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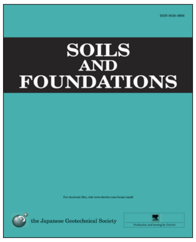

Strength development in silty clay stabilized with calcium carbide residue and fly ash

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Abstract

Calcium carbide residue (CCR) and fly ash (FA) are waste products from acetylene gas factories and power plants, respectively. The mixture of CCR and FA can produce a cementitious material because CCR contains a large amount of $Ca(OH)_2$ while FA is a pozzolanic material. Soil stabilization by CCR is classified using three zones: active, inert and deterioration. In the active zone, the natural pozzolanic material in the soil is adequate to produce a pozzolanic reaction. Hence, the input of FA into this zone does not significantly improve strength. Strength in the inert zone can be significantly increased by adding FA. FA improves the densification and pozzolanic reaction. The deterioration zone is not recommended for use in practice, even with the input of FA. The unsoundness due to free lime hinders strength development. Although the soaked and unsoaked strengths depend mainly on the CCR and FA contents, most of the ratios of soaked strength to unsoaked strength vary between 0.45 and 0.65. It is proved that a mixture of CCR and FA can be used for soil stabilization instead of ordinary Portland cement. The possible mechanism regarding the control of strength development presented in this paper can be applied to other clayey soils stabilized with different cementitious materials produced from $Ca(OH)_2$-rich and pozzolanic materials. This putative mechanism is also fundamental for further studies involving the development of rational dosage methodologies.

Keywords: Fly ash; Calcium carbide residual; Unconfined compressive strength; Soil stabilization; Pozzolanic reaction; Waste material

1. Introduction

Compacting in-situ soil mixed with cement slurry is an extensively used soil improvement technique for problematic soil that is in relatively a dry state. An advantage of this technique is that adequate strength can be achieved in a short time. To reduce stabilization costs, replacement of the cement with waste materials, such as fly ash, rice husk ash and biomass ash has been widely applied in practice. The effects of some influential factors such as water content, cement content, curing condition, replacement ratio and compaction energy on the microstructure and engineering characteristics of cement-stabilized soils have been extensively researched (Terashi et al., 1979, 1980; Tatsuoka and Kobayashi, 1983; Kamon and Bergado, 1992; Nagaraj et al., 1997; Yin and Lai, 1998, Consoli et al., 2000; Kasama et al., 2000; Miura et al. 2001; Horpibulsuk and Miura, 2001; Horpibulsuk et al., 2003, 2004a, 2004b, 2005, 2006, 2009, 2010b, 2011b, 2012b, Zillur Rabbi et al., 2011 Deng et al., 2012).

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In addition to cement, lime ($Ca(OH)_2$-rich material) has been widely used to stabilize clayey soils. The dissociation of $Ca(OH)_2$ leads to an increase in the pH values of the pore water. Strong bases dissolve the silica and alumina from the clay particles (a natural pozzolanic material) in a manner similar to the reaction between a weak acid and a strong base. The hydrous silica and alumina then gradually react with the calcium ions (pozzolanic reaction), which hardens with time (Herrin and Mitchell, 1961 Thompson, 1966). The variations in the strength of lime-stabilized soils under various influential factors such as lime content, curing time and curing temperature have been studied and reported by Liu et al. (2012) and Li et al. (2012).

To improve economic and environmental impacts, some waste $Ca(OH)_2$-rich materials can be utilized together with waste pozzolanic materials, such as fly ash, biomass ash and rice husk ash to develop a cementitious material. Calcium carbide residue (CCR) is a by-product of the acetylene production process that contains mainly calcium hydroxide, $Ca(OH)_2$. Between 1995 and 1998, the demand for calcium carbide for the production of acetylene gas in Thailand was 74,000 t (Tanalapasakul, 1998). This demand is continuously increasing each year. Due to its highly basic pH, CCR has been little utilized and was typically gone to a disposal area in the form of slurry. After being sun-dried for a few days, the slurry form changes to a dry form. Its production is described in the following equation:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2 \tag{1}$$

From Eq. (1), it can be seen that 64 g of calcium carbide (CaC_2) provides 26 g of acetylene gas (C_2H_2) and 74 g of CCR in the form of $Ca(OH)_2$.

Jaturapitakkul and Roongreung (2003) have introduced a cementitious material that is a mixture of CCR and rice husk ash. The cementing property was identified as a pozzolanic reaction between the two materials, and no Portland cement was included in the mixture. Consoli et al. (2001) have reported on the possibility of using CCR and fly ash to stabilize non-plasticity silty sand. For clayey soils, which have a high content of natural pozzolanic materials, stabilization by using CCR is very effective. Horpibulsuk et al. (2012a) and Kumpala and Horpibulsuk (2013) explained the possible mechanism controlling the engineering properties of CCR-stabilized clay based on macro- and micro-scale observations. The optimum water content (OWC) of the stabilized clay exhibits the highest strength because it engenders the densest packing and highest cementitious products. Strength improvement for a particular curing time is classified into three zones: active, inert and deterioration (*vide* Fig. 1). The data were obtained from an unconfined compression test under unsoaked condition on CCR-stabilized samples at optimum water content. In the active zone, strength increases remarkably with increased CCR content. All the input $Ca(OH)_2$ is consumed by the natural pozzolanic material in the soil to produce a pozzolanic reaction. This active zone can be determined from the CCR fixation point, which is obtained simply from the index test. CCR fixation is defined as the CCR content at which the plasticity index of the CCR-clay mixture changes insignificantly with the CCR input. Strength development in the inert zone tends to slow down; the incremental gradient becomes nearly zero and does not make any further significant improvement. A decrease in strength, which appears when the CCR content is in the deterioration zone, is caused by unsoundness due to free lime. This free lime [$Ca(OH)_2$] is clearly observed by the thermal gravity analysis (TGA) (Horpibulsuk et al., 2012a). Even with the high unsoaked strength in the active zone (Fig. 1), Kumpala et al. (2013a, 2013b) found that the wet-dry cycled strength of stabilized clay was considered insufficient according to recommendations by the ACI (1990) and the U.S. Army Corps of Engineers (2004). The input of FA (as a CCR replacement) may improve the strength of CCR stabilized clay when the CCR content is in excess of the active zone (i.e., in inert and deterioration zones) where natural pozzolanic material in the soil is not in sufficient quantities to react with the $Ca(OH)_2$. However, the optimal input of FA and the mechanism controlling strength development in these two zones are not clearly understood.

