# A review of mix design terminologies for cement admixed sandy clay

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## ABSTRACT

In densely populated countries, underground construction and land reclamation could be possible options to solve the demand for land space, thus securing sustainable long-term development of the nation. For example, in Singapore, land reclamation has been widely conducted using excavated materials from underground development. The excavated materials are commonly marine clays that contain sandy soils. To improve the mechanical properties of these soft soils, cement-treated soil stabilization is popularly adopted. In fact, many researchers have investigated the properties of pure cemented clay or pure cemented sand using conventional design parameters such as water content (water/solids) and cement content (cement/dry soil). However, can these terminologies be still used to accurately examine the role of sand in cemented sandy clay mixtures? Through unconfined compression testing, it is herein shown that the use of existing mix design approaches in the literature cannot properly explain the variation of strength with sand content for cemented sandy clay mixtures. A new mix design approach is thus proposed in this study, which ensures that the role of sand in a cemented clay matrix can be quantified.

**Keywords:** cemented sandy clay, land reclamation, unconfined compressive strength, water to cement ratio.

## 1. Introduction

Artificial cementation through deep cement mixing or jet grouting is one of the common methods of chemical soil stabilization. It helps in improving the mechanical properties of soft soil that has low bearing capacity and high compressibility. Extensive studies have been carried out to understand the mechanical properties of such cement mixed soft soils. The cementation process carried out by adding a binding admixture introduces 'structure' in soft soil through hydration. This 'structure' introduced through hydration improves the properties of the soft soil. The degree of improvement for a given soil type primarily depends on cement content, water content and water to cement ratio. The generally accepted definition of cement content is the mass ratio of cement to soil, while water content is defined as mass ratio of water to solids (solids include both soil and cement) (Lee et al., 2005; Tan et al., 1999)

The above-mentioned laboratory-based studies have been conducted on either pure clay or pure sand. However, for the abundant literature available on uncemented mixed soil (binary mixture) studies, it is clear that the behaviour of soil is dependent on the ratio of clay to sand. If cement is added to this binary mixture, the behaviour of the cemented mixed soil would most likely be dominated by the ratio of clay to sand. For the cemented binary mixtures, the interaction between binding agent and other phases are complex. Cement and clay in the cemented binary mixture have affinity towards water, while sand does not have water absorbing properties. Although the conventional definition of water content and cement content is widely accepted for design of cemented clayey soil, it is unclear whether they can still be effectively adopted to examine the role of sand in cemented clay mixtures. Hence, in this paper a review of mix design terminologies adopted for cemented binary mixture is performed, and their suitability is discussed.

### 1.1. Background

The mechanism of cement stabilization using Ordinary Portland Cement (OPC) as a binding agent has been well known. The calcium silicates and calcium aluminates present in OPC react with water to form hydrates of calcium silicates and hydrates of calcium aluminates, which are the cementitious products that conglomerate the clayey particles together. This process of artificial cementation introduces 'structure' to clayey soil (Chew et al., 2006; Coop and Atkinson, 1993; Subramanian et al., 2019) and alters the index properties of clayey soils (Locat et al., 1996; Uddin et al., 1997). Important parameters that affect the properties of cemented clay involve water content, cement content, and water to cement ratio (Lee et al., 2005; Tan et al., 1999). Besides the cement content and water content, there are also some external factors that can affect the repeatability or homogeneity of cement-treated soils such as mixing conditions (Nakamura et al., 1982), curing conditions (e.g., wet or dry curing) (Mishra et al., 2009; Park et al., 2009; Park, 2010; Subramanian et al., 2018), type of water used (Badiozamani et al., 1977), and temperature (Zhang et al., 2014). It was reported that the framework using porosity/cement index proposed by Consoli et al. (2010) and Consoli et al. (2021) is effective in predicting the tensile, compressive strength and the shear modulus of cemented soils.

