation that can readily satisfy design strength requirements while emitting relatively less carbon dioxide.

Keywords: cement/cementitious materials/CO₂ emission/geotechnical engineering/SEM analysis/soil stabilisation/triaxial compression test/unconfined compressive strength

Notation

A, B	empirical constants
b	cement blend content
c	cement content
$M_{\text{added water}}$	mass of added water
M_{cement}	mass of cement powder
$M_{\text{cement+DuraCrete}}$	mass of cement + DuraCrete
$M_{\text{cement+fly ash}}$	mass of cement + fly ash
$M_{\text{soil solids}}$	mass of soil solids
M_{water}	total mass of water
q_{peak}	peak deviator stress
W	total water content
σ_3	confining pressure

Introduction

Soft soil deposits such as mine tailings, hydraulic fills, soft estuarine or marine clays commonly exist across the planet. The available land for construction has decreased due to rapid urbanisation and population growth around the globe. Recent advances in the field of construction materials science considering environmental sustainability (Leong *et al.*, 2015, 2016a, 2016b, 2018a, 2018b; Ngu *et al.*, 2019) and characterisation of soils form the basis of interdisciplinary geoenvironmental and geotechnical design. In executing these novel approaches, challenges are often faced in laboratory testing (Mehdizadeh *et al.*, 2016, 2017), numerical simulations (Ong *et al.*,

2006; Pham *et al.*, 2021) and due to weak in situ geomaterial properties requiring sustainable stabilisation (Omoregie *et al.*, 2016, 2017, 2019a, 2019b, 2019c, 2020). For instance, key projects such as construction of coastal facilities such as shipyards (Ong *et al.*, 2018) and quay walls, urban deep excavation (Chong and Ong, 2020; Ong *et al.*, 2003a, 2003b) or deep foundations for building basements (Ong and Choo, 2011; Ong *et al.*, 2015), embankments on floodplains (Liu *et al.*, 2020; Sun *et al.*, 2021) and tunnelling (Cheng *et al.*, 2020; Peerun *et al.*, 2019, 2020) require construction on ground with appreciable soft soil deposits (Kang *et al.*, 2015; Liu *et al.*, 2017; Yao *et al.*, 2020). Therefore, it is crucial to understand the behaviour of soft soil or its stabilised variants so that sustainable projects can be constructed on this problematic ground.

Cement is one of the commonly used cementitious materials to stabilise soft soils. It has been widely adopted as a stabilising binder when mixed with soft soils, as it enhances strength and stiffness and decreases compressibility. The use of cement to stabilise soft soils and the behaviour of cement-stabilised soils have been extensively investigated in many previous studies (e.g. Ekinci, 2019; Horpibulsuk *et al.*, 2005; Jaubertie *et al.*, 2010; Kwan *et al.*, 2005; Liu *et al.*, 2019, 2020, 2021; Luis *et al.*, 2019; Ma *et al.*, 2014; Yao *et al.*, 2020; Uddin *et al.*, 1997; Zhang and Zhu 2020). It has been proven by these studies that the addition of cement can efficiently increase the strength and durability of stabilised soft soils by significantly reducing

the water content and creating cementation bonds between soil particles. In addition, the cost of cement is very cheap, and this material can be accessed easily anywhere in the world. Therefore, cement has been widely used as the stabilising binder.

However, the production of cement also brings a significant issue to the environment, which is the high emission of greenhouse gases, such as carbon dioxide (CO₂). Based on a study by Huntzinger and Eatmon (2009), 5–8% of anthropogenic carbon dioxide was emitted because of the production of cement. The global cement demand is forecast to continue to grow to 2050, with a compound annual growth rate of approximately 5% per annum for the rest of the 2020s (Imbabi *et al.*, 2012). Cement is a key ingredient both in concrete production and often in soil stabilisation in civil engineering projects. In addition to the cement used in stabilisation, civil engineering projects are material- and energy-intensive operations. Therefore, these two materials offer alternative approaches to stabilisation, that both reduce the portion of cement required and thus reduce carbon dioxide emissions ('carbon emissions') from cement production. In the case of DuraCrete, it also reduces the overall quantity of materials and time required for stabilisation, which reduces costs and carbon dioxide generated for both material transport and project implementation. Therefore, less carbon dioxide would be emitted during the soft soil stabilisation.

Fly ash is an industrial by-product resulting from the combustion of coal at power stations. The use of this material in soil stabilisation can significantly reduce the emission of carbon dioxide compared with the use of pure cement. For example, the carbon emission factor of cement is 0.82 tonnes carbon dioxide equivalent (tCO₂e)/t, while the emission factor of fly ash is only 0.027 tCO₂e/t, according to a study by Heidrich *et al.* (2005). However, from previous studies, it can be concluded that cement performs better than fly ash in terms of the mechanical behaviour of stabilised soils (Bolton, 2014; Buensuceso, 1990). The experimental results from those studies indicate that the unconfined compressive strength (UCS) of specimens stabilised by cement is higher than that of specimens stabilised by fly ash with the same additive content and curing period. This is because the main reaction between cement and soft soils is the hydration of cement, which produces a lot of calcium silicate hydrate (CSH), hydroxide ions and cementation bonds within very short period. However, the reaction between fly ash and soft soils mainly relies on the pozzolanic reaction, which requires an extra alkaline environment to activate the reactions (Buensuceso, 1990; Hanehara *et al.*, 2001). Pozzolanic reactions would take a much longer period without using suitable activators.

In general, based on the studies reviewed, it can be concluded that fly ash is an environmentally better material compared with cement, as a unit weight of fly ash produces much less carbon dioxide than pure cement. However, fly ash cannot be used alone as the stabilisation binder, due to the reasons mentioned previously. Therefore, it is not feasible to replace 100% cement with fly ash in soil stabilisation. However, some studies investigated the use of fly ash as a partial replacement of cement in soil stabilisation (Cheng

et al., 2018; Horpibulsuk and Raksachon, 2010; Horpibulsuk *et al.*, 2009, 2010, 2011). This means that fly ash was admixed with cement to obtain fly-ash-blended cement, and then it was used to stabilise soft soils. The hydration of cement provides an alkaline environment, as it produces hydroxide ions. Therefore, the pozzolanic reaction between fly ash and soft soils can be activated. By adopting fly-ash-blended cement in soil stabilisation, the strength requirements of the improved soil were satisfactorily met while reducing carbon emissions as a result of requiring less cement binder compared with the soil improved by cement only. Both fly ash and DuraCrete facilitate a reduction in the proportion of cement required to stabilise a given volume of soil, compared with cement-only stabilisation. The reduction in cement required means less carbon emissions generated during the energy-intensive heating of calcium carbonate in a rotary kiln to produce clinker. Fly ash, a by-product of coal-fired power stations, is thus a product of that carbon dioxide emitting ('carbon-emitting') process. The production of DuraCrete does not generate significant carbon emissions, as it does not require furnaces or other energy-intensive processes. DuraCrete is based on a blend of mineral oxides and alkaline-based materials.