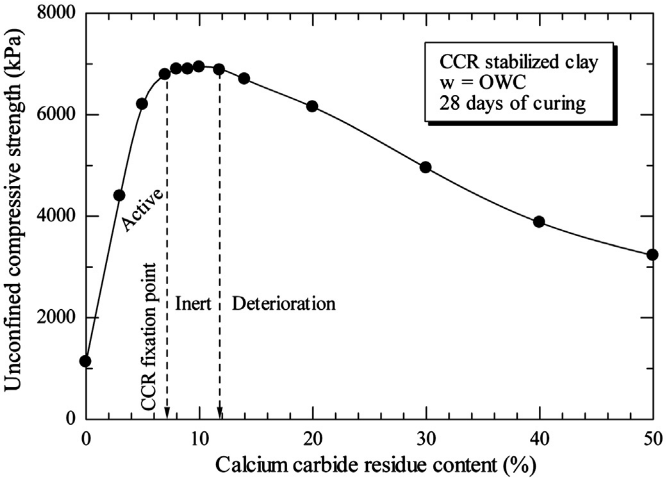

Fig. 1. Improvement zones (Horpibulsuk et al., 2012a).

This paper attempts to investigate the strength characteristics of the CCR- and FA-stabilized silty clay in the three improvement zones, mainly focusing on the role of FA in strength improvement in the inert and the deterioration zones. Unconfined compressive strength was used as a practical indicator to investigate strength development. Soaked and unsoaked strengths and the resulting strength ratio are examined throughout the curing time. Based on the strength test results, a possible mechanism controlling strength development is presented. This research will facilitate engineering decision on the mix proportion of soil, water, CCR and FA.

2. Materials and methods

2.1. Soil sample

The soil sample is a silty clay that was collected from the Suranaree University of Technology campus in the Nakhon Ratchasima province of Thailand at a depth of 3 m. It is a problematic soil, sensitive to changes in water content (Horpibulsuk et al., 2008). Fig. 2 shows the grain size distribution of the silty clay. It is composed of 2% sand, 43% silt and 55% clay. The average grain size, D_{50}, of the clay is 0.004 mm and the specific gravity is 2.76. The liquid and plastic limits are approximately 61% and 22%. Based on the Unified Soil Classification System (USCS), the clay is classified as high plasticity (CH). During sampling, the groundwater disappeared. The natural water content was 10%. The soil swelling potential of the tested clays was investigated by the free swelling test proposed by Prakash and Sridharan (2004) because it is simple and predicts dominant clay mineralogy of soils satisfactorily (Horpibulsuk et al., 2007). The free swell ratio, FSR, is defined as the ratio of equilibrium sediment volume of 10 g of oven-dried soil passing through a 425 μm sieve in distilled water (V_d) to that in carbon tetra chloride or kerosene (V_k). The clay is classified as low swelling with a free swell ratio (FSR) of 1.4. The Cation Exchange Capacity (CEC) is 27.6 meq/100 g. The chemical composition of the silty clay is shown in Table 1. The sum of SiO_2, Al_2O_3 and Fe_2O_3 is 60.54%, which is considered as high for pozzolanic reaction.

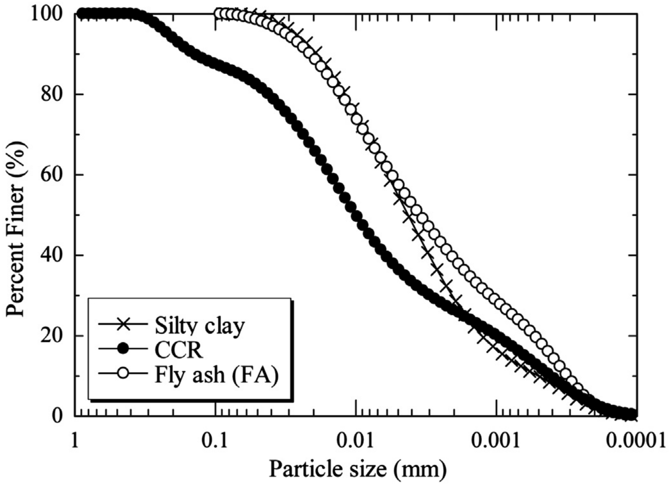

Fig. 2. Grain size distribution of silty clay, FA and CCR.

Table 1
Chemical properties of silty clay, fly ash, CCR and hydrated lime.

Chemical composition (%)	Silty clay	Fly ash	CCR	Hydrated lime
CaO	26.15	12.15	70.78	90.13
SiO_2	20.10	45.69	6.49	1.29
Al_2O_3	7.55	24.59	2.55	0.24
Fe_2O_3	32.89	11.26	3.25	0.49
MgO	0.47	2.87	0.69	0.22
SO_3	4.92	1.57	0.66	0.86
Na_2O	ND	0.07	ND	ND
K_2O	3.17	2.66	7.93	3.3
LOI	3.44	1.23	1.35	1.21

2.2. Binder

CCR from the Sai 5 Gas Product Co., Ltd., and FA from the Mae Moh power plant in the north of Thailand were used in this study. The CCR was oven-dried at 200 °C for 3 h and was then ground using a Los Angeles abrasion machine. Both the CCR and FA were passed through a no. 40 sieve (425 μm). The specific gravity values are 2.32 and 2.39, correspondingly. Table 1 shows the chemical composition of both the FA and CCR compared with that of hydrated lime. The total amount of the major components SiO_2, Al_2O_3 and Fe_2O_3 in FA are 81.48%. It is thus classified as class F FA in accordance with ASTM C 618. Table 1 summarizes the chemical composition of hydrated lime and CCR using X-ray fluorescence (XRF). The oxides were obtained from weight loss at temperatures lower than 800 °C. The weight loss of the samples at a temperature of greater than 800 °C was used to determine the loss of ignition (LOI). The CaO contents are 90.13% and 70.78% for hydrated lime and CCR, respectively. This result is in agreement with the XRD pattern (Horpibulsuk et al., 2012a). The XRD pattern of the CCR is similar to that of hydrated lime, indicating that the $Ca(OH)_2$ is a main component of CCR. The high $Ca(OH)_2$ and CaO contents of the CCR indicate that it can react with pozzolanic material and produce a cementitious material. The grain size distribution of the FA and the CCR compared with that of the silty clay is shown in Fig. 2. The curves were obtained from laser particle size analysis. The D_{50} of the FA is 0.0035 mm, which is close to

Table 2
Summary of the testing program.

