SOLIDIFICATION OF DREDGED MARINE CLAY WITH STEEL SLAG: REUSABLE GEOMATERIALS FOR THE CONSTRUCTION INDUSTRY

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ABSTRACT

Construction of marine structures as well as maintenance of shipping channels produce large amount of dredged materials. The dredged soils, generally categorized as marine clays, consist of clay minerals, sand, pebbles and fragments of shells. As it is considered unfeasible from an environmental point of view to discard the material in open sea, the dredged soils need to be disposed off in man-made facilities, like bulkheads and landfill. Various efforts were directed at reusing the material by pre-treatment with chemicals or proprietary substances. While these endeavors have shown successes, the high incurred costs and potentially hazardous modification of the dredged soils to surrounding environment have prevented wider applications. This paper describes an exploratory study to solidify dredged marine clays with steel slag, a waste product of the steel manufacturing process. Cementing properties of the slag enabled the clay structure to be strengthened for possible reuse or stabilized containment. The study showed that while the steel slag can effectively solidify dredged materials, several key factors which affect the strength enhancement must be taken into account. These include slag dosage, changes in water content and initial condition of the slag.

Keywords: dredged marine clay, steel slag, solidification

1 INTRODUCTION

Annually, the maintenance of water channel and marine construction resulted in 10-15 millions m^3 of dredged soils for disposal (Japan Port and Airport Association, 1999). Reports from over a decade ago showed that dredged soils for port and harbour construction constituted almost 50 % of the total wastes stored in specially built bulkheads. It was also recorded that an average of tens of billions of Japanese Yen was allocated for the construction of these bulkheads. Due to the nature of the dredged soils, which are typically low in shear strength and high in compressibility, their reutilization as a geomaterial is only possible with certain pre-treatment. An effective solution is induced solidification, which is the extension of an inland ground improvement technique adapted for transforming the dredged materials to usable forms.

Numerous studies have been carried out over the years on developing the induced solidification method for dredged soils, with successful implementations reported from time to time. As demonstrated by Sun et al. (2010), the Nagoya Port dredged soils mixed with cement and gypsum neutral stabilizer produced an improved material with a slow rate of structure decay and loss of over-consolidation, both indicators of enhanced stiffness. Okumura et al. (2000) pioneered the Super Geo Material (SGM), a lightweight treated soil formed by infusing the waste soils with air bubbles or expanded polystyrene beads. Tang et al. (2000) reported the use of custom-made ships equipped with a proprietary cement treatment system for simultaneous dredging and treatment of the dredged materials.

In short, the past decade has witnessed much advancement in the handling of these natural geo-wastes from the sea. The stabilizing agents used are primarily manufactured for the specific purpose, sourced from chemical compounds with potentially harmful effects, or incur additional costs for their production. Besides, recycling of the dredged soils have inadvertently met with certain resistance due to the higher costs involved. However, the reuse of these wastes can be more popularized if the stabilizing agents are retrieved from an identified source of waste too, hence reducing the costs and enhancing the sustainable ‘green’ appeal.

One of such materials is the by-product from steel processing, i.e. steel slag, which are often used as a substitute of aggregates in road construction due to their durability (Thomas, 2000). The free lime content in steel slag gives it the cementation effect similar to that of cement, though weaker due to other factors like the chemical composition, mineral phase and alkalinity (Altun and Yilmaz, 2002). Reports on quarter-century old test roads built with steel slag (in bound and unbound conditions) in Germany showed enhanced bearing capacity and resistance to surface wear (Motz and Geiseler, 2001), evidence of the durable solidification effects of steel slag when admixed with soils or other road building materials.

This paper describes an exploratory study conducted to examine the possibility of solidifying dredged Osaka clay with a locally sourced steel slag. The slag was used in several different forms to examine the effect on solidification of the dredged clay. The slag-clay specimens were then monitored and analyzed to better understand the resulting chemical interaction and induced solidification mechanism.

2 MATERIALS AND METHODS

2.1 Materials

The clay sample used was dredged from the Osaka Port shipping channel. The properties and particle size distribution curve of the soil can be found in Table 1 and Figure 1 respectively. The steel slag used in the study was supplied by a local steel manufacturer, and contained less than 7 % water in its as received state. The material's particle size distribution and chemical compositions are given in Figure 1 and Table 2 respectively. It was either ground (< 75 μm), sieved pass the 2 mm sieve and used as received, unless otherwise specified to suit the test purpose (Figure 2).

