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REUSE OF WASTE MATERIALS FOR CIVIL ENGINEERING PURPOSES

[1] Dr. Siau Chen Chian Darren
Department of Civil and Environmental Engineering, National University of Singapore, Singapore

Abstract- In view of land scarcity arising from the demand for more land for urban development and waste disposal, the reuse of waste materials such as soft clayey soils from dredged and excavated materials as construction material can potentially offer a sustainable built environment. Extensive suite of laboratory testing was carried out to ascertain the feasibility of these soft soils for land reclamation and cement substitute. Results showed that despite the initial poor shear strength and high compressibility, these unwanted materials are able to be adopted for land reclamation as fill material with reduced impact to the coastal environment. Substitution of environmentally deleterious cement with calcined clays have also shown to be able to provide better performance cement mortar as compared to conventional cement.

Keywords: Soft clay, land reclamation, cement substitute, environmental impact

I. Introduction

In view of the increasing urbanization globally, coastal cities are facing pressures to address land and infrastructure needs to keep up with growing population. In order to support continual societal and economic growth, land has to be created. Land reclamation is conventionally carried out with sand as the fill material. Sand is often preferred since long term settlement is minimal. However, obtaining sand from beaches elsewhere means coastal environment will be affected and hence undesirable. In addition to the need for more land space, building infrastructure has to be constructed to accommodate housing, work and recreational facilities. Reinforced concrete is a strong and economical building material which makes it one of the most common building type in many cities. Unfortunately the production of cement clinker generates huge amount of carbon dioxide. Limestones and other ingredients are heated to 1450°C and is the third largest source of greenhouse gas pollution. Making one ton of cement results in the emission of about one ton of carbon dioxide.

In order to address the challenges of land space and environmentally-friendly building material shortages, two initiatives were proposed at the National University of Singapore. Rather than disposing the annual 20 million tons of waste generated from sea dredging and excavated materials into landfills and offshore containment sites, land has been reclaimed with these materials recently. These materials, which are predominantly soft marine clay, can also be converted into calcined clay as a substitution to cement in construction materials.

In this paper, results on the use of these technologies would be discussed. The outcome would be a more sustainable solution in maximizing local resources and useable land space for more value-added purposes.

II. Creation of Space with Land Reclamation

A. Land Reclamation in Singapore

Being a geographically small island, Singapore faces the shortage of land for urban growth. The traditional approach of land reclamation using sand deposits was commonly used since the 1960s for a variety of purposes such as housing, industrial and infrastructure. Up to date, Singapore has claimed nearly 20% of the original land area, and the percentage is expected to increase as more reclamation projects are needed in order to cope the rising population and growth of the city as shown in Fig. 1.

Fig. 1: Land reclamation in Singapore (light red refers to land that has been reclaimed, dark red refers to future reclamation sites)

However, due to sand shortage, there is a need to look into alternative fill material to be used for land reclamation in order to reduce our dependency on imported sand. In recent years, increasing attention has been placed on the improvement of dredged and excavated materials. The stabilised dredged fill technology is a viable solution for Singapore given the abundance of these

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[1] **Corresponding Author**

waste materials, accompanied with the lack of disposal grounds.

However, the excavated materials are often highly compressible and low in shear strength, which are both undesirable qualities. Therefore, the excavated material properties need to be improved. This can be easily achieved by improving the soils with a binding additive. In view of the millions of cubic metres of fill material needed in land reclamation, the cost of improving these materials is highly sensitive. Therefore, cementitious binder was chosen. Portland Blast Furnace Cement, a type of more environmentally friendly cement, is attempted for this purpose. There are however challenges for such adoption in land reclamation.

Although cement stabilisation has been a well-established technique, it is presently used in conventional onshore soil improvement works, where large quantity of cement exceeding 25% of the mass of dry soil is added to increase the soil's shear strength. In contrast, the application to land reclamation requires only a low cement dosage of less than 15% of the dry soil mass and at much higher water content far exceeding the liquid limit of the soil as compared to conventional onshore soil improvement purposes. The required 91-day unconfined compressive strength requirement for the land reclamation perimeter bund at Pulau Tekong in Singapore was 280kPa [1]. In contrast, the 28-day strength requirement for onshore deep mixing column is much higher at typically 1 MPa and above [2]. Literature on cement-stabilised clay with low cement content is limited which hampers direct application of knowledge from conventional high cement dosage to the performance of low cement-stabilised clay.