Test	Binder (%)		Water content (%)	Curing time (days)
	CCR	FA		
Index properties	5	0, 5, 10, 15	–	–
	10, 20	0, 3, 6, 9, 12, 15, 18, 21, 24		
Compaction	0, 5, 10, 20	0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30	–	–
UC test (soaked condition)	5	0, 5, 10, 20, 30	OWC	7, 28, 60
	10	0, 3, 6, 9, 12, 15, 18, 21, 24	OWC	7, 28, 60, 90
	20	0, 3, 6, 9, 12, 15, 18, 21, 24	OWC	
UC test (unsoaked condition)	5	0, 5, 10, 20, 30	OWC	7, 28, 60
	10	0, 3, 6, 9, 12, 15, 18, 21, 24	OWC	7, 28, 60, 90
	20	0, 3, 6, 9, 12, 15, 18, 21, 24	OWC	

that of the clay, and the D_{50} of the CCR is 0.01 mm (2.5 times larger than that of the clay).

2.3. Methods

The silty clay was passed through a 2-mm sieve to remove the coarser particles. It was air-dried for at least 3 days and then the water content was adjusted for the compaction test. At least five compaction points were generated. Compaction was carried out using a Harvard Miniature Compaction Apparatus (described in ASTM D4609 and ASTM STP479), which consists of a standard mold (33.34 mm in diameter and 71.53 mm long) and a spring-loaded plunger. This apparatus was used instead of the Proctor compaction mold because the samples obtained have a diameter to height ratio of 0.5, which is recommended for unconfined compression test by the ASTM. The compaction characteristics (optimum water content, *OWC*, and maximum dry unit weight, $\gamma_{d,max}$) under modified Proctor energy are 18% and 16.9 kN/m^3, respectively. Generally, the standard Proctor energy is employed for the fill applications of unstabilized clay. The modified Proctor energy was performed on this stabilized clay to study its engineering properties for pavement bases and subbases. It was shown the stabilized clay compacted under the modified Proctor energy exhibited higher strength than that under the standard Proctor energy (Horpibulsuk et al., 2010b).

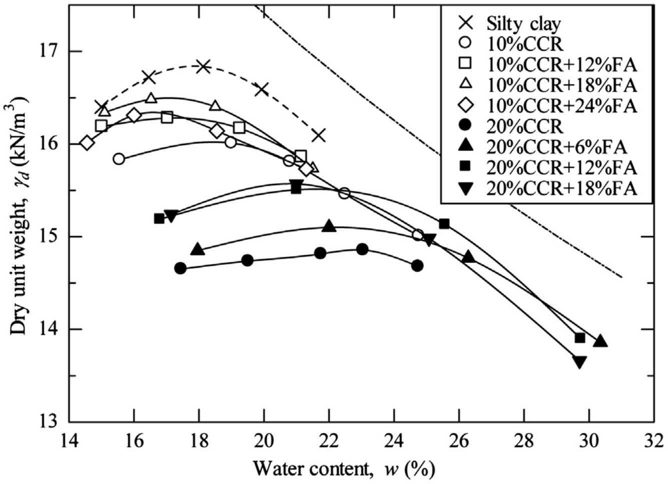

Fig. 3. Compaction curves of CCR- and FA-stabilized samples.

Having obtained the compaction curve, the air-dried clay was thoroughly mixed with CCR and FA and compacted at OWC under the modified Proctor energy. This water content provides higher strength than other molding water contents at the same compaction energy (Horpibulsuk et al., 2012a). The CCR contents were 5%, 10% and 20%, which are the representatives of the active, inert and deterioration zones, respectively. The FA contents were from 0% to 30% by weight of dry soil. The CCR or FA content is the ratio by weight of CCR or FA to clay, with both weight assessed in a dry state.