In addition to ordinary Portland cement (OPC), a traditional calcium-based stabilising binder, a number of studies have investigated the possible use of non-calcium-based stabilising materials, such as ions, lignin derivatives, acids, silicates, resins, geopolymers and magnesium chloride (Latifi *et al.*, 2015; Leong *et al.*, 2015, 2016a, 2018a, 2018b). DuraCrete is a commercial low-calcium stabilising additive that is used as a cement modifier to prompt hydration and strengthen crystalline cementitious formation. From its initial development in Germany, this product has been applied to 4000 ground improvement projects in firmer residual soils, such as a high-speed vehicle test track for Daimler Chrysler AG in Laredo, TX, USA; stabilisation for oil and gas drilling pads in Colorado, USA; ground improvement for a railway track base and rehabilitation of roads in Switzerland; rehabilitation and construction of a road link from Eberhardzell to Fischbach, as well as a high-load-bearing base layer for a timber yard and sawmill in Baruth, Germany; creation of a base layer for a logistics centre and warehouse in Arboga, Sweden; road rehabilitation in East Java, Indonesia; and mining roads and infrastructure in Alberta, Canada (Shamrock GeoScience, 2017). However, there is limited research on the use of this low-calcium-based material in stabilising very soft soils, particularly those with a high water content in excess of 100%. This original study will guide future potential applications in using this additive as a cement blend. To understand better the efficiency of DuraCrete in soft soil stabilisation, it is necessary to conduct some studies to evaluate the mechanical behaviour of soft soils stabilised by a mixture of DuraCrete and cement. UCS has been proven to be a reliable indicator of the mechanical behaviour of stabilised soft soils.

A common method of soil stabilisation is deep soil mixing (DSM). For the field application of DSM, the binder slurry can be mixed with soft soils in the ground to form columns that behave like concrete. In many circumstances, the depth of the deep-mixed soil-binder columns can be 10–40 m below ground level. For example, the deep-

mixed soil–cement columns adopted in an embankment project by Ye *et al.* (2013) have a depth of 15 m in general. Therefore, in such cases, the influence of confining pressure on the mechanical behaviour of soil cannot be ignored. UCS is not enough to evaluate the behaviour of the stabilised soils. In a study conducted by Cheng *et al.* (2018), regarding the mechanical behaviour of soft soil stabilised by fly-ash-blended cement, an empirical relationship between peak strength and confining pressure was proposed based on the triaxial compressive tests. However, the limitation of that study is that only one specific fly ash and cement ratio and one type of binder were considered. To consider the influence of confining pressure and the performance of each binder in triaxial testing conditions, a series of triaxial compression tests was also conducted in this study with specimens stabilised by the three binders as used for the preparation of UCS specimens. The following mechanical parameters were investigated in this study: stress–axial strain behaviour and excess pore pressure–axial strain behaviour. In addition, to determine the interactions between soil particles and cement, fly ash and DuraCrete, scanning electron microscopy (SEM) tests were conducted on all the test specimens.

The main aim of this research study is to investigate further the use of fly ash and DuraCrete on soft soil stabilisation, specifically for soft soils with a high water content, whether fly ash or DuraCrete is effective as partial replacements of OPC or not. A series of experiments was conducted to obtain the mechanical behaviour of stabilised soft soils specimens by using three types of binders: (a) pure OPC only (OPC) as the baseline study, (b) fly-ash-blended cement and (c) DuraCrete-blended cement.

Soil and materials used

The soil used in this study was soft marine clays collected from the Port of Brisbane (PoB) in Queensland, Australia. This marine clay is of dark grey colour and is a silty clay with a small amount of sand particles. The main source of this soil was deposits from the Holocene age (Wijeyakulasuriya *et al.*, 1999). The basic properties of this type of soil are summarised in Table 1. As shown in Table 1, the natural moisture content (NMC) of this soil is as high as 130%. Therefore, suitable binders and mixed design must be used to stabilise the soft soil before it is strong enough to support infrastructure loads.

The cement adopted in this study is OPC produced by Cement Australia. The main component of the cement used in this study is

Table 1. Summary of the basic properties of PoB clay

Property	Value
Clay content: %	79.8
Silt content: %	18.2
Sand content: %	2.0
Liquid limit: %	91.6
Plastic limit: %	36.7
Plasticity index: %	54.9
Natural moisture content: %	130.0

calcium compound; as mentioned previously, cement is a typical calcium-based binder. The fly ash used can be defined as type F according to its calcium content. The DuraCrete material used is produced by Shamrock GeoScience Ltd. X-ray fluorescence (XRF) was adopted to determine the chemical composition of each material. The XRF results were analysed, and the main chemical components of PoB soil and each type of material are presented in Table 2. Compared with cement, DuraCrete has a relatively much lower calcium content, which is similar to the calcium content of fly ash. Meanwhile, it is obvious that DuraCrete has much higher magnesium oxide (MgO) compared with both fly ash and cement. Also, both fly ash and DuraCrete have higher contents of silica compounds compared with cement. In general, DuraCrete can be classified as a magnesium-based additive, based on the XRF results.

Testing programme

To prepare the specimens, soil slurry with NMC 130% was mixed with (a) cement only, (b) fly-ash-blended cement and (c) DuraCrete-blended cement. The mixture was prepared by thoroughly mixing each type of design mix with distilled water at a water:cement or water/cement blend ratio of 0.5, as suggested by some previous studies (Bolton, 2014; Buensuceso, 1990; Cong *et al.*, 2014). The added water/cement or water/cement blend ratio is defined by Equations 1a and 1b, respectively, for the preparation of cement slurry to be mixed with the PoB soil.

$$1a. \quad \text{water/cement ratio} = M_{\text{water}}(\text{g})/M_{\text{cement}}(\text{g})$$

$$\text{water/cement blend ratio} = M_{\text{water}}(\text{g})/M_{\text{cement blend}}(\text{g})$$

1b.

Table 2. Summary of the main chemical components of each additive

Oxide	PoB soil: %	Fly ash: %	Cement: %	DuraCrete: %
LOI	14.84	2.76	2.42	13.36
Iron (III) oxide (Fe ₂ O ₃)	8.48	8.29	3.20	0.87
Calcium oxide (CaO)	1.44	7.19	65.21	5.57
Potassium oxide (K ₂ O)	1.61	0.80	0.45	5.00
Sulfur trioxide (SO ₃)	1.47	0.33	2.98	1.13
Silicon dioxide (SiO ₂)	48.00	54.29	19.85	38.88
Aluminium oxide (Al ₂ O ₃)	17.12	24.01	5.06	6.85
Magnesium oxide (MgO)	2.10	1.14	1.09	16.64
Sodium oxide (Na ₂ O)	3.36	0.26	0.22	4.91

LOI, loss on ignition

Then, the PoB soil was mixed with the cement slurry or cement blend slurry. The mixed soil and cement or cement blend was then poured into cylindrical poly(vinyl chloride) (PVC) moulds, each measuring 50 mm diameter and 100 mm high. During that process, the soil–binder slurry was also vibrated to eliminate any air bubbles trapped in the specimens. All the specimens were then wrapped in several layers of plastic wrap to ensure that there is no moisture ingress or egress during the curing period. These specimens were then placed in an isolated box and stored in a curing room at a constant temperature of 22°C and 80% humidity. After reaching the targeted 28-day curing period, the specimens were extruded from the PVC moulds.