B. Calcined Clay as Cement Substitute

An alternative solution to convert these unwanted clayey materials into usable resource is to heat them at temperature of about 900 degrees Celsius to undergo calcination. The motivation is the lower environmental impact as compared to conventional cement. The process of producing cement is energy intensive and highly carbon emissive.

Overall, the production of cement and concrete is estimated to account for around 5-8% of man-made CO_2 emissions [3]. As the world's growing population and need for habitation drives concrete demand, carbon emissions are consequently set to rise. The diversion of attention to calcined clay can potentially reduce the carbon emissions per tonne of concrete produced, therefore offering a significant contribution to controlling global carbon emission.

The high carbon emissions of cement production arise primarily from burning coal to generate the heat required and from the chemical process of limestone decarbonation. On average 0.8-0.9 tonne of CO_2 is emitted in the production of 1 tonne of ordinary cement concrete. 40-50% of the CO_2 emissions, originate from the heating of the kiln for cement production up to around 1450°C and from grinding and transportation to a lesser extent. Remaining 50-60% of the total amount of CO_2 comes from the decarbonation of calcium carbonate decomposing to calcium oxide, thereby liberating CO_2.

In order to reduce carbon emissions, alternative fuel technologies and energy efficiency have been studied in great detail and may be reaching a plateau of optimization due to technological constraints [4]. An alternate solution which has yet to be fully maximized would be to make use of supplementary cementitious materials (SCMs). SCMs are environmentally friendly partial replacements of cement, reducing the amount of cement used in producing concrete. Apart from the negative environmental impacts, the availability and affordability of cement in developing countries, where there is high demand for such basic building materials, is an issue. Thus, the subject area of interest is in finding a more environmentally friendly, sustainable and accessible SCM substitute for cement.

Some of the more widely used SCM include fly ash and blast furnace slags. However, existing reserves and forecast production of these industrial by-products will not meet the projected demand for cement [5]. Reserves of natural pozzolans such as volcanic ashes are conditioned by local geology and its availability is restricted to only certain geographical locations [6]. A promising SCM substitute discussed in this paper is calcined clay. This is given the wide availability of clay that can match projected concrete demand in long term. Compared to cement, energy savings and reduction in CO_2 emissions occur due to calcination temperatures being lower than those used for the clinkering process and no CO_2 emissions associated with the decarbonation of the raw materials. Calcined clay can be produced using existing equipment in a cement plant and does not require any major changes in concrete technology. This gives calcine clay a huge potential for rapid uptake of the technology with significant potential for carbon emission reduction and efficient use of resources.

II. Experimental Setup and Procedure

A. Low Cement-Stabilised Clay

The soil used in this study is Singapore Upper Marine Clay. It was dredged near Pulau Tekong, an offshore island northeast of Singapore. Impurities such as stones and shells were removed by sieving with sieve size opening of 2 mm. Results from classification tests as shown in Table 1 indicate that the soil was a high plasticity clay (CH) according to the Unified Soil Classification System (USCS).

Portland Blast Furnace Cement (PBFC) with 65% slag content was used as the stabilizing material in this study.

The reason for using PBFC is due to its more eco-friendly composition. In addition, it hardens and gain strength more gradually as compared to Ordinary Portland Cement (OPC). This implies that the PBFC is more suitable for quality control as it allows defective mixes to be identified while the cement is still weak. Higher rate of strength gain in the later stage of hydration for PBFC mix is also beneficial in land reclamation works, which is the focus of this study. However, it should be noted that lower strength gain would also make it more difficult to detect variations in strength. A minimum of 3-days for strength test is therefore suggested in this study. The basic physical properties and chemical compositions of PBFC are provided in Table 2.