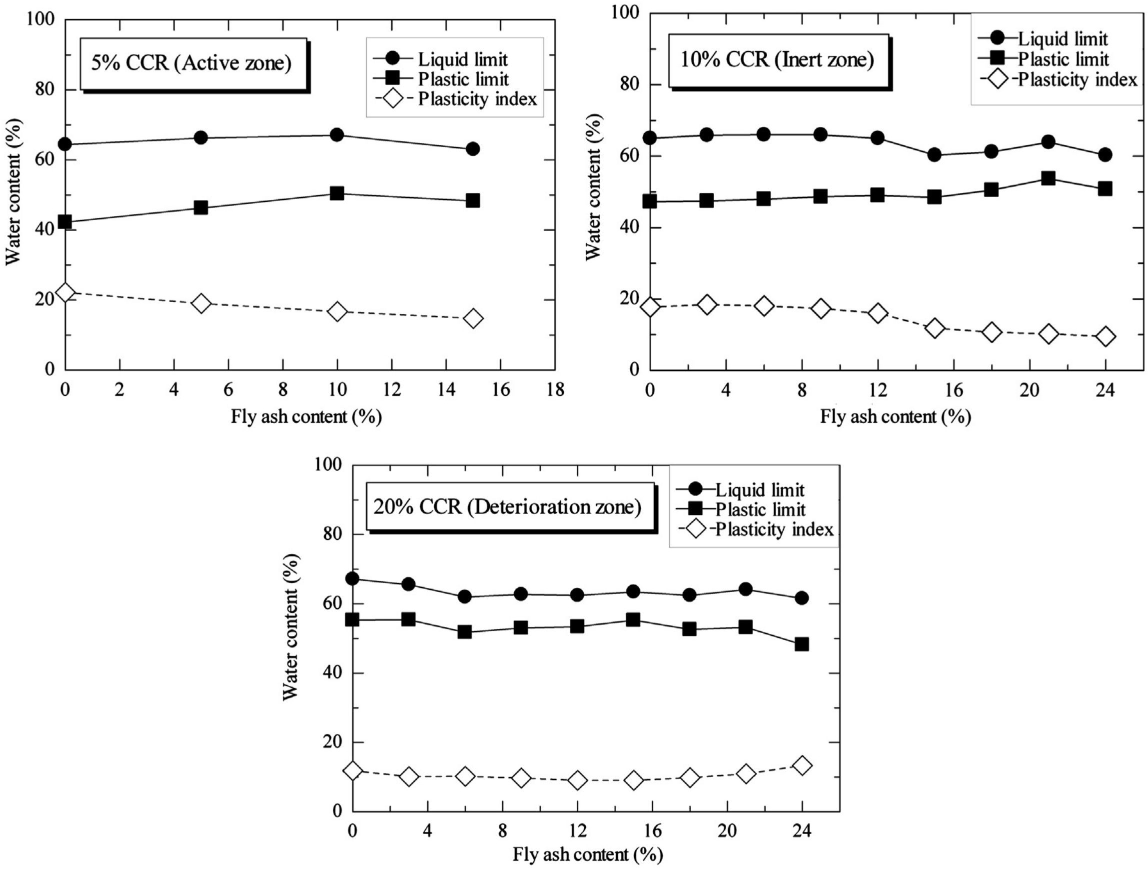

Fig. 4. Index properties of the CCR-stabilized clay for different FA.

The liquid and plastic limits of the CCR- and FA-stabilized samples were determined immediately after thorough mixing. The index tests were finished within 15 min after mixing. After 24 h of compaction, the stabilized samples were dismantled from the mold, wrapped in vinyl bags and stored in a humidity chamber of constant temperature (25 ± 2 °C). An unconfined compression (UC) test was run on the samples after 7, 28, 60 and 90 days of curing. Two sets of test sample were prepared for the unsoaked and soaked conditions. For the soaked condition, the samples were submerged under tap water for 2 h according to the specification of the Department of Highways, Thailand, DH-S 204/2533 (DH-S, 1990). The rate of vertical displacement for the UC test was fixed at 1 mm/min. The testing program is summarized in Table 2. For each curing time and combination of water content, CCR content and FA content, at least five samples were tested under the same conditions to check for the test consistency. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, *SD* ($SD/\bar{x} < 10\%$, where $\bar{x}$ is mean strength value).

3. Results

Fig. 3 shows the typical compaction curves for the stabilized samples at different CCR and FA contents. The maximum dry unit weight, $\gamma_{d,max}$ of the CCR-stabilized samples with no FA decreases as the CCR content increases; that is $\gamma_{d,max} = 15.9$ kN/m^3 and 14.8 kN/m^3 for 10% CCR and 20% CCR, respectively. This decrease in $\gamma_{d,max}$ is associated with the increase in OWC. $\gamma_{d,max}$ of the clay stabilized with CCR and FA increases with increases in FA content up to a certain FA content. However, all the CCR- and FA-stabilized clay samples show lower $\gamma_{d,max}$ than the compacted clay sample because the CCR and FA have a lower specific gravity than the clay.

The role of CCR relative to the plasticity index was revealed by Horpibulsuk et al. (2012a). The plasticity index of the CCR-stabilized clay with no FA decreases as the CCR content in the active zone increases and becomes almost constant in the inert and deterioration zones (unchanged with the CCR content). Fig. 4 shows the relationship between index properties and FA content of the CCR and FA stabilized clay in the active, inert and deterioration zones. As the FA content increases for the three improvement zones, the index properties of the stabilized clay are not significantly changed.

The unsoaked and soaked strengths of the stabilized clay samples for different FA contents at the OWC are shown in Figs. 5, 6 and 7 for the active, inert and deterioration zones, respectively. In the active zone, FA slightly improves strengths. Strength development in the inert zone is essentially dependent on the FA content. The strength increases sharply as the FA content increases up to the optimal value and then

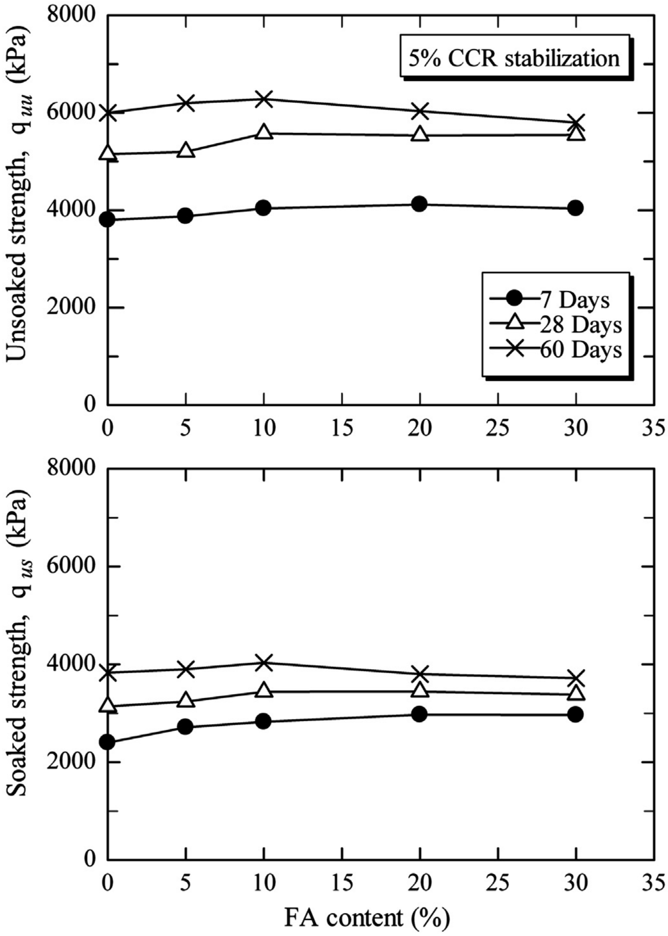

Fig. 5. Unsoaked and soaked strengths of CCR-stabilized clay in the active zone.

