Characteristics of stiffness and strength mobilization in steel slag-mixed dredged clays from immediately after mixing

Weerakoon Mudiyanelage Nilan Ranjana Weerakoon
Candidate for the Degree of Doctor of Philosophy
Supervisor: Assoc. Prof. Satoshi Nishimura
Division of Field Engineering for Environment

Introduction

For many years, a huge amount of dredged clays have been produced by coastal construction involving navigation channels, port facilities, large vessel seaports, breakwaters, land reclamation and sediment removal from channels. Recently, geotechnical engineering has developed a practice of chemically treating dredged clays to recycle them for construction and solve the lack of dumping capacity. For this reason, many researchers have worked on cement treated soils as a means to improve the dredged clays for construction uses. From their studies, several factors influencing the strength and stiffness mobilization of cement or lime treated soils have been found (Toohey et al., 2013; Xiao et al., 2014). Meanwhile, some researchers have proposed empirical formulae based on various indices to predict the strength of cement-treated soils for long curing time (Kasama et al., 2006; Kang et al., 2014; Sasanian et al., 2014).

Steel slag is retrieved from a source of waste in steel processing plants and the presence of high Ca(OH)₂ indicates a potential hydration capacity similar to that is widely recognized in manufactured cement. Hence dredged clays are sometimes mixed with steel slag to improve their engineering properties and are used for several engineering applications. A few studies have been carried out on this topic to understand the strength mobilization with curing time. The various factors affecting the strength mobilization after 3-day curing time was identified: the slag content and particle size of slag (Sun et al., 2009; Chan et al., 2012; Chan et al., 2014). The potential cementing property of steel slag can be greatly activated by the addition of proper activators. Therefore, steel slag mixed with alkali activators such as NaOH and/or Na₂SiO₃ can exhibit an acceleration of the hydration, with higher strength than those obtained from pure slag (Shi et al., 2004; Poh et al., 2006; Chan et al., 2014). From a viewpoint of chemistry, the formation of Calcium Silicate hydrate (C-S-H), Alumina Ferric Oxide monosulfate (AFm), or Friedel’s salt was considered as causes for strength development by reaction between Ca(OH)₂ in steel slag and silica in dredged clays (Kiso et al., 2008).

Despite these general pieces of knowledge, there is still a lack of a guide to which kind of combination of steel slag and clay leads to greater strength development. Clays with apparently similar properties in terms of gradation and plasticity often indicate significant differences in solidification processes when mixed with the same slag. Different types of dredged clay and steel slag, and their chemical-physical interactions that result in stiffness and strength mobilization need to be comprehensively and systematically studied. In practice, however, precisely predicting the eventual strength of a slag-clay mixture solely based on the constituents’ (i.e. slag and clay) properties will still be difficult, considering the complexity of the involved stabilization processes. The focus, therefore, should also be laid on how any sign of eventual solidification can be detected empirically at early stages of curing. This would facilitate the laboratory mix tests and initial design, by curtailing the standard 28-day curing and instead conducting many shorter-period trials.

Immediately after mixing, the sample still remained very soft. Therefore conventional laboratory tests such as unconfined compression tests and triaxial compression tests could not be carried out for initial curing time because the specimen was not strong enough to stand by itself. But immediately after mixing, the mixture can be poured and cured in the direct shear box. Therefore, direct shear tests were adopted for specimens at a wide range of curing times, from 0.5 hours to 28 days. However, the comparison of strength obtained by using two different tests method such as direct shear test (DST) and unconfined compression test (UCT) was carried out on the specimen cured from 3 days to 28 days. Further study was made on potential factors affecting the stabilization processes, such as the influence of pore water salinity and the grain size and shape. In this study, it is focused on the further investigation of the internal micro-structural characteristics in the steel slag-mixed clay specimen. Therefore image-based analysis of failure patterns was performed aided by X-Ray Computed Tomography (X-Ray CT) tests.

Hardening characteristics in steel slag-mixed dredged clays and non-marine clay

The strength and stiffness mobilization characteristics of four dredged clays from Japan named A, B, C and D, mixed with two steel slags, S1 and S2, were continuously investigated from immediately after mixing to 28 days of curing by using direct shear apparatus and bender elements. In addition to the dredged clays, a non-marine clay, Kasaoka clay (K), was also used to further investigate the strength and stiffness mobilization. The significant differences of the non-biogenic amorphous silica content were also detected in clay A to K. The total amorphous silica
amount was broadly in proportion to biogenic amorphous silica, due to the relatively smaller amount of non-biogenic amorphous silica. Slag S1 contained a notably higher Ca(OH)$_2$ amount than S2, as indicated by the higher spectral peak from X-Ray Diffraction (XRD) test. The slag content is defined as a volume-based ratio, as expressed as; the ratio between the volume of slag content/ total volume of slag and clay-water sample. Three values, 20%, 30% and 40%, for ratio were adopted in this study to understand the influence of different steel slag content on the strength and stiffness of the slag-clay mixture. Unlike in more conventionally adopted unconfined compression testing, these tests could be applied to mixed specimens since initial un-cemented states, and are useful in detecting the transition of the slurry-like states to more solid states.