TABLE I. Properties of Singapore Upper Marine Clay

Properties	**Values**
Liquid Limit (%)	70 – 90
Plastic Limit (%)	36 – 56
Specific Gravity	2.62-2.69
Clay Fraction (%)	>50
Sand Fraction (%)	<5

TABLE II. Physical properties and chemical compositions of Portland Blast Furnace Cement (PBFC)

Physical Properties	Value
Density	3000 kg/m^3
Fineness	404 m^2/kg
Initial Setting Time	~189 mins
Final Setting Time	~225 mins
Soundness	< 1 mm
Consistency	30%
Chemical Composition	% m/m
Silica, SiO_2	39.41
Aluminia, Al_2O_3	11.63
Ferric Oxide, Fe_2O_3	3.35
Calcium Oxide, CaO	36.35
Magnesium Oxide, MgO	5.52
Sodium Oxide, Na_2O	0.32
Potassium Oxide, K_2O	1.21
Sulfate, SO_3	1.84
Chloride, Cl^-	< 0.02

A suite of experimental testing was conducted to study the effects of mixing ratio and curing time on strength development of cement stabilized clay. Given the limited literature on low cement dosage (i.e. less than 15% of mass of dry soil) in clays, the focus of this study was on Singapore marine clay with low cement content so as to relate to applications in land reclamation. A wide range of water/cement *w/c*, soil/cement *s/c* and *curing time t* were studied while maintaining sufficiently high water content similar to conditions in land reclamation at sea, as shown in Table 3. Samples were prepared for testing at 3, 5, 7, 28 and 91 days of curing. In order to make comparison with high cement dosage, mix batches at low *w/c* (≤ 6.8) and *s/c* (≤ 4.0) values were prepared and tested at 7 and 28 days of curing.

Soil samples were first mixed using the Hobart mixer to ensure the homogeneity of the soil batch. A small amount of water was added to the sample to facilitate mixing. Thereafter, small amount of samples were taken to determine the initial water content a day before mixing with PBFC. After determining the water content, more water was added and mixed with the soil sample to achieve the desired final water content prior to adding PBFC. The amount of PBFC was computed based on the target cement content by weight of the dry mass of clay. The mixing process with PBFC was maintained at 10 minutes in total, of which 1 minute was allowed for manual mixing to scrap the materials attached to the sidewall and bottom of the mixing bowl of the mixing apparatus. The mixing duration was according to the Japanese standard JGS 0821 [7].

After 10 minutes of mixing was completed, the sample was placed into disposable plastic molds of 50 mm in diameter and 100 mm in height, followed by compaction using manual tamping in order to minimize entrapped air within the specimen. The specimens were then fully immersed in water for curing under a controlled laboratory temperature of 23 ± 2^{O}C. Unconfined compression tests (UCT) were conducted to determine the unconfined compressive strength q_u of the cement-stabilised clay in this study.

TABLE III. Mix design and experimental programme of low cement-stabilised clay

Mix	**Water/ Cement w/c**	**Soil/ Cement s/c**	**Water Content (%) w/s**
13-7.5	13	7.5	170
12-7.5	12	7.5	160
11-7.5	11	7.5	150
10-7.5	10	7.5	130
9.5-7.5	9.5	7.5	130
8.5-7.5	8.5	7.5	110
13-7	13	7	190
12-7	12	7	170
11-7	11	7	160
10-7	10	7	140
9.5-7	9.5	7	140
8.5-7	8.5	7	120
13-6.5	13	6.5	200
12-6.5	12	6.5	180
11-6.5	11	6.5	170
10-6.5	10	6.5	150
9.5-6.5	9.5	6.5	150
8.5-6.5	8.5	6.5	130
6.8-4	6.80	4.00	170
4.25-2.5	4.25	2.50	170
3-1.76	3.00	1.76	170
2.43-1.43	2.43	1.43	170

B. Calcined Clay

The same sieved kaolinite rich Singapore marine clay was used for the calcined clay. Thin layer of approximately 2mm of the marine clay was applied onto crucibles and left in a furnace at 900°C for an hour. A visible change in colour from greenish grey to whitish red was observed, indicating the undergoing process of calcination. The calcinated clay was thereafter grinded to powder with a common household blender.

Using the same Hobart mixer as the stabilized clay cement, the grinded calcined clay and cement with water was mixed for the same 10 minutes before transferring to the disposable plastic molds and immersed in a water bath till the desired curing period before testing. Table 4 shows the range of tests with different mix ratios and percentage substitution of cement.