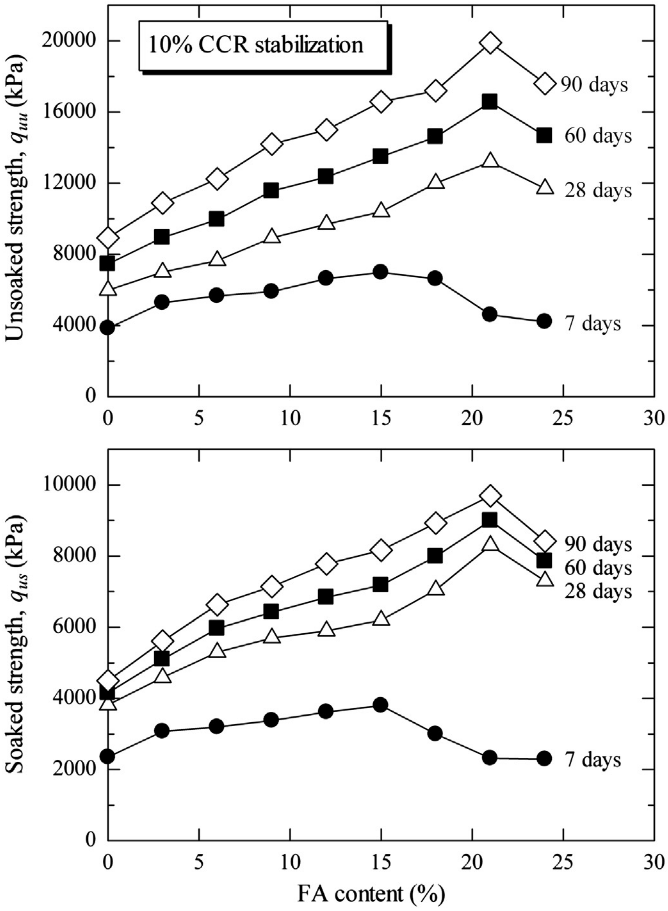

Fig. 6. Unsoaked and soaked strengths of CCR-stabilized clay in the inert zone.

decreases as the FA content decreases. For a short curing time (< 7 days), the optimal FA content is at 15%; for a long curing time (> 28 days), it is 21%. In the deterioration zone (*vide* Fig. 1), the strength of CCR stabilized clay is lower than that in the inert zone. The reduction in strength with increasing CCR content is caused by unsoundness due to the free lime content. That FA can improve this detrimental effect as indicated by the increase in strength with increasing FA content, as seen in Fig. 7. However, the strength increase is gradual up to an optimal FA content at about 12% for 7 days of curing and about 21% for longer curing times. Even with low FSR, this compacted silty clay is collapsible when the water content increases and thus has the capacity to cause damage to a superstructure (Horpibulsuk et al., 2008). The soaked strength of this compacted clay is null. Consequently, both the unsoaked and soaked strengths are important for the design of earth structures. For the three improvement zones, the soaked strengths are lower than the unsoaked strengths for all curing times (*vide* Figs. 5 to 7).

The typical strength development with curing time is shown in Figs. 8 and 9 for the inert and deterioration zones, respectively. For FA contents less than the optimal value (FA content < 12%), the strength development for both improvement zones and with different FA contents has a similar pattern and can be represented by the logarithm function, which is similar to the strength development in cement-stabilized clay (Horpibulsuk et al., 2003, 2009, 2011a, 2011b, 2012b). This strength development with time is due to pozzolanic reaction.

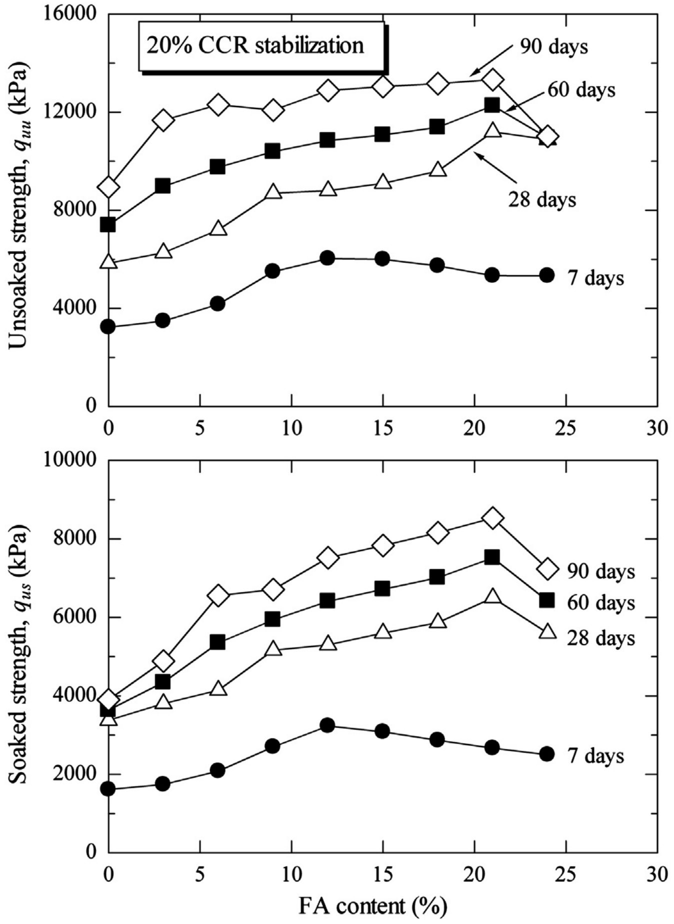

Fig. 7. Unsoaked and soaked strengths of CCR-stabilized clay in the deterioation zone.

