Solidification of Dredged Marine Clay for Sustainable Civil Engineering Applications: A Laboratory Study

Chee-Ming Chan¹, Taka-aki Mizutani² and Yoshiaki Kikuchi³

Abstract— Dredging of shipping channels is necessary to maintain the functionality of seaports. It has long been recognized that if disposed offshore, the dredged material poses high risks of contamination and disruption to benthic as well as aquatic organisms. Hence its containment in landfills and bulkheads are commonly practiced. Nonetheless this geo-waste can be effectively reborn as a useful geo-material by pre-treatment of solidification. By adding a binding agent to the clay, the soft material is strengthened and simultaneously contained when properly compacted. The solidified clay can then be applied in various civil engineering works, such as restoration of eroded seafront, construction of retaining structures and road embankments. This paper presents a laboratory study on the solidification of dredged marine clay from Osaka Port, Japan, using an industrial waste, i.e. steel slag. The experimental results demonstrate potential reuse of the otherwise geo-waste for environmental protection and sustainable development, by the enhanced engineering properties through solidification.

Keywords—Dredged clay, reuse, solidification, sustainable.

I. INTRODUCTION

Seaports are vital economic organs of a nation, especially one surrounded by the sea, such as Japan. There is over 1050 ports in Japan, which consisted of designated major ports for active international trade, major and local ports catering for national interest, and refuge ports for sheltering ships during storms [1]. The shipping channels in these ports need to be regularly maintained by dredging for several key reasons, as outlined by the Marine Department of Malaysia [2]:

- High sedimentation rate of the channels.
- Erosion of riverbanks upstream.
- Shallow channels necessitate longer waiting time for high tide to provide adequate navigation depth into the port-revenue loss.
- Safety of the vessels may be compromised due to traffic congestion.

With such high frequency of dredging activities, the large volume of dredged marine clay accumulated is therefore not unexpected.

Kapsimalis et al. [3] warned of the severe degradation of natural coastal or marine ecosystems due to uncontrolled offshore dumping of dredged soil. Such open dumping can also result in exposure to the risk of contamination by critical levels of heavy metals and hydrocarbon [4], where release of the contaminants can cause long term damaging pollution [5].

Aware of the adverse environmental impact from irresponsible disposal of the geo-waste, it is therefore generally contained in specially built bulkheads and landfills, incurring additional costs and land use of limited benefits. Nonetheless the waste material could be effectively reused by introducing certain pre-treatment via the solidification mechanism. The solidification technique is not novel, but widely employed to improve soft, weak soils on land or on reclaimed land, for long term load-bearing purposes. Binders like cement and lime are admixed with the soil to promote chemical hardening of the mixture, transforming the low strength material to one with sufficiently increased strength and stiffness, as required of a usable geo-material. The method is applicable to dredged clay, to produce ‘secondary raw materials’ [6] or ‘manufactured soils’ [7] for reutilization. Also, salvaging the otherwise geo-waste destined for disposal makes the method uniquely sustainable as an engineered solution, as reported by Chan [8] and Lee and Chan [9].

This paper briefly describes the benefits and practical applications of the revived dredged marine clay, and includes the experimental work on solidification of the material using an industrial waste, i.e. steel slag. It is apparent that treatment of the geo-waste with other waste material embodies an eco-friendly and sustainable philosophy to the engineering approach. The results show viable solidification potential, improved engineering properties and practical reuse of the dredged marine clay for sustainable civil engineering applications.

II. BENEFITS AND APPLICATIONS OF TREATED GEO-WASTES

As the treated material is essentially ‘manufactured’, construction period that utilizes it can be controlled and shortened. This is especially useful for staged construction and development projects with a tight schedule. Besides, the target or design strength of the treated material can be pre-
determined and adapted for specific use, avoiding wastage of binders in producing excessively strong geo-material. It renders an otherwise waste material reusable, hence reducing the procurement of new raw materials and setting up of disposal facilities. By containing the dredged soil with the binders, contamination and pollution can be minimized. Economic-wise, this second life given to the dredge clay reintroduces it to profitable yet sustainable life cycle.