Unconfined compressive strength

First, to investigate the strength development of PoB soft soils stabilised by cement, in total 20 sets of specimens stabilised by cement only were prepared in this study. The experimental results of these specimens are considered as the benchmark of this study. Furthermore, another 40 sets of specimens stabilised by a combination of cement and fly ash (fly-ash-blended cement) or a combination of cement and DuraCrete (DuraCrete-blended cement) were then prepared. These results were compared with the experimental results of the cement-stabilised specimens to investigate the efficiency of fly ash and DuraCrete as partial replacements of cement.

Twenty sets of soft soil specimens stabilised by cement only were prepared at moisture contents of 130% (NMC) using cement-only as a binder at 10, 15, 20, 25 and 30% for each moisture content. For each cement-only test, three specimens were prepared, and the average results were calculated and reported as the representative strength. The cement content is defined as the ratio between the mass of cement and the mass of dry soil solids as shown in the following equation:

$$2a. \text{ cement content (\%)} = M_{\text{cement}}(\text{g})/M_{\text{soil solids}}(\text{g})$$

Another 20 sets of soft soil specimens stabilised by fly-ash-blended cement were then prepared. For specimens stabilised by fly-ash-blended cement, the total mixture contents are also 10, 15, 20, 25 and 30%, consistent with the cement-only contents. The total mixture content is defined as the ratio between the mass of total mixture (cement + fly ash) and the mass of dry soil solids as shown in Equation 2b. The adopted mixing ratios between fly ash and cement are 1:1, 1:2, 1:3 and 1:4 at each total mixture content. This means that 50, 33, 25 and 20% of cement by weight is replaced by fly ash. These fly ash/cement mixing ratios were selected based on previous studies in terms of the use of fly-ash-blended cement in soil stabilisation. For instance, Horpibulsuk *et al.* (2010) recommended that 25% of cement can be replaced by fly ash (fly ash/cement ratio 1:3), which has the most effective dispersing effect. Xiao *et al.* (2017) and Cheng *et al.* (2018) investigated soft soils stabilised by fly-ash-blended cement where a ratio between fly ash and cement of 1:2 (33% of cement was

replaced by fly ash) was adopted in their study. In this study, four replacement ratios were adopted as mentioned earlier.

$$2b. \text{ total mixture content (\%)} = M_{\text{cement+fly ash}}(\text{g})/M_{\text{soil solids}}(\text{g})$$

Then, another 20 sets of specimens were prepared by using DuraCrete-blended cement to stabilise the soft soils. For specimens stabilised by DuraCrete-blended cement, the total mixture contents are consistent with the cement-only and fly-ash-blended cement. The total mixture content is defined by Equation 2c. The adopted mixing ratios between DuraCrete and cement are 3:100 (or 3%), 5:100 (or 5%), 7:100 (or 7%) and 9:100 (or 9%) at each total mixture content.

$$2c. \text{ total mixture content (\%)} = M_{\text{cement+DuraCrete}}(\text{g})/M_{\text{soil solids}}(\text{g})$$

The specimens were then tested by using a loading system manufactured by Geocomp at a constant shear rate of 1 mm/min in accordance with the ASTM D 2166 test method (ASTM, 2016). The testing was terminated once a 15% displacement was achieved or a peak deviator strength was obtained, whichever occurs first.

Consolidated isotropic undrained test

The application of deep-mixed columns is usually 10–40 m below the ground; therefore, the effect of confining pressure cannot be ignored in this case. Hence, a series of consolidated isotropic undrained (CIU) tests was conducted to investigate further the behaviour of the stabilised specimens under confining pressure. Like the preparation of the UCS specimens, the specimens for CIU tests were prepared in three groups, and each group of specimens was stabilised by a type of binder. These specimens were stabilised by cement only, fly-ash-blended cement and DuraCrete-blended cement, respectively. In the preparation of CIU specimens, for each type of design mix (cement only, fly-ash-blended cement and DuraCrete-blended cement), the mixture content was fixed at 20%. The UCS experimental results proved that for specimens stabilised by fly-ash-blended cement, the highest UCS was achieved when the ratio between fly ash and cement was 1:4. Therefore, a fly ash/cement ratio of 1:4 was adopted in preparing specimens stabilised by fly ash/cement. For the same reason, a DuraCrete/cement ratio of 3:100 (or 3%) was adopted when preparing the specimens stabilised by DuraCrete-blended cement. The confining pressure ranged from 50 to 200 kPa. This pressure range was adopted based on the soft soil profile and properties in PoB, South East Queensland, where the soil samples were collected. Table 3 summarises details such as confining pressure and binder components of each CIU test conducted in this study. The preparation process of specimens in CIU tests followed the same procedures as the preparation of UCS specimens. After reaching a 28-day curing period, the specimens were extruded from the curing moulds and tested in accordance with ASTM D 4767

(ASTM, 2011). A GDS triaxial testing system was used in this study. The specimens were first saturated under a 500 kPa back pressure until a B value of 0.98 was achieved. Filter paper strips were used during testing to accelerate the saturation and consolidation phases. Then, the specimens were consolidated at each targeted confining pressure. The strain rate in the shear phase adopted in this study was 0.005 mm/min, which was calculated based on the consolidated results during the consolidated phase, and this shear rate was also suggested by previous studies for stabilised specimens (Cheng *et al.*, 2018; Head, 1998; Xiao *et al.*, 2017).

Results and analysis

Unconfined compressive strength

Cement-only-stabilised specimens

Figure 1 shows the stress–strain curves of cement-stabilised soil specimens at different cement contents. The results of each specimen are also summarised in Table 4. Based on the observations, it can be concluded that the increase in strength and stiffness is obvious. Specimens with cement contents of 10 and 15% show an obvious ductile behaviour, with the post-peak stress decreasing gradually with the increase in strain. Specimens with cement contents ranging from 20 to 30% show a brittle behaviour, in which the stress decreased rapidly with the increase in strain after reaching the peak stress. In general, this trend is consistent with the previous studies in terms of soft marine clay (Chew *et al.*, 2004).

To evaluate further the strength development of the tested specimens, the water/cement ratio of each specimen was calculated and is summarised in Table 4. The water/cement ratio has been proven to be a reliable parameter in indicating the strength of stabilised soils (Horpibulsuk *et al.*, 2005, 2011). It is defined as the ratio between the total water content (W) and cement-only content (c). W is the total water content in the

soil/cement mixture or soil/cement blend mixture, which equals the NMC of soil plus the added water in the cement-only and cement blend slurry, as shown in the following equations:

$$\text{3a. } \frac{\text{total water content, } W (\%)}{\text{NMC } (\%) + \text{added water } (\%)}$$

$$\text{3b. } \text{added water } (\%) = M_{\text{added water}}(\text{g})/M_{\text{soil solids}}(\text{g})$$

The strength of specimens at each water/cement ratio (W/c) for each group of specimens is plotted in Figure 2. It can be concluded from

Figure 1. Stress–strain curves of cement-only-stabilised specimens with an NMC of 130%