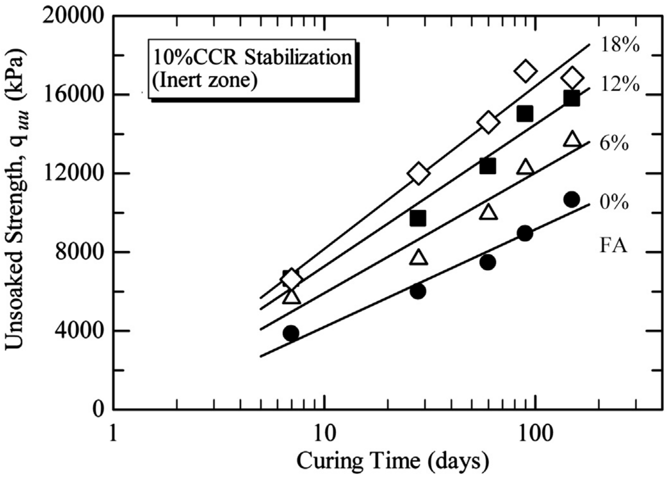

Fig. 8. Strength developmenet of the CCR-stabilized clay in the inert zone.

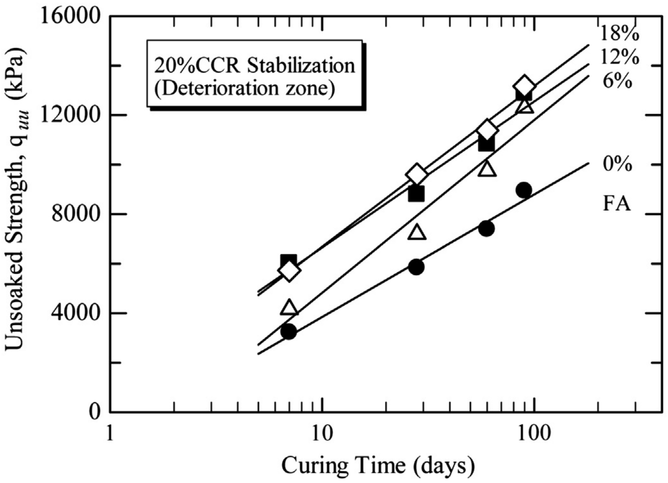

Fig. 9. Strength developmenet of the CCR-stabilized clay in the deterioration zone.

4. Analysis and discussion

From this study, it was found that soil stabilization by the CCR alone decreases the maximum dry unit weight due to the lower specific gravity of CCR and the flocculation of the clay particles caused by cation exchange. The flocculation is primarily responsible for the reduction in the plasticity index of the clay (Thompson, 1966). Horpibulsuk et al. (2012a) and Kumpala and Horpibulsuk (2013) showed that as the CCR content increases, the plastic limit, *PL* of the CCR-stabilized silty clay significantly increased, whereas the liquid limit, *LL*, tended to change by a small magnitude, resulting in a decrease in the plasticity index, *PI*. The larger and harder aggregations due to the flocculation cause large pore spaces and thus lower the dry unit weight. Because the FA surface is neutral (with no cation exchange with CCR), the FA does not significantly affect the physicochemical interaction of the mixture, as indicated by the lack of a significant change in the index properties of the CCR- and FA-stabilized clay for the three improvement zones. Due to the similar grain size distributions of the FA and clay, and the neutral surface of the FA, the fabric of the CCR-stabilized clay does not change significantly with the FA content, and the change in compaction curves with FA content is not caused by cation exchange. The spherical shape of the FA may improve the soil compaction efficiency and densification. It helps soil and CCR particles slip across each other and move into a densely packed state. However, excessive FA does not significantly improve the densification, as observed by the slight change of $\gamma_{d,max}$. The changes in $\gamma_{d,max}$ and the corresponding OWC of the stabilized samples with the FA content are shown in Figs. 10 and 11, respectively. The excessive FA begins at approximately 12% and 21% FA for 10% and 20% CCR, respectively.

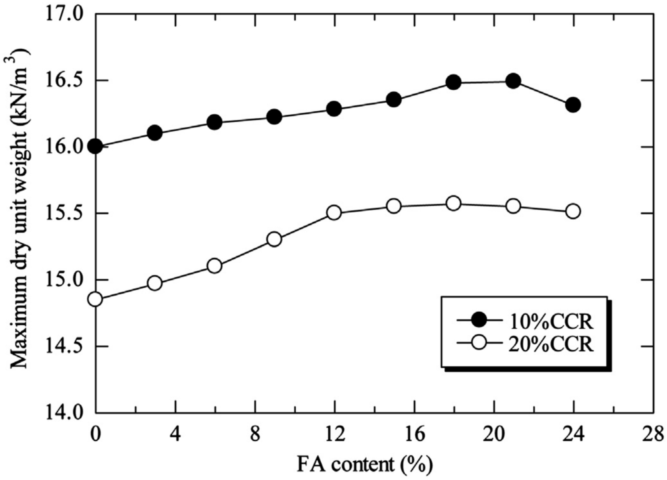

Fig. 10. Maximum dry unit weight and FA content relationship of the CCR-stabilized clay.

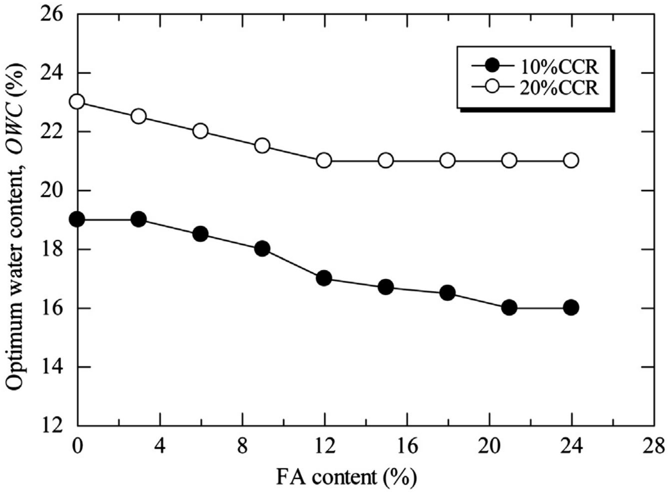

Fig. 11. Optimum water content and FA content relationship of the CCR-stabilized clay.