Table 1: Properties of dredged Osaka clay

Natural water content, w_{nat}	124.4 %
Specific gravity, G_s	2.712
Liquid limit, LL	113.5 %
Plastic limit, PL	43.5 %
Plasticity index, PI	70.0 %

Table 2: Primary chemical composition of steel slag

Oxides	Percentage (%)
CaO	55
SiO_2	18
Fe_2O_3	14
Al_2O_3	4
MnO	2
MgO	2
SO_3	2
P_2O_5	2

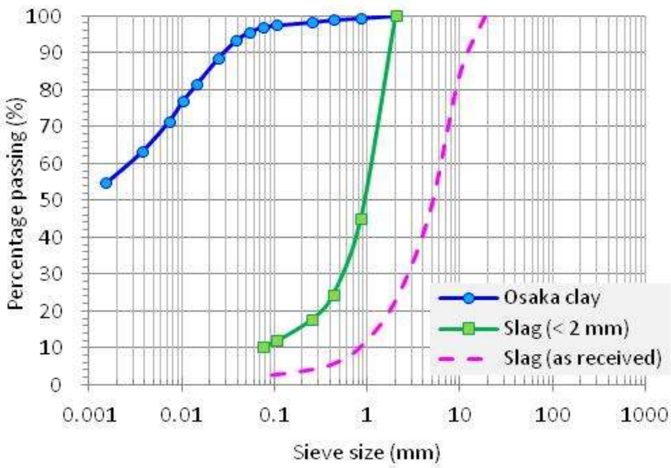


Figure 1. Particle size distribution of clay and slag

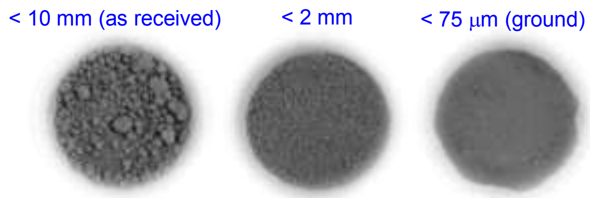
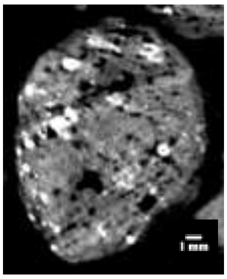
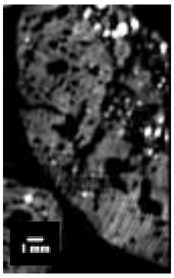


Figure 2. Steel slag- different particle sizes

As the steel slag was a by-product of steel-making, the physical properties are likely to be non-uniform. This is especially so for the larger slag particles. Figure 3 shows the X-ray CT (computer-tomography) images of a couple of typical large slag particle. The different degrees of grey, within the extreme ends of black and white, indicate the density, i.e. density increases with decreased grey level. White spots within the particle represent areas of high density, suggesting hydrated compounds within the particle. The black spots, on the other hand, indicate voids. Overall, the images inform of a material potentially high in porosity (with many voids formed during the cooling process), and also the presence of solidified pockets within the particle, which could result in less solidification potency of the slag when added to the clay. In image (a), the voids were estimated to constitute approximately 7 % of the total 2-dimensional surface area. Scanning and analysis of other particles have shown that the void percentage can reach as high as 17 %, e.g. image (b). These point to a material which is inherently non-uniform in terms of physical properties and chemical reactivity, solidification-wise.



(a)
7 % voids



(b)
17 % voids

Figure 3. CT (computer tomography) images of slag particle

For the test specimens, the clay was mixed with the steel slag at mass ratios of clay/slag (C/S) within the range of 3/7 to 7/3. The mixing water content was based on multiplications of the clay's liquid limit (LL), i.e. 1.5LL, 2.0LL and 3.0 LL. In most cases the slag was used as received, except for several instances where the slag was pre-treated by oven-drying (7D-dried) or soaking (7D-soaked and 14D-soaked) prior to mixing with the clay. To examine the particle size effect of slag addition to the clay, a variation of coarse range particles and ground slag were used in some specimens. In order to simulate various initial conditions of the slag, a number of specimens were prepared with slag devoid of fines, via washing and wet sieving prior to mixing. These could affect the potency of the slag as an effective binder.