Although the behaviour of cemented clay has been well documented over the years, the literature available on cemented binary mixture is scarce. Liu and Starcher (2012) conducted a series of unconfined compressive strength tests on cemented kaolin clay mixed with Nevada sand at 1:1 ratio. The liquid limit of the mixture was 31%. Only one mix ratio was investigated in this study. The water content was chosen based on the workability of the mixture by trial and error procedure. They found the unconfined compressive strength increases with increasing curing stress and curing time. Chian et al. (2016) studied the influence of sand impurities on the unconfined compressive strength of cemented clay. The authors proposed the concept of 'free water to cement ratio" [$(w/w_L)/c$], where the water content is normalized with respect to liquid limit of the binary mixture, to account for the effect of cement, sand, and water. Subramanian and Ku (2017) adopted the free water to cement ratio concept to study the effect of sand on the small strain shear modulus of cemented marine clay. The small strain shear modulus was found to increase with sand content. The stiffness of cemented clay with 50% sand content was nearly five times higher than that of cemented clay. However, the increase in stiffness was attributed to the combined effect of sand, cement, and water. Recently, Subramanian and Ku (2023) discussed in detail the framework to investigate the effect of sand on strength of cemented clay, which is an extension of the current paper.

The literature thus far discusses the behaviour of cemented sandy clay as a whole matrix, without addressing the effect of sand on the behaviour of cemented clay. Hence, the motivation of this study is to propose a methodology to study the effect of sand in cemented clay matrix and systematically investigate the effect of sand on the strength of cement clay.

## 2. Material and sample preparation

Powdered kaolin clay used in this study has a liquid limit of 80% and plastic limit of 40%. A uniformly graded sand with a $D_{50}$ of 0.71 mm is used in this study. Table 1 shows the liquid limit of binary mixture measued using fall cone method. The liquid limit decreases linearly with increase in sand content.

Based on the mix terminologies adopted in each case studies (refer to Methodology section), the required amount of clay, sand, cement and water is prepared accordingly. Firstly, the dry kaolin powder and some portion of water are mixed in a Hobart mixer for 5 minutes. Then, the required amount of sand is added to the wet clay and mixed for 5 minutes. Finally, cement and the remaining water are added to the sandy clay mixture and mixed initially for 5 minutes, after which the Hobart mixer is stopped, and manual mixing is carried out to scrape the soil sticking to the sides of the mixing bowl. Finally, the sample is mixed for another 5 minutes and then the homogenous mixture is transferred in three layers to PVC moulds of 50 mm diameter and 100 mm height. Each layer is tamped to remove the entrapped air. Both the ends of the mould are sealed with a plastic cover and kept inside water for curing.

At the end of 7 days curing, the samples are extracted, and their bulk density ($\rho_b$) is measured. Then the bender element testing is carried out to determine the shear wave velocity ($V_s$) of the cemented binary mixture. Knowing the bulk density and shear wave velocity, the small strain shear modulus ($G_{max}$) is then calculated. The same sample is then tested for unconfined compressive strength (UCS) testing to measure the strength ($q_U$) of the cemented samples. A strain rate of 1mm/minute is adopted as recommended by ASTM D2166/D2166M (Astm, 2013).

**Table 1.** Liquid limit of binary mixture

| Sand Content (%) | Liquid Limit (%) |
|---|---|
| 0 | 80 |
| 10 | 70 |
| 30 | 55 |
| 50 | 40 |

## 3. Methodology

Three case studies are considered in this study, and their respective terminologies are described in the following section. The sand content ($SC$) definition, which is the ratio of mass of sand to total mass of soil, is the same in all the case studies considered.

Case 1: This case is bsed on the definitions that are commonly adopted in the literature to describe cement-soil mixtures, wherein the water content ($w$) is defined as the ratio of mass of water ($M_w$) to the total mass of solids ($M_s$), and cement content ($CC$) defined as the ratio of mass of cement ($M_c$) to mass of soil solids ($M_{soil}$).

Case 2: The ratio of water content ($w$) of the soil-cement mix to the liquid limit ($w_L$) of the soil is kept constant. For example, when $w/w_L$ is 1.3, the total water content is 1.3 times of the liquid limit of the binary mixture. Then, the mass of water in the mix is given by $1.3w_L$ times the mass of solids. Table 1 shows the liquid limit of the untreated binary mixture for different sand contents. Cement content is the same as in Case 1.

Case 3: The water content ($w$*) is defined as the ratio of mass of water to the combined mass of clay and cement (i.e., excluding sand). The rationale is that due to the high-water content used in the current study, the sand grains cannot hold water as compared to the clay and cement particles. To avoid confusion, the water content defined in this study is named as binding "clay-cement" water content (in short, binding water content) as it is defined in terms of clay and cement (note that sand has a poor water holding capacity). The cement content ($CC^*$) is defined as the mass ratio of cement to clay. Again, to avoid confusion with the conventional cement content, the cement content used in this study is referred as modified cement content. For cemented clay, that is $SC$ = 0%, $CC^*$ = $CC$ and $w^*$= $w$.