Strength development with the FA content in the active zone is not significant because the amount of natural pozzolanic material in the clay is sufficient to react with the $Ca(OH)_2$ and to produce a pozzolanic reaction (Horpibulsuk et al., 2012a). For the inert zone (CCR content = 7–12%) (Fig. 1), even with the increase in $Ca(OH)_2$ (CCR content), the strength is almost constant. This result occurs because the input of CCR is in excess of the pozzolanic reactive capacity of the clay particle. The FA, which is spherical and contains a very high amount of pozzolanic material, improves the densification and the pozzolanic reactive capacity. Even with the insignificant change in index properties, the strength development, which is time-dependent, is governed by the FA content. Since the index properties were tested immediately after mixing the clay and CCR with FA, the effect from pozzolanic reaction on the index properties is minimal. The maximum strength in the inert zone is at the optimal FA content. The strength of the CCR-stabilized clay is augmented by two main components: mechanical and chemical. The mechanical component is governed by the soil density, which is insignificantly affected by curing time, while the chemical component is time dependent. Kumpala et al. (2013a, 2013b) recently showed that for a particular CCR content, the one-day (short-term) strength of the CCR–FA stabilized clay is higher than that of the CCR stabilized clay, indicating the packing effect on strength development. The optimal FA content is thus an appropriate combination of these two components. It is observed that the highest 7-day strength is at the optimal FA content of 12% (Figs. 6 and 7) and is associated with the highest $\gamma_{d,max}$ (Fig. 10). Pozzolanic reactions come into play for the long curing time, as demonstrated by the increase in the optimal FA content after 7 days of curing. The long term strengths (from curing time >28 days) decrease when the FA content exceeds 21%. Under this condition, the excess FA may surround the CCR grains and hinders the interaction between water and the CCR grains. This observation is similar to that of the cement- and FA-stabilized clay reported by Horpibulsuk et al. (2011a, 2012b).

In the deterioration zone, even though the strength increases as the FA content increases, the rate of strength development is low. This low rate is caused by unsoundness due to free lime, which is also found in concrete with high free lime content. Consequently, the improvement in the deterioration zone is not economical compared with that in the inert zone. For engineering, economical and environmental considerations, the active zone is recommended for low-strength requirements whereas the inert zone with the optimal FA content is recommended for high-strength requirements. In practice, the optimal FA content in the inert zone can be approximated from the relationship between $\gamma_{d,max}$ and FA because the short-term (7-day) strength is generally used to design earth structures.

Based on the effective stress concept, the influence of cementation is regarded as akin to the effect of an increase in the effective stress (attractive inter-particle forces) and yield stress and hence, the yield surface (Gens and Nova, 1993; Horpibulsuk, 2001; Kasama et al., 2000; Kavvadas and Amorosi, 2000; Rouainia and Muir Wood, 2000; Baudet and Stallebrass, 2004; Lee et al., 2004; Horpibulsuk et al., 2010a;

Suebsuk et al., 2010, 2011). The increase in the yield stress and yield surface with cement content is clearly understood from the compression and shear test results (Horpibulsuk et al., 2004a, 2004b, Miura et al., 2001). The strength of the CCR stabilized clay is thus higher than the unstabilized clay. Kumpala and Horpibulsuk (2013) conducted water absorption and oedometer soaking tests. It was found that water absorption increased with immersion time, which was associated with an increase in vertical swelling and swelling pressure. The swelling pressure is the pressure applied to the samples until the vertical swell becomes null. This swelling pressure induces repulsion between the cemented clay particles. Consequently, the soaked strength is lower than the unsoaked strength. It is of interest to mention that even though the strength development in both the soaked and unsoaked samples depends on the CCR and FA contents, the ratio of the soaked strength to unsoaked strength is almost the same for all the CCR and FA contents tested. Most of the ratios vary between 0.45 and 0.65, with an average of 0.55 (*vide* Fig. 12). However, this range is based on the samples stabilized at OWC and might be dependent upon the state of water content (dry and wet side of optimum). The ratio for the dry side of optimum might be lower due to having higher water absorption capacity.

Strength development with curing time can be represented using a logarithm function. Because the short-term strength of about 7 days of curing is generally used for design, strength development with time for the FA contents of less than 12% (optimal FA content for the short term) is important and thus is examined in this paper. Fig. 13 shows strength development under both unsoaked and soaked conditions for both inert and deterioration zones. The 28-day strength was taken for the examination of the normalized characteristic, as was done by Horpibulsuk et al. (2003, 2009, 2011a, 2011b, 2012b). Although the strengths are different for different CCR and FA contents and soaking conditions, the normalized strength, q_D/q_{28} is essentially the same. Soaking condition does not significantly affect the normalized strength because the ratio of soaked strength to unsoaked strength varies in a narrow range within an average of 0.55. The normalization equation shows that the 1-day strength is approximately null. However, the 1-day strength is not null; it is relatively low compared with other strengths at longer curing times, reflecting the time dependency of the pozzolanic reaction process. To illustrate the effectiveness

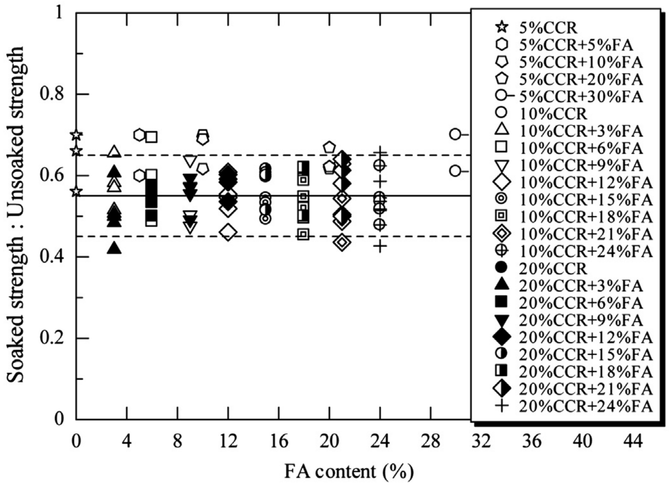

Fig. 12. Strength ratio of the CCR-stabilized clay with different FA content.