Table 3. Summary of CIU tests performed

Set 1: cement-only-stabilised specimens			
Test	Confining pressure: kPa	OPC only: %	
1	50	20	
2	100	20	
3	200	20	
Set 2: fly ash/cement-stabilised specimens (at optimum ratio of 1:4)			
Test	Confining pressure: kPa	OPC: %	Fly ash: %
4	50	16	4
5	100	16	4
6	200	16	4
Set 3: DuraCrete/cement-stabilised specimens (at optimum ratio of 3:100)			
Test	Confining pressure: kPa	OPC: %	DuraCrete: %
7	50	19.4	0.6
8	100	19.4	0.6
9	200	19.4	0.6

Table 4. Measured UCS results of cement-only-stabilised specimens

OPC: %	Total <i>W</i> (added water + NMC): %	<i>W/c</i>	UCS: kPa
10	135.0	13.5	64.6
15	137.5	9.2	140.9
20	140.0	7.0	291.0
25	142.5	5.7	499.4
30	145.0	4.8	887.4

c, cement content; *W*, total water content

Figure 2 that the strength of the specimens decreased with the increase in water/cement ratio. The relationship between the strength and water/cement ratio can be expressed by the following equation:

$$4. \quad UCS = \frac{A}{[(Wc)/c]^B}$$

where UCS is the unconfined compressive strength of the stabilised specimens after reaching the targeted curing period and *W* and *c* are the total water content and cement content, respectively. *A* and *B* are empirical constants. A similar tendency between strength and water/cement ratio was also observed in previous studies in terms of soft soil stabilisation (Horpibulsuk *et al.*, 2011; Ma *et al.*, 2014). In general, the trend between strength and water/cement ratio observed in Figure 2 is consistent with the experimental results in previous studies of soft soils in Bangkok and Singapore marine clays (Chew *et al.*, 2004; Lee *et al.*, 2005; Ma *et al.*, 2014), indicating that the experimental results obtained in this study are reliable and consistent. Based on the experimental results, the best-fitting trend line is plotted (Figure 2) to estimate the empirical equation, as presented in Equation 5. The detailed results are also summarised in Table 4, for better clarity.

Figure 2. Relationship between UCS and water/cement ratio for cement-only-stabilised specimens

$$5. \quad UCS = \frac{42\,621}{(Wc/c)^{2.531}} \quad \text{with } R^2 = 0.991$$

Stabilised specimens using fly-ash-blended and DuraCrete-blended cement

The results of the specimens stabilised by cement blends (fly-ash-blended cement and DuraCrete-blended cement) are presented and discussed in this section. For the specimens stabilised by cement blends, as the stabilisation agent is a combination of two materials (cement and fly ash or cement and DuraCrete), therefore the parameter water/cement ratio (*W/c*) introduced previously is replaced by the water/cement blend ratio (*W/b*) hereafter. It is defined as the ratio between the total water content (*W*) and cement blend (*b*).

For the specimens stabilised by fly-ash-blended cement, the specimens were stabilised at total mixture contents ranging from 10 to 30%, which is consistent with the cement-only group. As mentioned previously, cement-blended fly ash is prepared by mixing fly ash and cement at four ratios: 1:1, 1:2, 1:3 and 1:4. The experimental results of specimens stabilised by cement-blended fly ash are summarised in Table 5. In particular, the cement content (OPC), fly ash content, total water content (*W*), water/cement blend ratio (*W/b*) and also the average strength of each set of specimens are presented in Table 5.

The UCS of the tested specimens stabilised by fly-ash-blended cement is presented in Figure 3, where empirical equations are derived from the best trend-fitting curves. As shown in Table 5, it can be concluded that cement-only performs better than the cement-fly ash blend at same mix percentage. For a fixed mix percentage, specimens stabilised by cement-only achieved higher strength than the cement-fly ash blend – that is, the former has a higher rate of increase in strength than the latter. With the increase in fly ash/cement ratio, the strength of specimens decreased.

Based on the best-fit trend lines plotted in Figure 3, the following empirical equations for each set of specimens were determined (Equations 6a–6d). Both parameters *A* and *B* decreased with the increase in the fly ash/cement ratio.

For specimens stabilised with a fly ash/cement ratio of 1:4

$$6a. \quad UCS = \frac{20\,802}{[(Wc)/b]^{2.266}} \quad \text{with } R^2 = 0.992$$

For specimens stabilised with a fly ash/cement ratio of 1:3

$$6b. \quad UCS = \frac{19\,315}{[(Wc)/b]^{2.283}} \quad \text{with } R^2 = 0.970$$

Table 5. Measured UCS results of specimens stabilised by fly-ash-blended cement

Row	Cement-only or cement-fly ash blend content: %	OPC: %	Fly ash: %	W: %	W/b	UCS: kPa
A	10	10.0	0	135.0	13.5	64.6
B	15	15.0	0	137.5	9.2	140.9
C	20	20.0	0	140.0	7.0	291.0
D	25	25.0	0	142.5	5.7	499.4
E	30	30.0	0	145.0	4.8	887.4
F	10	8.0	2.0	135.0	13.5	60.4
G	15	12.0	3.0	137.5	9.2	126.7
H	20	16.0	4.0	140.0	7.0	248.6
I	25	20.0	5.0	142.5	5.7	386.7
J	30	24.0	6.0	145.0	4.8	651.0
K	10	7.5	2.5	135.0	13.5	57.6
L	15	11.5	3.5	137.5	9.2	105.9
M	20	15.0	5.0	140.0	7.0	229.4
N	25	18.5	6.5	142.5	5.7	351.0
O	30	22.5	7.5	145.0	4.8	564.1
P	10	6.5	3.5	135.0	13.5	55.2
Q	15	10.0	5.0	137.5	9.2	92.4
R	20	13.5	6.5	140.0	7.0	195.5
S	25	16.5	8.5	142.5	5.7	330.5
T	30	20.0	10.0	145.0	4.8	452.5
U	10	5.0	5.0	135.0	13.5	34.6
V	15	7.5	7.5	137.5	9.2	75.7
W	20	10.0	10.0	140.0	7.0	105.7
X	25	12.5	12.5	142.5	5.7	204.8
Y	30	15.0	15.0	145.0	4.8	257.7

Figure 3. Relationship between UCS and water/binder ratio for fly-ash-blended cement-stabilised specimens

For specimens stabilised with a fly ash/cement ratio of 1:2

$$6c. \quad UCS = \frac{12\,311}{[(Wc)/b]^{2.113}} \quad \text{with } R^2 = 0.988$$

For specimens stabilised with a fly ash/cement ratio of 1:1:

$$6c. \quad UCS = \frac{5672}{[(Wc)/b]^{1.975}} \quad \text{with } R^2 = 0.989$$

Table 6 summarises the results of specimens stabilised by DuraCrete-blended cement with DuraCrete/cement ratios of 3:100 (or 3%), 5:100 (or 5%), 7:100 (7%) and 9:100 (9%), respectively. The total mixture contents (cement + DuraCrete) range from 10 to 30%, which is consistent with the specimens stabilised by cement only or fly-ash-blended cement. The relationship between compressive strength and total mixture content for each set of specimens is plotted in Figure 4. From Table 6 and Figure 4 it can be observed that the addition of DuraCrete is very effective in improving the strength of stabilised specimens. In the addition of DuraCrete, a small quantity can bring a rapid increase in terms of strength. For clarity, Figure 4 presents the relationship between the strength and DuraCrete/cement ratio at each total mixture content. Therefore, it can be concluded that for a fixed total mixture content, specimens stabilised by DuraCrete-blended cement achieved higher strength compared with specimens stabilised by cement only. Moreover, at a fixed total mixture content, the strength of specimens increased with the increase in DuraCrete/cement ratio at first. After it had reached a 'saturation point', the further increase in DuraCrete content resulted in a decrease in the strength.