2.2 Preparation of specimens

Using the 'wet' method, the test specimens were prepared based on the mixing water content used. Liquid to semi-liquid mixture was first formed in a conventional food mixer with pre-determined quantities of clay, slag and de-ionized water. After 6 minutes of mixing, the uniform mixture was transferred to a cylindrical plastic mould (50 mm diameter, 130 mm height) and tapped to remove any entrapped air. 50 times tapping of the mould ensued the placement of each layer of materials in the mould, and 2 layers were found to be satisfactorily compacted into a homogenized specimen. Capped and carefully taped, the specimen was left to cure at room temperature (average 20°C) for periods up to no more than 3 months. At pre-determined intervals up to at least 28 days, a pair of specimens was extracted from the mould, trimmed to 100 mm height, and subjected to the unconfined compressive strength test. The complete specimen list can be found in Table 3, where the clay:slag ratio were determined by dry weight of the materials.

Table 3: List of specimens

No.	Specimen	Clay	Slag	Mixing water content		Description of slag used
1	A-1.5LL-3/7	3	7	1.5	LL	< 2 mm
2	A-1.5LL-5/5	5	5	1.5	LL	< 2 mm
3	A-1.5LL-7/3	7	3	1.5	LL	< 2 mm
4	A(NoFines)-1.5LL-5/5	5	5	1.5	LL	< 2 mm; washed on sieve 850 mm
5	A(washed)-1.5LL-5/5	5	5	1.5	LL	< 2 mm; washed
6	A(coarse)-1.5LL-5/5	5	5	1.5	LL	coarse slag; > 2 mm, < 4.75 mm
7	A(ground)-1.5LL-5/5	5	5	1.5	LL	ground slag; < 75 µm
8	A-2.0LL-6/4	6	4	2.0	LL	< 2 mm
9	A-2.0LL-7/3	7	3	2.0	LL	< 2 mm
10	A(7D-dried)-2.0LL-7/3	7	3	2.0	LL	< 2 mm; oven-dried for 7 days
11	A(7D-soaked)-2.0LL-7/3	7	3	2.0	LL	< 2 mm; soaked for 7 days
12	A(14D-soaked)-2.0LL-7/3	7	3	2.0	LL	< 2 mm; soaked for 14 days
13	A-3.0LL-5/5	5	5	3.0	LL	< 2 mm
14	A-3.0LL-6/4	6	4	3.0	LL	< 2 mm
15	A-3.0LL-7/3	7	3	3.0	LL	< 2 mm

2.3 Unconfined compressive strength test

The UCS test was conducted according to the procedure prescribed by Japanese standards, JIS A1216-1993 (1993). The test measures compressive strength under conditions of no confinement to the specimen. The loading rate was 1 % per minute, where the load-displacement data was automatically logged for subsequent analysis and processing. Analysis and discussion of the results are focused on the unconfined compressive strength (q_u) derived from the UCS tests.

3 RESULTS; ANALYSIS AND DISCUSSION

3.1 Slag dosage effect

Figure 4 shows the strength gain of the Osaka clay, 1.5LL and added with different amounts of steel slag, tested at various age (D) up to at least 56 days. At the mix ratio of C/S = 5/5, ground slag, slag washed of fines and slag washed over sieve 850 μm were used to prepare specimens C/S=5/5 (ground), C/S=5/5 (washed) C/S=5/5 (NoFines) respectively (see Table 3). Higher slag portions induced more significant strength gain in the stabilized material, but it can be observed that slag addition up to 60 % or C/S=7/3 resulted in negligible strength improvement. This suggests a threshold slag dosage for any meaningful solidification to take place. Also, specimens with more slag addition (C/S=5/5) but devoid of fines, i.e. C/S=5/5 (washed) and C/S=5/5 (NoFines) demonstrated similar strength range as the C/S=7/3 specimen, indicative of the significant influence of fines content in the slag used for effective solidification to take place.