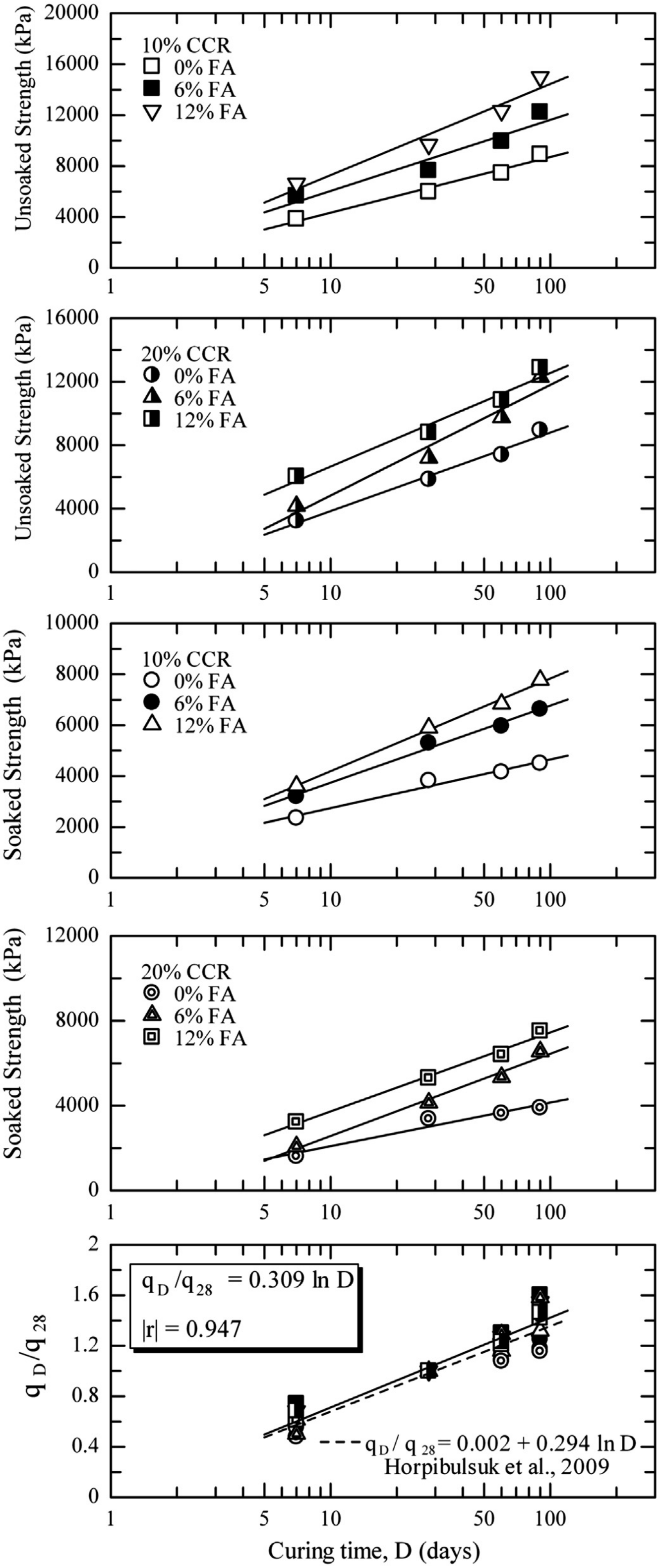

Fig. 13. Strength development with time of the CCR-stabilized clay and the normalization.

of CCR- and FA-stabilization, the normalized strength of the CCR stabilized silty clay is compared with that of the cement-stabilized silty clay (data from Horpibulsuk et al., 2009) in Fig. 13. The relationships between normalized strength and curing time are practically the same. Soil stabilization by CCR yields a slightly higher normalized strength development. This finding shows the advantage of using the two waste materials (CCR and FA) as a cementing material that can be equivalent to the ordinary Portland cement.

5. Conclusions

This paper deals with the analysis of strength development in CCR- and FA-stabilized clay. A possible mechanism controlling strength development is presented. The following conclusions can be drawn:

1. CCR has a very high $Ca(OH)_2$ content of about 76.7%. It can be used alone to improve problematic clayey soils that contain high levels of natural pozzolanic material. CCR can be used together with FA for higher strength requirement when the natural pozzolanic material is completely consumed by the input CCR.
2. In the active zone, the natural pozzolanic material is adequate for reactions with the CCR. Hence, the input of FA does not significantly improve strength. In the inert zone, the input FA enhances strength. The FA improves the densification and the pozzolanic reactive capacity. For the short-term, the strength increase is mainly caused by the packing effect because the pozzolanic reaction is a time-dependent process. The highest short-term strength is thus associated with the highest maximum dry unit weight. Over the time, a higher FA content is needed for the pozzolanic reaction; therefore, the optimal FA content increases. Improvement in the deterioration zone is not recommended in practice, even with the input of FA. Unsoundness due to the free lime content hinders the strength development by pozzolanic reactions.
3. The soaked strength is generally lower than the unsoaked strength because the absorbed water increases repulsive forces. Even though the strengths of the stabilized clay are strongly dependent upon the CCR and FA contents, the ratio of soaked strength to unsoaked strength is almost equal. Most of the ratios vary between 0.45 and 0.65 with an average of 0.55.
4. The normalized strength and curing time relationships of the CCR stabilized clay and the cement stabilized clay are similar. This result indicates the advantage of the mixture of two waste materials (CCR and FA) as a cementing agent for soil improvement. The application of both FA and CCR to the stabilization of problematic soil is an engineering, economical and environmental challenge.

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