Table 2 shows the phase relationship diagram used for all case studies. It should be noted that the terminologies from the above three cases work only when the clay is dominent in the binary mixture (clay content > sand content) and may not be extended to pure cemented sand, that is $SC$ = 100%. For the range of water content considered in this study, extending Case 1 to accommodate 100% sand content would result in bleeding, with all the sand particles settling to the bottom of the mixture. With regard to Case 2, the terminology cannot be used because the concept of liquid limit is not applicable to sand. As for Case 3, the modified cement content would be infinity (since the mass of clay is zero) and water content would go to zero. The scope of this paper is limited to the clay and sandy clay part of the soil spectrum. Also, the sample preparation procedure changes when the sand content is extended to 100%.

**Table 2.** Terminologies used in case studies

| Case | Sand Content | Cement Content | Water Content |
|---|---|---|---|
| 1 | | $\frac{M_{cement}}{M_{soil}}$ | $\frac{M_w}{M_{solids}}$ |
| 2 | $\frac{M_{sand}}{M_{soil}}$ | | $\frac{\left[\frac{M_w}{M_{solids}}\right]}{w_L} = constant$ |
| 3* | | $\frac{M_{sand}}{M_{clay}}$ | $\frac{M_w}{M_{cement} + M_{clay}}$ |

Note: *Case 3 adopts new terminologies proposed in this study.

## 4. Results and discussion

### 4.1. Case Study - 1

As aforementioned, Case 1 involves definitions that are commonly adopted in the literature to describe cement-soil mixtures (refer to Table 2). Figure 1 shows the variation of UCS, $G_{max}$, void ratio, bulk density, and water content with sand content, for specimens with constant $w$ = 105% and $CC$ = 30%. Based on these definitions, each mix contains a fixed amount of water, irrespective of the sand content.

Sand is a stiffer material than clay, so intuitively, increasing $SC$ was expected to increase the strength and stiffness of cemented clay. But, the strength and stiffness of the cemented clay reduces with increasing $SC$, which is counter intuitive. The water added to the cemented clay plays an important role in reducing the strength of cemented clay with sand. Water is known to be strongly attracted to clay particles, giving rise to plasticity. On the other hand, granular particles have less affinity towards water and do not develop significant plasticity. The amount of water that clay particles can hold, i.e., water holding capacity, at a shear strength of 2 kPa is given by the liquid limit of the clayey soil (Mitchell and Soga, 2005). A water content beyond the liquid limit results in slurry-like mixture with zero shear strength. Hence, as the sand content of the mixture increases, so does the water in excess of the liquid limit of the clay. Consequently, the mixture with high sand content behaves in a water-like consistency during sample preparation; this causes bleeding and segregation of the sand grains at the bottom of the mixing bowl, thereby making it difficult to transfer the material from the mixing bowl to PVC moulds while still maintaining its uniformity.

As shown in Figure 1(c), the specimens with $SC$ = 50% contain more water than the rest (shown by increasing void ratio). To validate this claim, cemented clayey sand mixes were prepared and kept in measuring cylinder for 2 hrs to see the amount of water bleeding out of the sample. As shown in Figure 1(d), when the sand content increases, the amount of water bleeding from the cemented sandy clay increases. This indicates that more water was transferred to the PVC moulds while casting such specimens, and the actual sand content could not be maintained.

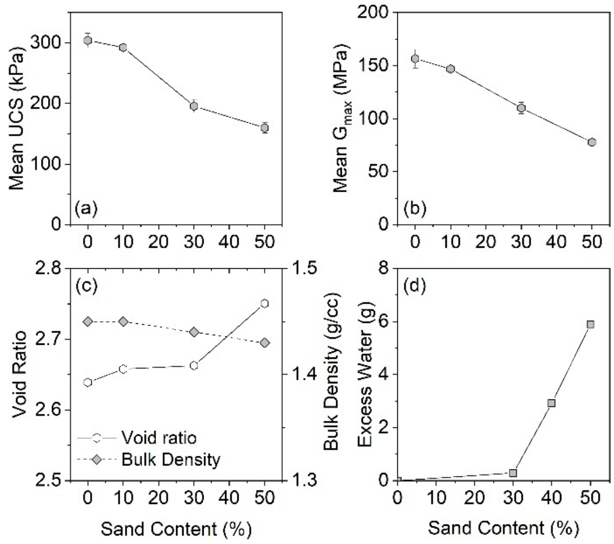


**Figure 1**. Variation of (a) mean UCS, (b) mean $G_{max}$ and (c) post-cured void ratio & bulk density with sand content for case 1. (d) excess water on top of the sample after 2 hours. The specimens have a constant $CC$ = 30% and $w$ = 105%.