TABLE IV. Mix design of calcined-cement mortar

Mix	Cement (by part)	Cement (by part)	Cement (by part)
1-0-0.5	1	0	0.5
0.9-0.1-0.5	0.9	0.1	0.5
0.8-0.2-0.5	0.8	0.2	0.5
0.7-0.3-0.5	0.7	0.3	0.5

III. Results and Discussion

A. Low Cement-Stabilised Clay

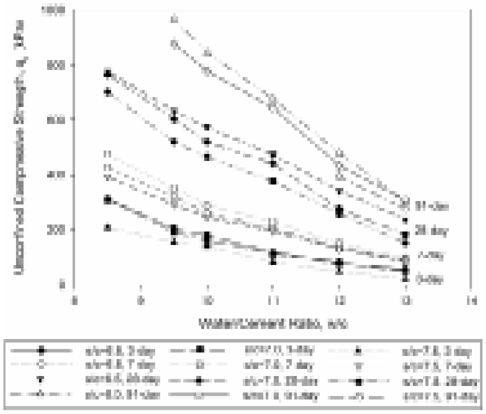

Fig. 2: Effect of water/cement ratio and soil/cement ratio on unconfined compressive strength at different curing time

A wide variations to the amount of water, cement and soil by mass were introduced to examine the effect of water/cement ratio *w/c* and soil/cement ratio *s/c* on the strength development of cement-stabilised clay over time. This is represented in Fig. 2. As shown in the figure, the unconfined compressive strength q_u increases with decreasing *w/c*. This is in agreement with previous findings [8, 9], which highlighted that the *w/c* is the governing factor affecting the strength of cement stabilized soil. The *s/c* also contributes to the strength development; however the effect is not as significant as compared to the *w/c*. Fig. 2 also shows uniform strength development trends over the range of curing time, suggesting the prospect of predicting later-stage (28-day) strength with the early stage (3-day) results. This is confirmed with Fig. 3 which shows strong linearity in relationships between 3, 7, 28 and 91-day strengths.

Apart from the mix ratio effect, the strength development of cement-stabilised clay with time was also investigated and found to follow either logarithmic or hyperbolic trend, where the strength gained is rapid in the beginning followed by a decreasing rate at later curing age, similar to cementitious materials.

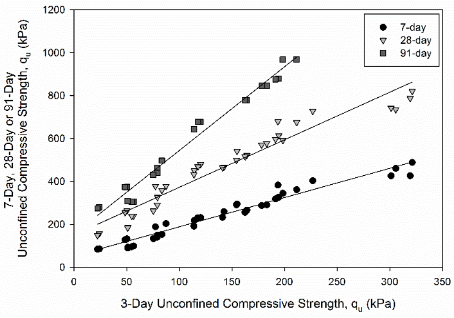

Fig. 3: Correlation between early-age (3-day) and later-age (7-day, 28-day and 91-day) unconfined compressive strength

In order to observe the gain in strength of cement-stabilised clay with respect to the final strength at 91-days, the normalized strength versus curing time is plotted in Fig. 4. In the figure, the points fall within a narrow bound delineated by a near linear relationship in the semi-log scale. This finding is in line with the suggestion of normalisation with a reference mix to give a logarithmic relationship with curing time for cementitious alike materials [10]. In addition, similar normalized strength versus curing time pattern is obtained over a range of *w/c* and *s/c*, implying that the development characteristics are comparable.

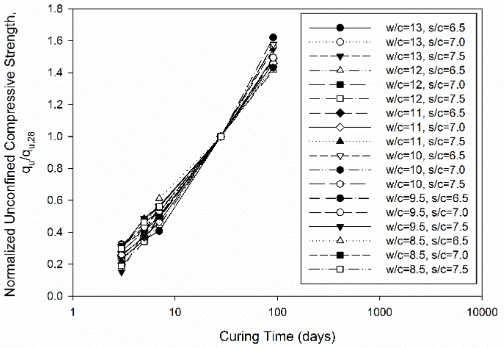

Fig. 4: Effect of curing time and water/cement ratio on normalised unconfined compressive strength

Having identified that *w/c* is the major factor affecting the unconfined compressive strength of cement-stabilised soil, the Abrams' law, a common cementitious strength model was used to depict the influence of mix proportions on the strength development of cement-stabilised clay. For the effect of curing time *t*, it was demonstrated earlier in Fig. 4 that the effect can be illustrated with a semi-log relationship with time. The Abrams' equation is therefore modified with the addition of a natural logarithmic term:

$$q_u = \frac{X}{Y^{w/c}} \ln(t) \qquad (1)$$

Where X and Y are fitting constants. This is a simplified version of the extended predictive strength model [11]. It should be noted that based on Fig. 4, the effect of curing time should comprise of a constant (i.e. the y-intercept) in the logarithmic form. However, the objective of this paper is to produce a simplified model with minimal fitting parameters, while accepting some slight inaccuracies. Since the y-intercept is likely to be of a small value, the term is neglected.