As the treated material has enhanced strength and stiffness, it can be used in a variety of civil engineering areas, as any good geo-materials are applied (Fig. 1). Some typical examples are, as backfill materials for quay walls, retaining walls, reclaimed marsh land, road embankments and excavation pits, as those found in mining or quarry sites. In the geo-environmental area, the treated material is expedient to the rehabilitation of tidal floodplains, restoration of eroded shorelines, creation of artificial beach (as a foundation layer), and building of marine farming plots and platforms.

**III. MATERIALS AND METHODOLOGY**

The clay sample used was dredged from the Osaka Port, Japan. Properties and particle size distribution of the soil are given in Table 1 and Fig. 2 respectively. The steel slag (Fig. 3) contained less than 7 % water in its original form. The material’s chemical composition is shown in Fig. 4. The high content of lime (CaO) indicates potential binding capacity, similar to that widely recognized in manufactured cement. The slag, in its received form, contained particles of irregular shapes and different sizes, some as large as 2 cm.

Considering the relative size of the test specimen (50 mm diameter, 100 mm height), and the high natural porosity of the slag, it was first sieved using a 2 mm sieve. Therefore the slag used in the study was mainly < 2 μm and used as received, except for specimens prepared with (1) slag devoid of fines, where wet sieving with a 0.85 mm sieve was carried out; and (2) ground slag of particle size < 75 μm. This enables an examination of the slag particle size effect on solidification.

In preparing the mixture, the clay was mixed with the steel slag at dry mass ratios of clay/slag (C/S) of 3/7, 5/5 and 7/3. The mixing water content was kept constant at 1.5 times the liquid limit (i.e. 113.5 %) of the Osaka clay, hence giving a mixing water content of 170.25 %. The additional water ensured ease and uniformity in the mixing process, resulting in suitable flowability for moulding the specimen afterwards.

The liquid to semi-liquid mixture was first formed in a conventional food mixer with pre-determined quantities of clay, slag and de-ionized water. The uniform mixture was next transferred to a cylindrical plastic mould (50 mm diameter, 130 mm height) and tapped to remove any entrapped air. Capped and carefully sealed, the specimen was left to cure at room temperature (average 20 °C) for periods up to 56 days. At pre-determined intervals, a pair of specimens was extracted from the mould, trimmed to 100 mm height, and subjected to the unconfined compressive strength (UCS) test.

The UCS test was conducted according to the procedure prescribed by the Japanese standards [10]. 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. The basic parameters derived from the test were unconfined compressive strength (q_u), failure strain at peak stress or q_u (ε_f), and the elastic modulus E (Young’s modulus, taken as the slope from the origin to the peak stress of the stress-strain plot).

**TABLE 1**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural water content, w_{nat}</td>
<td>124.4 %</td>
</tr>
<tr>
<td>Specific gravity, G_s</td>
<td>2.712</td>
</tr>
<tr>
<td>Liquid limit, LL</td>
<td>113.5 %</td>
</tr>
<tr>
<td>Plastic limit, PL</td>
<td>43.5 %</td>
</tr>
<tr>
<td>Plasticity index, PI</td>
<td>70.0 %</td>
</tr>
</tbody>
</table>

![Fig. 1. Some applications of the treated geo-waste (dredged clay).](image1)

![Fig. 2. Particle size distribution of the dredged marine clay and steel slag.](image2)
IV. RESULTS ANALYSIS AND DISCUSSIONS