### 4.2. Case Study – 2

In Case 2, the ratio of water content ($w$) of the soil-cement mix to the liquid limit ($w_L$) of the soil is kept constant. Cement content is the same as defined in Case 1. While studying the strength of cemented sandy clay, Chian et al. (2016) introduced the free water to cement ratio ($(w/w_L)/c$), wherein ($w/w_L$) is defined as the normalized water content. As shown in Table 1, the liquid limit of the uncemented binary mixture reduces with increasing sand content. This is attributed to the reduction in water-holding capacity of the mixture. The results are consistent with Chian et al. (2016).

Figure 2(c) shows the variation of void ratio with increasing sand content for w/wL=1.0 and w/wL=1.3. In this case, the void ratio reduces almost linearly with sand content because the total water is proportional to the liquid limit, which also reduces linearly with sand content. As shown in Figure 2(a) and 2(b), the strength and stiffness increase exponentially with sand content. Similar results were observed by Subramanian and Ku (2017) for cemented marine clay mixed with sand. Moreover, Figure 2(d) shows that the UCS also decreases exponentially with void ratio, irrespective of the sand content and w/wL.

This suggests that the change in the strength and stiffness for Case 2 is not solely attributed to the varying sand content. As can be seen in Table 3, the water to cement (w/c) ratio, which is an important parameter that affects the strength of cemented soils (Lee et al., 2005; Tan et al., 1999), is not constant for every mix in Case 2. Hence, the pseudo-increase in UCS with sand content actually results from the combined effect of water, cement, and sand.

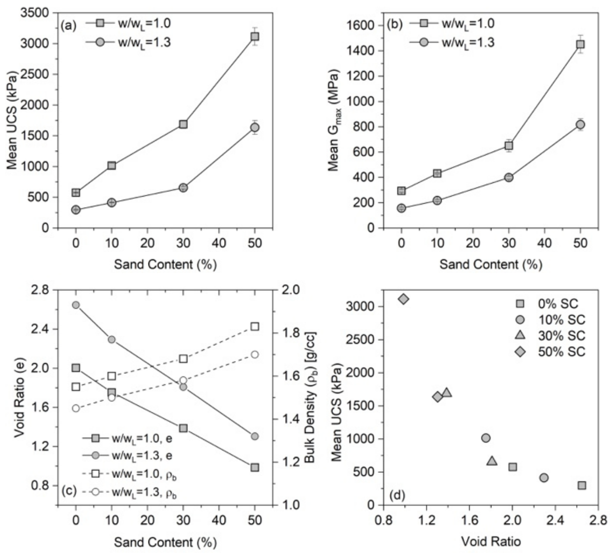


**Figure 2**. Variation of (a) mean UCS, (b) mean $G_{max}$, (c) void ratio & bulk density with sand content for Case 2. (d) mean UCS vs void ratio. The specimens have a constant *CC* = 30% and $w/w_L$ = 1.0, 1.3%.

## 4.3. Case Study – 3

For Case 3, a binding water content (*w**) is defined as the ratio of mass of water to the combined mass of clay and cement (i.e., excluding sand). This is based on the rationale that clay and cement are much more effective in holding water than sand grains. The modified cement content (*CC**) is defined as the mass ratio of cement to clay. For a purely cemented clay mix, that is *SC* = 0%, *CC** = *CC* and *w**= *w*.

From the above two cases, it was demonstrated that sand should replace equal proportions of clay, cement and water, so that the ratio of water to the combined sum of clay and cement remained constant and comparable to that of pure cemented clay. This is akin to treating sand like an inclusion so that any change in strength and stiffness is influenced by the sand content as a controlling variable. Figure 3 shows the results obtained for Case 3.