In the case of soil/cement ratio *s/c*, it is observed that the difference in the ratio appears to shift the curve vertically as shown in Fig. 2. A lower *s/c* produces a higher strength across the range of *w/c*, and vice versa. It is therefore postulated that the effect of *s/c* can be considered directly as a multiple variable in the numerator term of Eq. (1). Fig. 5 shows the goodness of fit between predicted and measured unconfined compressive strength for the full range of tests in this study using X and Y values of 3500 and 1.35 respectively. This justifies the robustness of the equation in estimating the strength development of cement-stabilised clays.

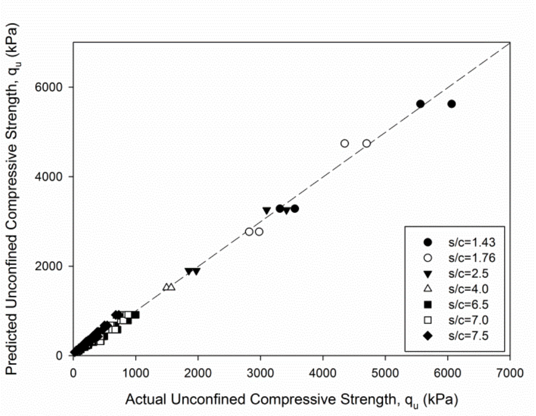

Fig. 5: Predicted versus actual unconfined compressive strength

B. Calcined Clay

Fig. 6 shows the compressive strengths of the range of mixes studied in this paper. It can be observed that despite the introduction of non-binding calcined clay in the mix, the compressive strength remained comparable with conventional pure cement mortar. This is because following the hydration of cement, calcium hydroxide was produced as a by-product which reacted with calcined clay to form more strength enhancing calcium silicate hydrate. This secondary strength gaining with reduced porosity process is known as pozzolanic reaction. Therefore, the overall strength development is expected to maintain as observed in the above figure. The calcined clay substitution mixes tend to produce a higher early age strength between 1 to 7 days of curing. At 28 days, the strength of the mixes converges with the mix with 20% calcined clay faring more alike to the conventional cement mortar mix. Such use of native marine clay has not been studied as building material thus far, hence there is little references available locally for comparison of performance. Nevertheless, literature on pure kaolinite clay [4,12] do show similar equivalent or increased strength benefits as reported in this paper.

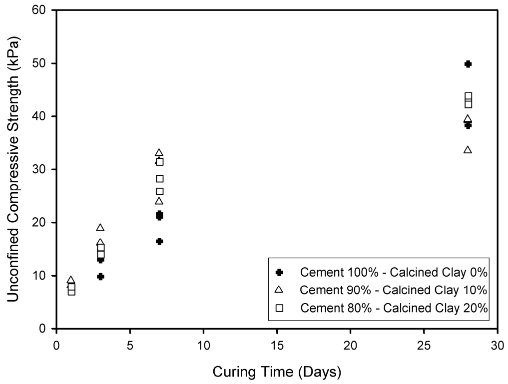

Fig. 6: Unconfined compressive strength and cement percentage substitution

IV. Conclusion

Attempts had been made to reuse unwanted dredged and excavated clayey materials as land reclamation fill or cement substitution. A comprehensive suite of experiments were conducted to assess the unconfined compressive strength of low dosage cement specimens which has not been well reported in literature at present. A simplified strength predictive model is proposed which show good agreement with the actual strength development. The ratio of later to early age strength has also been found to be linearly correlated which offers the opportunity to be adopted as an early quality control when adopted as a land reclamation fill.

The unwanted clayey material was also calcined and used to substitute a small percentage of cement to ascertain its potential to be used as part of a cementitious building material. Results show that the strength are similar to conventional cement mortar mix, thereby opening up opportunities to be widely used to reduce excessive demand in cement and correspondingly minimise impact to the environment,

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