Referring to the same figure, when the slag portion was increased to C/S=5/5 and 3/7, equivalent to 100 % and 140 % slag additions respectively, the unconfined compressive strength (q_u) showed remarkable departure from the low strength range of 50 kPa and below. Corresponding to the 40 % increase in slag portion between C/S=3/7 – C/S=5/5 and C/S=5/5 – C/S=7/3, q_u at 28 days was measured to be 3.5 and 6.2 times that with the lowest slag portion. The strength gain rate was also significantly more pronounced with increased slag portions, from the relatively flat trend line for specimens C/S=7/3 to 7.89 q_u/days and 4.35 q_u/days for specimens C/S=3/7 and C/S=5/5 respectively.

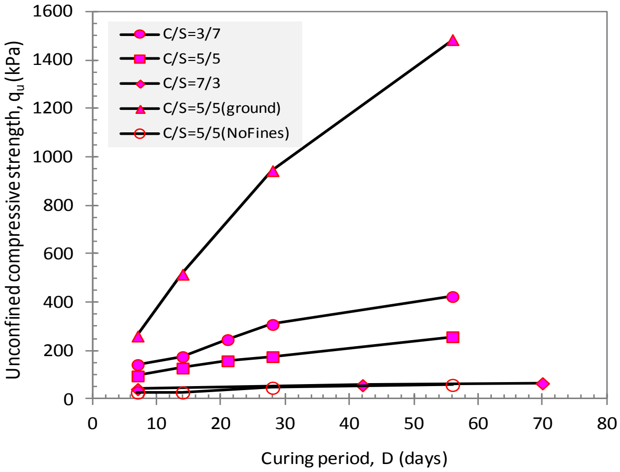


Figure 4. q_u – curing period plot for specimens with 1.5LL mixing water content

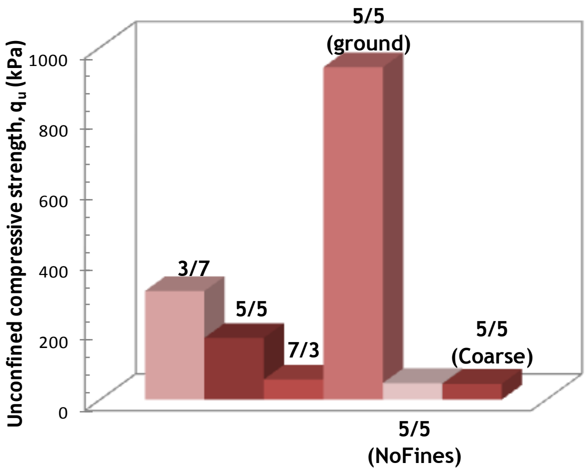


Figure 5. 28-day strength of specimens with 1.5LL and various C/S ratios

The strength gain rate for specimens with ground slag stands out in Figure 4, as being markedly above all other trend lines, even in comparison with specimens with high slag dosage, like C/S = 3/7, When ground to finer particles, the increased surface area of the slag apparently enhanced the chemical reaction within the specimen for solidification. In Figure 5, q_u of the 1.5LL specimens at 28 days are presented in a bar chart. The effect of fines in effective solidification cannot be more obvious, where presence of fines in the slag could more than compensate for lower dosages added to the clay. This corresponds with reports by Chi (2002), who examined the cementitious characteristics of several steel slags and concluded that the fineness of slag has a significant effect on the strength regardless of the mineral composition.

Definitions for controlled low-strength material by the American Concrete Society (1994) stipulated that compressive strengths of 0.35-0.70 MPa is sufficient for load-bearing in common applications. From Figures 4 and 5, clearly the target strengths can be achieved by either changing the slag portion or slag particle size. On the other hand, the Ministry of Land, Infrastructure and Transport, Japan (2005) requires a minimum q_u of 200 kPa for the Fourth Type of Construction Geomaterials, which makes steel slag a favourable solidification agent for the reuse of such dredged materials.