As Figure 3(c) shows, the void ratio decreases linearly with increasing sand content, with the trend of decrement in void ratio being comparable to that of Case 2. However, the increase in UCS and Gmax with sand content (Figure 3(a) and 3(b)) is modest and not as prominent as compared to Case 2 (Figure 2(a) and 2(b)). As shown in Figure 3(d), the reduction in strength with increasing void ratio shows a unique trend for each sand content or binding water content; the rate of decrease in strength is the highest for samples with SC=50% and the lowest for SC=0%. Furthermore, the mixture with the highest binding water content exhibits a higher rate of decrease in void ratio with sand content but the corresponding increase in UCS is not significant (Figure 3(d)). Conversely, specimens with the lowest binding water content show the lowest rate of decrease in void ratio, with a greater increase in the UCS. This can be attributed to the lower porosity of the mix at low water to cement ratio (Figure 3(c)), which results in enhanced grain-to-grain contacts.

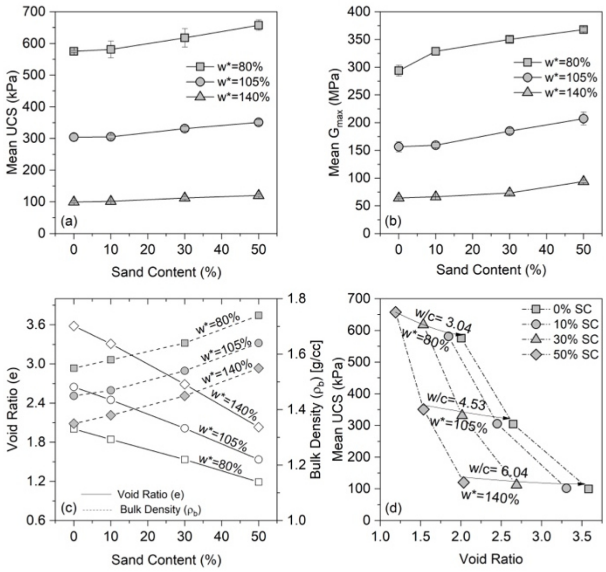


**Figure 3.** Variation of (a) mean UCS, (b) mean $G_{max}$, (c) void ratio & bulk density with sand content for Case 3. (d) mean UCS vs void ratio. The specimens have a constant *CC** = 30% and *w** = 80, 105, 140%.

To understand the influence of sand in a cemented clay mixture, one must first of all look at the case of uncemented binary mixtures. Thevanayagam (1998) mentioned that the presence of sand is viewed as a discontinuity and has no effect on the force chain in finer particles. However, a cemented clay matrix is much stiffer than that of pure clay due to the hydration of cement into cementitious products.

## 4.4. Applicability of binding water content and modified cement content

Adopting Case 3 terminologies, the experimental data for Case 1 and Case 2 are re-visited for validation. Their corresponding binding water content and water to cement ratio are calculated. The variation of binding water content from Case 1 data and Case 2 data is shown in Figure 4. As shown in the Figure 4(a), the reduction in strength for case 1, which originally appeared to be a consequence of the sand content, is attributed to the increase in binding water content. Figure 4(b) shows the variation of binding water content for Case 2 data, in comparison with Case 3 data. As shown in Figure 2(a), Case 2 data showed a drastic increase in strength with increasing sand content. From Figure 4(b), this drastic increase in strength can be explained by the reduction in both binding water content and water to cement ratio.

The concept of binding water content when applied to Case 1 and 2 readily explains the variation in strength that was otherwise attributed to a change in sand content. Similar observation are made for Gmax results obtained in Case 1 and Case 2 as shown in Figure 4(c) and 4(d).

The results from all the case studies are summarized in Table 3.