For all clay mixtures, stiffness and strength mobilization patterns can be clearly categorized into distinct stages according to curing time. The stiffness and strength increase rates in the second, main stage of evolution in the clay-slag mixtures were found to be loosely correlated to the amorphous silica amount. The correlation was also influenced by the Ca(OH)$_2$ amount in slag. The results can be used to screen out clays that are hard to solidify in the medium term, based on quick on-site measurement of amorphous silica amount. For quality control in practice, the strength–stiffness relationship was critically examined as means to assess the strength with non-destructive stiffness probes. In this work, the strength and stiffness correlation of steel slag-mixed dredged clays was examined from early to intermediate curing range, i.e., from 0.5 hours to 28 days. Fig.1 shows the correlation between stiffness ($G$) and strength ($S_u$) derived from the present study. As given in Fig.1, the two separate regressions were applied to dredged clays and all the five clays. The linear relationships between log $G$ and log $S_u$ may be considered.

The two equations are identified with fair regression coefficients for dredged clays and all the five clays respectively. For these relationships, the measured $G$ values range over six orders, from 0.05 MPa to 1060 MPa. Although the two linear relationships are nearly the same, a slight difference may be caused by the 10 times greater stiffness of Kasaoka clay mixture compared to the other mixtures. In this interpretation, there are widely outlying points at medium strength levels for all the clays, because the clear differences were seen between the periods for each strength and stiffness development stage, i.e., strength and stiffness evolution was not completely concurrent. A close observation revealed that representing a wide range of curing time and mixing conditions by a single line, as proposed in existing studies, could be misleading. A new interpretation of the relationship is proposed.

![Fig.1: Correlations between shear modulus ($G$) and shear strength, $S_u$](image1)

By considering the dramatic evolution of the strength and stiffness during curing, an alternative interpretation is proposed, as shown in Fig.1. Four parallel lines are drawn here, each representing (i) the state immediately (30 minutes) after mixing of dredged clays (the lowermost line), (ii) the state immediately after mixing of Kasaoka (non-marine clay) mixtures, (iii) only the third stage of stiffness mobilization in the dredged clays, and (iv) only the third stage of stiffness mobilization in all clays (the uppermost line). Two parallel lines separately for the dredged clays mixtures and the Kasaoka clay mixtures are introduced to the state of immediately after mixing. The reason for these two lines is the stiffness in the Kasaoka clay mixtures at the first stage, more than 10 times greater than those for the dredged clays. Although the two upper lines at the third stage are parallel, the whole correlation is nearly 1.5 times greater than that for the dredged clays only. This discrepancy can be anticipated by the lower strength and high stiffness of 20% and 30% mixtures in Kasaoka clay compared to the other clays.
More specifically, the data points of the $G>5\text{MPa}$ cluster close to the upper line. It follows that, if $G$ is measured in a sampled core or in the field and if it is greater than approximately 5MPa, the strength is better estimated by two upper equations than an overall equation, as it is not biased by the initial ‘no strength development’ stage.

**Further investigation of the factors affecting measured strength and stiffness**

The comparison of strength obtained by using two different test methods, direct shear test (DST) and unconfined compression test (UCT), was carried out on the specimen cured from 3 days to 28 days. For strength, less than 400 kPa, a significant difference of undrained strength obtained by direct shear test (DST) and unconfined compression test (UCT) was identified due to changes in specimens’ anisotropic properties and the difference in the loading rates between the UCT and the DST, and based on $S_u$ definition. Further study was made on potential factors affecting the stabilization processes, such as the influence of water salinity and the grain size and shape.

Although there is no significant influence of pore water salinity on strength, stiffness at initial curing may differ in seawater compared to the distilled water. This difference in initial curing may depend on the different rheological properties of the clay in distilled water and seawater mixtures, and the delaying the arrival time of shear wave under the seawater mixing condition at initial curing. The finer gradation in steel slag, which leads to a larger specific area provides a greater degree of solidification by enhancing the strength and stiffness. Under the same gradation, the strength increase rates induced by S1 and S2 were even more different, suggesting that the original difference between S1 and S2’s gradation is not the cause of the observed difference. There is no significant difference in average circularities between S1 and S2 slags. It implies that the grain shape is not the cause for observed the difference degree of solidification between two slags. Therefore it can be confirmed that the amount of Ca(OH)$_2$ presence in between S1 and S2 is the key factor for explaining different solidification behavior in the two steel slags.

The investigation was conducted on the internal micro-structural characteristics in the steel slag-mixed clay specimen by X-Ray Computed Tomography scanning on the specimen before and during the shear. The visual observation let in identifying the uniform distribution of the specimen. As a quantitative assessment, the adopted mathematical method shows the coincidence of the center of the specimen domain and the center of geometry of the slag grain assembly of each plane. It implies that three sectional views show no bias of grain concentration to a particular edge of the specimen. This understanding further confirmed that the specimen preparation method adopted in this study was effective in allowing no segregation or grain separation in the specimen.

It can be obviously noticed that 1-hour curing specimen, soft specimen underwent ductile behavior. But 14-day cured specimen clearly showed brittle tendency by the formation of clear cracks. Although a similar tendency of shear stress mobilization was observed between two sets of direct shear apparatus, different magnitudes of strength were detected by the two, possibly due to a variety of differences between two direct shear tests, friction and the movement of the top loading platen in the direct shear test of Port and Air Port Research Institute (PARI).

**References**