As mentioned earlier on the non-uniform particle size and shape of the steel slag, it is therefore of particular interest to examine if the former has a significant effect on the solidification mechanism. Shown in Fig. 5 are the stress-strain curves derived from the UCS tests for specimens of C/S = 5/5, as received (< 2 mm) and with no fines (< 2 mm, > 0.85 mm). It is immediately apparent that the strength of specimens with slag washed of fines resulted in almost 5 times lower strength improvement, even after a prolonged 56-day curing. Also, the gentler climb of the plots as well as flatter peaks of the ‘no fines’ specimens display characteristics typical of soft, weak soils. The greater gradient of the stress-strain curve indicates larger displacement under loading, while the flatter peak approach points to further deformation, detrimental to the load-bearing performance of a good geo-material. Fig. 6 compiles the peak stress or unconfined compressive strength (q_u) obtained from Fig. 5, and the solidification potential of both slag portions is clearly discernible. In terms of curing period or age of the solidified specimens, the ones added with slag ‘as received’ had an improvement rate of q_u/D = 3.2, while those admixed with slag washed of fines registered a far lower q_u/D = 0.7. This highlights the importance of fines in the slag used, to ensure effective solidifying and strengthening of the dredged clay.

A compilation of the q_u-D plots for all specimens are given in Fig. 7. Comparing the C/S ratios, as expected, higher slag portions induced more significant strength gain in the
stabilized material. Nevertheless it appears that slag addition up to 60 % (i.e. C/S=7/3) resulted in negligible strength enhancement, hinting at the possibility of a threshold slag dosage for effective solidification to take place. Interestingly, the C/S=7/3 specimen fell within the same strength range as those exhibited by the specimens with more slag addition (C/S=5/5) but devoid of fines, i.e. C/S=5/5 (No Fines). This observation could be indicative of the fines content being a more dominant factor than the slag portion in solidification. As finer particles provide a larger specific surface for chemical reaction to take place, it is intuitive that the same slag portion with different fines content would produce varying strength enhancement rate.

When the slag portion was increased to C/S=5/5 and 3/7, equivalent to 100 % and 140 % slag additions respectively, q_u showed remarkable departure from the low strength range of 50 kPa and below (Fig. 7). 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 with time was also significantly more pronounced with increased slag portions, from the relatively flat trend line for specimens C/S=7/3 to 7.9 q_u/days and 4.4 q_u/days for specimens C/S=3/7 and C/S=5/5 respectively.

The trend line for specimens with ground slag stands out in Fig. 7, as being markedly above all other trend lines, even that of specimen C/S=3/7. In pulverized form, the slag apparently has far greater surface area for chemical reaction within the specimen. In addition, it has been reported that fineness of the slag has a significant effect on the strength regardless of the mineral composition [11]. One may be tempted to assume that higher water absorption by the finer slag particles accounted for the effective solidification, but the water content data of the specimens after tests show otherwise (Fig. 12), where there was marginal changes in the water content.

Referring to the definitions for controlled low-strength material by the American Concrete Society [12], compressive strengths of 0.35-0.70 MPa is sufficient for load-bearing in common applications. From Fig. 7, 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 [13] requires a minimum q_u of 200 kPa for the Fourth Type of Construction Geomaterials, which makes steel slag an acceptable low-cost, if not free of charge, solidification agent for the reuse of such dredged materials.

Failure strains (ε_f) of the specimens are plotted against q_u in Fig. 8. It is in agreement with reports of similar work on treated soils, where higher q_u tallies with lower ε_f [14, 15, 16]. This is attributed to the increased rigidity and stiffness of the solidified soil matrix, which were manifested in a brittle failure mode with little deformation before reaching the peak strength. The weaker specimens, on the other hand, underwent greater deformation prior to failure. This is evident in the stress-strain plots, as can be referred to in Fig. 5. Note that the specimens admixed with ‘ground’ slag showed relatively similar ε_f, albeit the wide strength range attained within 56 days. The brittle but stiff nature of the effectively solidified specimens is obvious, though the post-test specimens did reveal a different rupture failure pattern. It was observed that as q_u increased (with longer curing period), the failure plane became less diagonal and more inclined to vertical splitting (see insets in Fig. 8).