**Table 3.** Summary of test results

| Case | *SC* (%) | $w/w_L$ | *w/c* | *w** | *CC** | $q_U$ (kPa) |
|---|---|---|---|---|---|---|
| 1 | 0 | 1.31 | 4.53 | 1.05 | 0.30 | 304 |
| | 10 | 1.50 | 4.53 | 1.13 | 0.33 | 293 |
| | 30 | 1.90 | 4.53 | 1.36 | 0.43 | 196 |
| | 50 | 2.64 | 4.53 | 1.70 | 0.60 | 160 |
| 2 | 0 | 1.0 | 3.40 | 0.80 | 0.80 | 0.80 |
| | 10 | 1.0 | 3.02 | 0.75 | 0.75 | 0.75 |
| | 30 | 1.0 | 2.39 | 0.72 | 0.72 | 0.72 |
| | 50 | 1.0 | 1.72 | 0.64 | 0.64 | 0.64 |
| | 0 | 1.3 | 4.53 | 1.05 | 1.05 | 1.05 |
| | 10 | 1.3 | 3.92 | 0.98 | 0.98 | 0.98 |
| | 30 | 1.3 | 3.11 | 0.93 | 0.93 | 0.93 |
| | 50 | 1.3 | 2.23 | 0.84 | 0.84 | 0.84 |
| 3 | 0 | 0.98 | 3.40 | 0.80 | 0.30 | 575 |
| | 10 | 1.04 | 3.40 | 0.80 | 0.30 | 581 |
| | 30 | 1.07 | 3.40 | 0.80 | 0.30 | 618 |
| | 50 | 1.12 | 3.40 | 0.80 | 0.30 | 658 |
| | 0 | 1.31 | 4.53 | 1.05 | 0.30 | 304 |
| | 10 | 1.38 | 4.53 | 1.05 | 0.30 | 305 |
| | 30 | 1.43 | 4.53 | 1.05 | 0.30 | 332 |
| | 50 | 1.49 | 4.53 | 1.05 | 0.30 | 351 |
| | 0 | 1.74 | 6.04 | 1.40 | 0.30 | 100 |
| | 10 | 1.85 | 6.04 | 1.40 | 0.30 | 102 |
| | 30 | 1.90 | 6.04 | 1.40 | 0.30 | 112 |
| | 50 | 1.99 | 6.04 | 1.40 | 0.30 | 120 |

Note: *SC* = Sand content, $w_L$ = Liquid limit of the binary mixture, $w/w_L$ = normalized water content, *w/c* = water to cement ratio, *w** = binding water content, *CC** = modified cement content, $q_U$ = unconfined compressive strength.

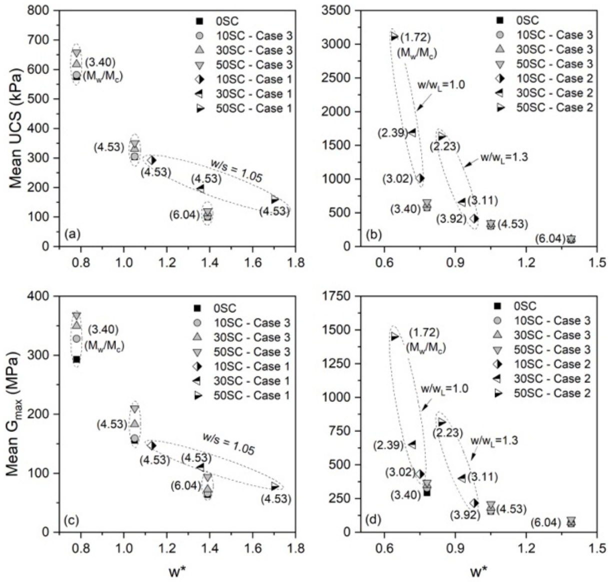


**Figure 4**. Applying the definition of modified water content to the experimental data of: Strength results of (a) Case 1, (b) Case 2, and comparing with Case 3 results. Stiffness results of (c) Case 1, (d) Case 2, and comparing with Case 3 results. Note: (*Mw/Mc*) = water to cement ratio, *w/s* = water to solids ratio and $w/w_L$ = water content to liquid limit ratio.

## 5. Summary and conclusion

This study has addressed experimental design issues about the effect of water, sand, and cement on the behaviour of cemented binary mixtures. The findings are summarized as follows:

- The use of conventional mix-design definitions leads to presence of excess water over the water holding capacity of the clay in a cemented binary mixture, hence causing a drastic drop in strength and stiffness with increase in sand content. In a typical cement stabilization operation in the field wherein the water to cement ratio of the injected cement slurry is usually held constant, if the marine clay layers bear significantly varying sand content, then drastic variations in strength and stiffness of the treated soil mass may be encountered if the presence of sand is ignored in design.
- The use of free water to cement ratio resulted in an increase in strength and stiffness with sand content, but the increase was contributed by a combined effect of water, cement and sand. For the same free water to cement ratio, the water to cement ratio reduces with increasing sand content, causing an increase in strength and stiffness.
- The effect of sand on cemented clay can be studied by keeping water to cement ratio, modified cement content, and binding water content constant. This approach clearly delineates the effect of sand on cemented clay mixture. The applicability of the proposed terminologies (i.e., modified cement content, binding water content) to other cases was also demonstrated.

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