3.2 Changes in water content

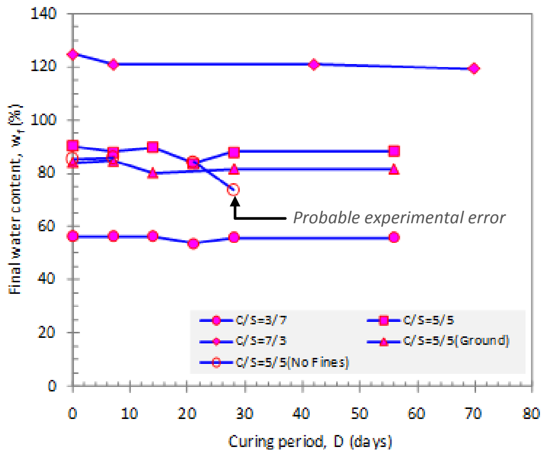


Figure 6. Water content change with time (1.5LL specimens)

Taking into account the relatively slow strength development of slag-soil mixtures (Poh et al., 2006), long term chemical reactions of the slag-clay mixture requires an adequately moist environment. As such, one would have thought that the pattern of water content change would reflect that of the strength gain as seen in Figure 4. However the initial and final water content did not demonstrate dramatic variations, if any at all. In addition, it was noted that at C/S=5/5, regardless of the slag particle size, the specimens exhibited very similar water consumption pattern (Figure 6). This is suggestive of a stabilizing agent which reacting water content is determined by its dosage than its particle size content. This unique characteristic could be used for quick estimation of the amount of water required for initial mixing.

3.3 Initial condition of slag effect

Figure 7 illustrates the effect of pre-treating the slag (<2 mm) prior to mixing with the clay. All the specimens were prepared at 2.0LL and C/S=7/3. The strength of specimens added with soaked slag, irrespective of whether the slag has been soaked for 1 or 2 weeks (i.e. 7D-soaked and 14D-soaked), constantly lay below that of the Normal specimens, where the slag were used as received. Although the difference is arguably small, the strength gain rate of the specimens with soaked slag obviously decreased after approximately 14 days. The soaked slag was originally intended to be an indicator of diminished potency of the slag as a solidifying agent due to exposure to damp environment, such as in an open storage. However the plots clearly show that the slag, when received, were already at their lowest potency, considering the very small difference between the Normal and soaked strength data. The results of Li et al. (2010) on slag-clay mixtures also displayed signs of limited strength gain in the solidification process due to long term outdoor exposure of the slag, where much of the material's cementitious potency diminished in reaction with moisture.

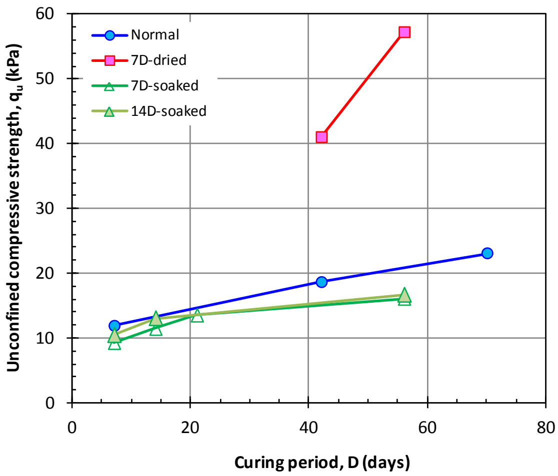


Figure 7. Effect of initial condition of slag on q_u

The 7D-dried specimen trend line lies way above the rest in the same figure, pointing towards the possibility of water filling up the voids within the slag itself, consequently drying up the specimen in the process. Water content measurements indicated that the change in initial and average final water contents of the Normal and 7D-dried specimens were 15 and 30 % respectively. The double amount of moisture loss in the specimens with dried slag addition implied as much. Besides, drying in the oven at 105°C was not thought to have altered the properties of the slag as temperatures exceeding 1000°C is required to effect such transformations, as in the slag production.

4 CONCLUSION

- While higher slag portion added to the dredged clay induces greater strength improvement, the fines portion of slag used was found to have considerable influence on the solidification effect. This is mainly attributed to the larger specific surface of the finer particles compared to the larger ones.
- The solidification effect was accentuated with prolonged curing, and the time effect was more pronounced with higher slag percentage and fines content.
- The final water content was not found to change much despite the slag dosage, suggesting excess water present in the mixture.
- Drying the slag prior to mixing with the clay can induce better strength enhancement, especially if the slag was initially exposed to weathering, as commonly found in the steel-making plants.
- Finally, different clay types react differently with steel slag, which is only to be expected, considering the complex chemical interaction between the slag and clay minerals.

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