![Fig. 7. Unconfined compressive strength (q_u) – curing period (D) relationship of all specimens.](image)

![Fig. 8. Failure strain (ε_f) - unconfined compressive strength (q_u).](image)
line through the data points. This will yield the following equation $E = 151q_u$.

Overall, higher $q_u$ corresponded with higher $E$ values. This is as depicted by the stress-strain plots (e.g. Fig. 5), where specimens more effectively solidified demonstrated a steeper climb to the peak than the poorly solidified ones. Also, the tendency of solidified specimens reaching greater peak strength at lower failure strain ($\varepsilon_f$), as shown in Fig. 8, further supports this observation.

Bulk density ($\rho_b$) of the solidified specimens was proportionate to the amount of slag admixed with the clay (Fig. 10). Increased slag addition caused an increase in $\rho_b$, where 40 % increase in slag dosage resulted in approximately 24 % rise in $\rho_b$. Self-weight of the slag is of concern if the solidified geo-material is to be lain over a relatively soft soil stratum, as the imposed load could lead to excessive overall subsidence of the completed made ground post-construction. Besides, $\rho_b$ was not found to be sensitive to the particle size of the slag used, as shown by the C/S = 5/5 specimens, regardless of whether the slag added was used as received (< 2 mm), deprived of fines or ground. This suggests that inherent voids of the slag particles were not filled up by the clay or finer slag particles during mixing and moulding, and could perhaps be superficially sealed off by the induced cementation of the slag. As such, the risk of high permeability could be reduced, consequently making the slag-solidified clay a suitable capping or backfill geo-material against moisture penetration. This is of importance, for example, in the backfilling of retaining walls, where excessive water infiltration could increase the lateral pressure behind the wall and cause unexpected failures.

Fig. 11 shows the final water content ($w_f$), as taken post UCS tests, plotted against the bulk density ($\rho_b$). $w_f$ is clearly independent of the particle size of the slag added to the clay, as evident in the cluster of data points based on the C/S ratio. Also, higher slag content increased water consumption of the mixture, resulting in lower $w_f$ after curing. Low dosages of slag, e.g. C/S = 7/3, required less water for the chemical reactions, which explains $w_f$ that remained high after 56 days of curing. Besides, it is clear from Fig. 12 that prolonged curing had negligible effect on $w_f$. The plot also validates that slag dosage dominates the water consumption rate of the solidification process, independent of the slag particle size.

Recalling that all specimens were prepared initially at a standardized mixing water content of 1.5LL (i.e. 170.25 %), Fig. 11 indicates that $w_f$ is linearly proportionate to $\rho_b$, which is in turn linearly related to the slag dosage. It can then be calculated that for every 40 % of slag addition to the clay, $\rho_b$ is increased by 1.1 times while $w_f$ is reduced by 1.55 times. Therefore, for every part (by dry weight) of slag added to an equal part of clay, the corresponding water consumption rate is approximately 40 %. This implies the need to have sufficient mixing water content in the clay-slag mixture for optimal chemical reactions, hence solidification, to occur. Of course, this is notwithstanding the other factors governing the resulting improved strength of the solidified material, such as fines content, mixing efficiency and slag dosage itself.
Higher slag portion in the dredged clay induces greater strength improvement.

- Nevertheless the fines portion present in the slag was found to have a significant influence on the solidification effect. This is attributed to the larger specific surface of the finer particles.
- Prolonged curing showed increased solidification, and the time effect was more pronounced with higher slag percentage and fines content.
- Bulk density of the solidified clay was dependent on the slag dosage, primarily due to the self-weight of the slag.
- The water consumption rate, as reflected in the final water content measured, suggests that approximately 40% of mixing water is necessary for every part of dry slag added to the clay (i.e. 1 part dry clay to 1 part dry slag).

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**REFERENCES**