In particular, when the total mixture content was 10 and 15%, maximum strength was achieved for specimens stabilised by DuraCrete-blended cement at a DuraCrete/cement ratio of 5:100 (or 5%). When the cement blend content was 20, 25 and 30%, the specimens stabilised by DuraCrete-blended cement at a DuraCrete/cement ratio of 3:100 (or 3%) achieved the highest strength. To understand better the strength development of specimens stabilised

Table 6. Measured UCS for specimens stabilised by DuraCrete-blended cement

Cement or cement blend content: %	OPC: %	DuraCrete: %	W: %	W/b	UCS: kPa
10	10.0	0	135.0	13.5	64.6
15	15.0	0	137.5	9.2	140.9
20	20.0	0	140.0	7.0	291.0
25	25.0	0	142.5	5.7	499.4
30	30.0	0	145.0	4.8	887.4
10	9.7	0.3	135.0	13.5	81.2
15	14.6	0.5	137.5	9.2	160.7
20	19.4	0.6	140.0	7.0	349.7
25	24.3	0.8	142.5	5.7	712.6
30	29.1	0.9	145.0	4.8	960.7
10	9.5	0.5	135.0	13.5	94.6
15	14.3	0.8	137.5	9.2	173.3
20	19.0	1.0	140.0	7.0	312.7
25	23.8	1.3	142.5	5.7	587.4
30	28.5	1.5	145.0	4.8	800.6
10	9.3	0.7	135.0	13.5	64.5
15	14.0	1.1	137.5	9.2	169.0
20	18.6	1.4	140.0	7.0	241.5
25	23.3	1.8	142.5	5.7	386.3
30	27.9	2.1	145.0	4.8	758.9
10	9.1	0.9	135.0	13.5	72.3
15	13.7	1.4	137.5	9.2	123.1
20	18.2	1.8	140.0	7.0	240.0
25	22.8	2.3	142.5	5.7	368.1
30	27.3	2.7	145.0	4.8	701.8

Figure 4. Measured UCS strength of specimens stabilised by DuraCrete-blended cement

Figure 5. Relationship between UCS and water/cement blend ratio for DuraCrete-blended cement-stabilised specimens

by DuraCrete-blended cement, the relationship between the strength of specimens at each DuraCrete/cement ratio and water/cement blend ratio (W/b) are plotted in Figure 4 and relative empirical equations are proposed for each set of specimens. The fitted curve based on the experimental results of the specimens is plotted in Figure 5. The empirical equations derived from those best-fitting curves are the following.

For specimens stabilised by DuraCrete-blended cement with a DuraCrete/cement ratio of 3%

$$7. \quad UCS = \frac{49\,665}{[(Wc)/b]^{2.509}} \quad \text{with } R^2 = 0.985$$

For specimens stabilised by DuraCrete-blended cement with a DuraCrete/cement ratio of 5%

$$8. \quad UCS = \frac{22\,193}{[(Wc)/b]^{2.136}} \quad \text{with } R^2 = 0.985$$

For specimens stabilised by DuraCrete-blended cement with a DuraCrete/cement ratio of 7%:

$$9. \quad UCS = \frac{22\,042}{[(W_c)/b]^{2.245}} \quad \text{with } R^2 = 0.977$$

For specimens stabilised by DuraCrete-blended cement with a DuraCrete/cement ratio of 9%:

$$10. \quad UCS = \frac{17\,556}{[(W_c)/b]^{2.166}} \quad \text{with } R^2 = 0.969$$

CIU triaxial compression behaviour

Three sets of specimens were tested under CIU conditions to determine the behaviour of stabilised specimens. These three sets of specimens were stabilised by cement only, fly-ash-blended cement and DuraCrete-blended cement, respectively. The confining pressure ranged from 50 to 200 kPa. The cement content for the cement-only group was fixed at 20%. Meanwhile, the total mixture content for the cement blend group (fly-ash-blended cement or DuraCrete-blended cement) was also fixed at 20%. For specimens stabilised by cement blends, the ratios between fly ash or DuraCrete and cement were fixed at the optimum mixing ratio, which is 1:4 for fly-ash-blended cement and 3:100 for DuraCrete-blended cement. Figures 6(a) and 6(b)

Figure 6. (a) Excess pore pressure–axial strain and (b) deviator stress–axial strain relationships for fly-ash-blended cement and DuraCrete-blended cement

present the excess pore pressure–axial strain and stress–strain behaviour under different confining pressures during CIU tests. Figure 7 summarises the testing conditions, binder contents and peak deviator stress of each specimen.

The peak deviator stress (q_{peak}) of specimens stabilised by each group of binder increased with increasing confining pressure. Figure 6(b) shows that most stress–strain curves have an apparent peak point. The stress decreases swiftly after this point, indicating that most specimens developed a strain-softening response. Meanwhile, specimens stabilised by fly-ash-blended cement at confining pressures of 50 and 100 kPa show a strain-hardening response, as indicated in Figure 6(b). Besides, the results also show that specimens at low confined pressures developed more strain before reaching the peak stress than those under high confining pressures.

Figure 7 summarises the tested specimens and peak strength of each specimen derived from the experimental results. As shown in Figure 7, the peak deviator stress of specimens stabilised by each type of mix design increases nearly linearly with confining pressure; this relationship can be described by the following equations:

For specimens stabilised by cement

$$11. \quad q_{\text{peak}} = 0.62\sigma_3 + 223 \text{ kPa}$$

For specimens stabilised by fly ash/cement

$$12. \quad q_{\text{peak}} = 0.62\sigma_3 + 167 \text{ kPa}$$

Figure 7. Peak deviator stress as a function of confining pressure and binder type

For specimens stabilised by DuraCrete/cement

$$13. \quad q_{\text{peak}} = 0.90\sigma_3 + 200.4 \text{ kPa}$$

where q_{peak} is the peak deviator stress (in kPa) and σ_3 is the confining pressure.

By comparing Figures 6(a) and 6(b), it was found that the change in the trend of pore pressure was similar to that of deviator stress. The deviator stress and the pore water pressure almost reached their peak values at the same strain level, which can be identified in Figures 6(a) and 6(b). For the specimens stabilised by cement, the pore water pressure becomes negative when the axial strain exceeds 9% under a confining pressure of 50 kPa, suggesting a high dilation potential. In general, all the specimens show a dilative behaviour as shown in the excess pore pressure–strain curves. Both the stress–strain and excess pore pressure–strain behaviours are in complete agreement with the results of a previous study in terms of soft soil stabilised by cement or fly ash (Uddin *et al.*, 1997; Xiao *et al.*, 2017). For specimens stabilised by fly-ash-blended cement and DuraCrete-blended cement, the excess pore pressure increased with the increase in axial displacement at first and then decreased after reaching the failure point. However, no negative values in excess pore pressure were observed for specimens stabilised by these two types of binders. In general, the behaviour of all three groups of stabilised specimens is like that of heavily overconsolidated clays based on the excess pore pressure–strain relationship. It needs to be pointed out that the specimens stabilised by cement only show the most obvious dilative behaviour. For example, the specimen with cement at 50 kPa confining pressure shows negative excess pore pressure after 9% in axial displacement. Meanwhile, the reduction in excess pore pressure for specimens stabilised by cement is also higher than that of specimens stabilised by fly-ash-blended cement and DuraCrete-blended cement, indicating that specimens stabilised by cement show a very typical behaviour of stiff clay compared with specimens stabilised by other two groups of binders. As shown in Figure 8, the average failure angle is about 61° based on the tested specimens.

In particular, the average failure angle for each group of specimens is 59° for specimens with fly-ash-blended cement, 61° for specimens with cement only and 63° for specimens with DuraCrete-blended cement. Figure 8 also shows the typical failure modes of specimens. All specimens developed an inclined shear failure plane. In addition to shear plane, a few specimens exhibited deformation around the failure surface, which can be attributed to crushing or bulging deformation of the specimen. DuraCrete-blended cement-stabilised specimens generally exhibited greater peak strength than cement-only and fly-ash-blended cement-stabilised specimens at the same confining pressure, implying that specimens stabilised by cement only had a softer initial response than those stabilised by DuraCrete-blended cement.

Figure 8. Failure angles as observed from UCS tests for (a) fly ash/cement – 50; (b) fly ash/cement – 100; (c) fly ash/cement – 200; (d) cement – 50; (e) cement – 100; (f) cement – 200; (g) DuraCrete/cement – 50; (h) DuraCrete/cement – 100; and (i) DuraCrete/cement – 200

Microstructure of stabilised soils

Figures 9(a)–9(f) show the microstructures of soft estuarine soils stabilised with (a) cement only, (b) fly-ash-blended cement and (c) DuraCrete-blended cement. A total of six specimens were selected to analyse the microstructure of the specimens. These specimens are (a) specimen stabilised by cement only with a cement content of 10% (Figure 9(a)), (b) specimen stabilised by cement only with a cement content of 25% (Figure 9(b)), (c) specimen stabilised by fly-ash-blended cement with a total mixture content of 25% at a fly/cement mixing ratio of 1:1 (Figure 9(c)), (d) specimen stabilised by fly-ash-blended cement with a total mixture content of 25% at a fly/cement mixing ratio of 1:4 (Figure 9(d)), (e) specimen stabilised by DuraCrete-blended cement with a total mixture content of 25% at a DuraCrete/cement ratio of 3:100 and (f) specimen stabilised by DuraCrete-blended cement with a total mixture content of 25% at a DuraCrete/cement ratio of 9:100. A magnification of $\times 5000$ was selected to study the development of micropores in different stabilised soils.

To comprehend the microstructural development with varying cement content or total mixture content and its correlation with strength improvement, SEM images with $\times 5000$ magnification were analysed. It is obvious in these images, in which cementitious products are observed owing to the occurrence of a pozzolanic reaction (e.g. CSH, calcium aluminate hydrates, calcium aluminium silicate hydrates and ettringite) that the microstructure spaces have been enhanced because

the large pores have been filled and the bonding of the soil particles has improved—hence the observation of strength improvement in the stabilised specimens.

From Figures 9(a) and 9(b), with the increase in cement content, the number of large pores decreases while the number of smaller pores increases. This is because the hydration products have bound the soil particles together, creating a denser structure. This is consistent with the UCS strength development observed.

Figures 9(c) and 9(d) show the microstructure of samples stabilised with 25% fly-ash-blended cement at two fly ash/cement mixing ratios (1:1 and 1:4, respectively). A distinct reduction in the numbers of large pores and an increment in small pores can be observed in samples with a lower fly ash/cement mixing ratio. The increase in fly ash/cement mixing ratio is due to the less amount of cement in the fly ash/cement mixture, thus hindering the degree of cement hydration and resulting in a strength reduction.

By comparing Figures 9(b), 9(e) and 9(f), it is evident that the addition of DuraCrete produces a large amount of needle-shaped bonds that bond soil particles together and form a denser structure, which indicates that DuraCrete can promote the formation of cementation bonding and result in strength development. However, an excessive amount of DuraCrete can impede the generation of hydration products that counteract the

Figure 9. SEM images of stabilised samples with (a) 10% cement only, (b) 25% cement only, (c) 25% fly-ash-blended cement at a fly ash/cement ratio of 1:1, (d) 25% fly-ash-blended cement at a fly ash/cement ratio of 1:4, (e) 25% DuraCrete-blended cement at a DuraCrete/cement ratio of 3:100 and (f) 25% DuraCrete-blended cement at a DuraCrete/cement ratio of 9:100

development of pores. This phenomenon is accordant with UCS results in which 3:100 (or 3%) is the optimum DuraCrete/cement mixing ratio. Therefore, the observations from the SEM images are consistent with the observations from the UCS results.

Reduction in cement and carbon dioxide footprint

In this section, the reduction in the use of cement by adopting fly ash or DuraCrete as partial replacement of cement is calculated and presented. In the previous sections, the strength of the PoB soft soil specimens stabilised by (a) cement only, (b) fly-ash-blended cement and (c) DuraCrete-blended cement, at cement contents or total mixture contents of 10, 15, 20, 25 and 30%, was determined. The empirical equations for describing the correlations between the strength and soil specimen stabilised by fly-ash-blended cement and DuraCrete-blended cement were also derived, based on the experimental results. By using these empirical equations, the total mixture content (cement + fly ash or cement + DuraCrete) required to achieve the same performance at each cement content, such as 10, 15, 20, 25 or 30%, can be calculated, as shown in Tables 7 and 8.

For example, when the cement content was 10%, the strength of the improved soils after 28-day curing was calculated. If it is desired that fly-ash-blended cement was to replace cement-only and also obtain the strength as the specimens stabilised by 10% cement, then the following four alternative plans can be proposed:

(a) 8.47% cement + 2.12% fly ash, (b) 8.38% cement + 2.79% fly ash, (c) 7.54% cement + 3.77% fly ash and (d) 7.11% cement + 7.11% fly ash, as shown in Table 7. The percentage of the reduction in cement for each corresponding design mix was also calculated and is indicated in Table 7. It is defined as the ratio between the amount of cement that can be reduced (e.g. 10–8.47, 10–8.38, 10–7.54 and 10–7.11%) and the original amount of cement (e.g. 10%). The last column in Table 7 shows the percentage of cement (or the reduction in cement in percentage) that can be reduced after partially replacing cement with fly ash, at each fly ash replacement ratio.

When 25% cement-only content is adopted in the mix design, the UCS strength of the stabilised specimen is estimated to be about 500 kPa, based on the experimental results. The same strength can also be obtained by adopting four alternative plans by using fly-ash-blended cement at different fly ash replacement ratios. These alternative mix designs using fly-ash-blended cement are (a) 22.20% cement and 5.55% fly ash, (b) 21.87% cement and 7.29% fly ash, (c) 21.36% cement and 10.68% fly ash and (d) 22.24% cement and 22.24% fly ash. By adopting any of the mix designs mentioned previously, the UCS of the soil specimen after the stabilisation is estimated to be 500 kPa as well. The percentage of the reduction in cement in this case is the ratio between the cement additive content that can be reduced (e.g. 25–22.20% in plan (a)) and the original

Table 7. Reduction in cement percentage by using fly ash to replace cement partially

Cement-only design benchmark		Alternative fly-ash-blended cement design		Reduction in cement: %
Cement-only content: %		Total mixture content: %	Cement: % Fly ash: %	
10 (UCS = 64.6 kPa)		10.59	8.47	15.33
		11.17	8.38	16.25
		11.31	7.54	24.59
		14.23	7.11	28.86
15 (UCS = 140.9 kPa)		15.18	12.15	19.03
		15.99	11.99	20.06
		16.68	11.12	25.87
		21.69	10.84	27.72
20 (UCS = 291.0 kPa)		21.38	17.1	14.48
		22.49	16.87	15.67
		24.15	16.1	19.52
		32.51	16.26	18.72
25 (UCS = 499.4 kPa)		27.75	22.2	11.21
		29.16	21.87	12.53
		32.04	21.36	14.56
		44.48	22.24	11.03
30 (UCS = 887.4 kPa)		36.9	29.52	1.61
		38.75	29.07	3.12
		43.75	29.16	2.79
		63.17	31.58	-5.28

Table 8. Reduction in cement percentage by using DuraCrete to replace cement partially

Cement-only design benchmark		Alternative DuraCrete-blended cement design		Reduction in cement: %
Cement-only content: %		Total mixture content: %	Cement: % DuraCrete: %	
10 (UCS = 64.6 kPa)		9.54	9.26	7.39
		8.73	8.32	16.8
		10.05	9.39	6.1
		10.16	9.32	6.8
15 (UCS = 140.9 kPa)		13.19	12.81	14.63
		12.77	12.16	18.95
		14.45	13.51	9.94
		14.81	13.59	9.42
20 (UCS = 291.0 kPa)		17.92	17.39	13.03
		18.29	17.42	12.89
		20.4	19.07	4.67
		21.18	19.43	2.84
25 (UCS = 499.4 kPa)		22.59	21.93	12.27
		24.04	22.89	2.11
		26.51	24.78	0.22
		27.82	25.52	-0.52
30 (UCS = 887.4 kPa)		29.06	28.21	5.96
		32.39	30.85	-2.82
		35.3	32.99	-9.97
		37.49	34.4	-14.66

cement content (25%), which is 11.21%. Therefore, based on the same approach, the percentage of reduction in the use of cement at other fly ash replacement ratios can also be calculated. In particular,

if the other three fly ash/cement ratios, in plans (b), (c) and (d), are adopted, the reduction in the use of cement is 12.53, 14.56 and 11.03%, respectively.

The reductions in cement for other cement content ratios, such as 15, 20 and 30%, are also calculated and summarised in Table 7. It can be concluded that (a) fly ash is effective in replacing cement to reduce the amount of cement in soil stabilisation. However, (b) the replacement of cement with fly ash will also result in the increase in total mixture content (cement + fly ash). For example, the cement content is only 25% (25% cement only) to achieve 500 kPa in UCS. However, to achieve the same UCS by using fly-ash-blended cement, the total mixture content (fly ash% + cement %) would increase to 27.75% (22.20% cement + 5.55% fly ash), 29.16% (21.87% cement + 7.29% fly ash), 32.04% (21.36% cement + 10.68% fly ash) and 44.48% (22.24% cement + 22.24% fly ash). It can be seen that with an increasing fly ash replacement ratio, more cement can be replaced by fly ash, and the use of cement is reduced. However, to achieve the target UCS strength (500 kPa in this example), the total mixture content (cement% + fly ash%) also needs to increase. By knowing this important outcome, engineers can optimise their soil stabilisation design, which can minimise the negative impact to the environment by reducing the use of cement.

The same calculations are also conducted for DuraCrete-blended cement-stabilised specimens. The results are summarised in Table 8. From the results in Table 8, it can be concluded that DuraCrete is more effective than fly ash as partial replacement of cement to increase strength. In the previous example, the addition of cement only at a cement content of 25% can achieve 500 kPa UCS in the stabilised specimens. To achieve the same target strength by using DuraCrete-blended cement, the alternative mix designs are (a) 21.93% cement + 0.66% DuraCrete, (b) 22.89% cement + 1.14% DuraCrete, (c) 24.78% cement + 1.73% DuraCrete and (d) 25.52% cement + 2.30% DuraCrete.

It can be concluded that by using DuraCrete-blended cement as the replacement of cement only, the target UCS (500 kPa) can be achieved with a lower total mixture content. As a result, the cement content adopted to stabilise the soil is reduced and, simultaneously, the total mixture content is also reduced. To achieve UCS strength of 500 kPa, the required cement content is 25% when the cement-only mix is adopted as the binder. When the cement/DuraCrete blend is adopted and to achieve the UCS (500 kPa), the total mixture content (cement% + DuraCrete%) would be 22.59% (21.93% cement + 0.66% DuraCrete), 24.04% (22.89% + 1.14%), 26.51% (24.78% + 1.73%) or 27.82% (25.52% + 2.30% DuraCrete). This is an important advantage by using DuraCrete compared with using fly ash. Comparing the proportional quantities of fly ash and DuraCrete required, the quantity of fly ash required is between 6.1 times and 9.7 times the proportional quantity of DuraCrete required. As mentioned previously, the use of fly ash can reduce the amount of cement but increase the total mixture content (fly ash% + cement%) to achieve the target UCS. However, it must be mentioned that the cement/DuraCrete blend cannot provide as much reduction in cement as the cement/fly ash blend. Compared with the cement-only mix design, alternative designs using DuraCrete-blended cement can reduce the use of cement by 12.27, 2.11 and 0.22%, respectively. The maximum reduction in cement under this circumstance is

12.27%, lower than the reduction in cement required for fly-ash-blended cement (14.56% under the same circumstances). This is to say that, even though the use of DuraCrete can reduce the amount of cement used and can also reduce the total mixture content, it cannot provide as much reduction in cement as fly ash does.

Take another example: when the cement content is 15%, the estimated UCS is 141 kPa. To achieve the UCS by using DuraCrete-blended cement, the maximum reduction in the use of cement is 18.95% (see Table 8). If fly-ash-blended cement is adopted, to achieve the same UCS, the maximum reduction in cement is 27.72% (see Table 7). Therefore, both materials (fly ash and DuraCrete) have good potential as replacements of cement. Nonetheless, the choice of which additive is more suitable as replacement of cement depends on the circumstances (e.g. NMC, target UCS, and budget). For instance, when the maximum reduction in cement is the only factor under consideration, then fly ash is more suitable than DuraCrete, as it facilitates a greater reduction in cement. However, if both reduction in cement and the total mixture content are considered, DuraCrete might be more appropriate, as it not only reduces the use of cement but also reduces the total mixture content required.

It should also be mentioned that there is a saturation point with the DuraCrete replacement ratio. It can be observed from the experimental results that the saturation point of DuraCrete replacement ratio is between 5 and 7% (see Figure 5). Above the saturation point, further increases in the DuraCrete replacement ratios will not increase the strength. This is consistent with the explanation in the literature review (Latifi *et al.*, 2015), as DuraCrete is, in part, a magnesium-based additive. As discussed previously, when magnesium oxide is used as the cement modifier, there is always a saturation point. Before reaching the saturation point, the addition of magnesium oxide is very effective in activating the cement reaction. However, after the saturation point, further addition in magnesium oxide will not be as effective.

By knowing these important outcomes, engineers have more design options from which to meet their strength requirements while having the opportunity to reduce the use of cement. They can also optimise their designs, to achieve a balance between the reduction in cement and the budget, hence the contribution of this study.

As discussed earlier, the soil specimens stabilised by cement only achieved higher strength than those stabilised by fly-ash-blended cement at the same total mixture content. This means that if fly-ash-blended cement is adopted, the percentage of total mixture content (fly ash% + cement%) would be higher than the cement-only content, as shown in Table 7. The carbon dioxide footprint can still be reduced because the carbon emission rate of fly ash is much less than that of pure cement. Fly ash has an emission rate of 0.027 kg/t, while the carbon emission rate of cement is 0.82 kg/t. Based on the emission rates, the reduction in carbon emission after partially replacing cement with fly ash or DuraCrete can be calculated as shown in Figure 10. It can be concluded that fly ash can give a greater reduction in terms of

carbon emissions. Meanwhile, DuraCrete is also very effective in replacing cement, as a very small portion of DuraCrete can replace a significant portion of cement while attaining the same strength outcomes. This cost advantage will be discussed later.

Advantages for soil stabilisation at land reclamation sites

The data outlined earlier provide a comparative analysis of the portions and quantities of fly ash + cement and DuraCrete + cement to achieve results comparable with the outcomes produced with cement only. These results then enable calculation related to carbon emissions from the production of fly ash and cement. Unlike cement and fly ash, the production of DuraCrete is not carbon dioxide intensive. The production of DuraCrete does not

produce carbon emissions, as it does not require a furnace, nor is it a by-product of a carbon-emitting process.

In addition to these considerations, there are opportunities in terms of savings in construction time to completion, labour and machinery requirements and design capabilities, as a result of differences that the three stabilisation options produced.

As regards construction time, conventional solar drying and natural consolidation process from surcharging of PoB reclamation paddocks is a time-intensive process requiring a few years. Utilising cement blends such as fly ash and DuraCrete with cement will easily improve the bearing capacity of the dredged mud comparatively quickly, thus enabling earlier access to the project site for more productive purposes.

Figure 10. Reduction in carbon dioxide (CO₂) emissions for different cement blend ratios: (a) fly-ash-blended cement; (b) DuraCrete-blended cement

With regard to economics, the anticipated large reduction in machinery use time (e.g. hydraulic sand filling process) is another advantage of using cement blend mix design as a viable soil stabilisation method. This is so because the cement blend mix design is an in situ mixing process utilising the dredged mud in a single application process with multiple passes. After allowing a minimum of 7 days for initial curing, a much stronger and more stable construction platform for machinery access can thus be successfully formed.

Conclusions

This study investigated the mechanical, physical and microstructural properties of PoB soft soils that are stabilised by three different cement-based binders: cement, fly-ash-blended cement and DuraCrete-blended cement.

Firstly, a series of experiments was conducted on the soft soils treated by cement only, to establish reliable empirical equations for estimating the UCS of the stabilised specimens at each water/cement ratio. Then, a further series of tests was conducted to investigate the use of fly ash and DuraCrete as partial replacement of cement. Based on the experimental results, the UCS values of the soil specimens stabilised by fly-ash-blended cement and DuraCrete-blended cement were investigated and analysed. To evaluate further the effectiveness of fly-ash-blended cement and DuraCrete-blended cement, SEM tests and CIU triaxial compression tests were then conducted on specimens stabilised by each cement-based binder.

The UCS results show that both fly ash and DuraCrete are very effective as partial replacements of cement to reduce the cement content and carbon emission. Fly ash can provide the highest reduction in cement replacement content, and it can provide the highest reduction in carbon emission. However, at the same mixture content (e.g. 25%), the UCS of the specimens stabilised by fly-ash-blended cement is lower than that of the specimens stabilised by cement only. That is to say, more material is needed when using fly ash as the partial replacement of cement to maintain the same UCS, although the carbon dioxide footprint can still be reduced because the carbon emission rate of fly ash is much lower than that of pure cement, as discussed in this paper. Therefore, fly ash is effective as partial replacement of cement to reduce the use of cement and also carbon emission.

Compared with fly ash, DuraCrete is more effective as a partial replacement of cement, in some circumstances. For example, to achieve a target strength of 500 kPa, the total mixture content is reduced. This is an important advantage when using DuraCrete compared with using fly ash. Comparing the proportional quantities of fly ash and DuraCrete required, the quantity of fly ash required is between 6.1 times and 9.7 times the proportional quantity of DuraCrete required. Even though the use of DuraCrete can reduce the amount of cement used and can also reduce the total mixture content, it cannot provide as much reduction in cement as fly ash does. This is because there is a saturation point with the DuraCrete replacement ratio. If this saturation point is exceeded, DuraCrete will not be as effective anymore, being mainly a magnesium-based additive.

Therefore, when the maximum reduction in cement is the only factor under consideration, then fly ash is more suitable than DuraCrete, as it facilitates a greater reduction in cement. However, if both reduction in cement and the total mixture content are considered, DuraCrete might be more appropriate, as it not only reduces the use of cement but also reduces the total mixture content required. Most importantly, unlike cement and fly ash, the production of DuraCrete is not carbon dioxide intensive. The production of DuraCrete does not produce carbon emissions, as it does not require a furnace, nor is it a by-product of a carbon-emitting process.

From the SEM images, it can be observed that the addition of DuraCrete produces a large amount of needle-shaped (ettringite) bonds, which bind the soil particles and form a denser structure, thus promoting the formation of cementation bonds that eventually result in strength increment. However, an excessive amount of DuraCrete can impede the generation of hydration, thus providing evidence of the existence of a saturation point for the DuraCrete replacement ratio. The observations from the SEM images are consistent with the observations made from the UCS results.

These important outcomes can help engineers reliably customise the soil stabilisation design to achieve optimal strength, environmental friendliness and cost saving. As such, engineers can have more design options to meet the strength requirement while having the opportunity to minimise the negative impact to the environment by reducing the use of cement. They can also achieve a balance between the reduction in cement and the budget, hence the important contribution of this study.

It must be mentioned that all the experimental tests in this study were conducted in a geotechnical laboratory. It is acknowledged that there is a limitation on laboratory tests in simulating the in situ (or field) conditions. For example, soil specimens prepared in the laboratory are cured without the presence of confining pressures. However, in reality, the in situ mixed soil–cement columns are cured under a certain confining pressure, as these specimens are buried underground. Hence, it is recommended that relevant field tests be conducted in the future to investigate further the mechanical or microstructural properties of in situ mixed soil–cement or soil–cement blend columns.

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