Calcium Carbide Residue - A Cementing Agent for Sustainable Soil Stabilization

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ABSTRACT: The high unit cost and energy intensive process in the production of Portland cement are the driving forces for the need to seek for alternative cementitious additives. Calcium Carbide Residue (CCR) has been recently introduced as a sustainable cementing agent. The recent research on the engineering properties of CCR stabilized clay as a subbase/base materials is reviewed and presented in this paper. CCR alone as well as a mixture of CCR and fly ash (FA) can be used for soil stabilization instead of ordinary Portland cement. The suitable ingredient of CCR, FA and clay results in a moderately high strength and durable geomaterial. The CCR fixation point obtained from the index test is proved as a practical indicator for determining the CCR content to obtain the required engineering properties. For a particular CCR content, the optimum water content is the most appropriate in terms of strength, swelling and durability against wetting and drying (w-d) cycles. Significant strength and durability improvement is noticed when FA is utilized with CCR. The input FA at optimal content reacts with the excessive $Ca(OH)_2$ from the CCR and this results in a significant improvement of the strength and durability. The strength analysis shows that the durability is directly related to the unsoaked strength (prior to the w-d cycles). Consequently, the relationship between the w-d cycle strength and unsoaked strength is proposed. It is useful for the quick determination of the unsoaked strength for mix design to attain the target strength at the design service life.

Keywords: Calcium carbide residue, Fly ash, Strength, Swelling, Durability, Stabilized clay

1. INTRODUCTION

Portland cement is commonly used for soil stabilization in geotechnical and pavement applications. Effects of some influential factors i.e., water content, cement content, curing time and compaction energy on the microstructure and engineering characteristics of cement stabilized soils and aggregates have been extensively researched (Terashi et al., 1979; Tatsuoka and Kobayashi, 1983; Kamon and Bergado, 1992; Nagaraj et al., 1997; Yin and Lai, 1998; Kasama et al., 2000; Miura et al. 2001; Horpibulsuk and Miura, 2001; Horpibulsuk et al., 2003, 2004a, b, 2005, 2006, 2010a, b, 2011a, b, Chinkulkijniwat and Horpibulsuk, 2012; Suebsuk et al., 2010, 2011; 2014; Disfani et al., 2013; Mohammadinia et al., 2014 and others). The high unit cost and energy intensive process of Portland cement are the prime driving forces for the need to seek alternative cementitious additives.

Calcium carbide residue (CCR) is a by-product of acetylene production process, which contains mainly calcium hydroxide, $Ca(OH)_2$. It was recently proved as a waste cementing agent for soil stabilization (Horpibulsuk et al., 2012 and 2013; and Kampala and Horpibulsuk, 2013; Kampala et al., 2013; and Vichan et al., 2014). Its production is described in the following equation:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2 \quad (1)$$

From Eq.(1), it is seen that 64 g of calcium carbide (CaC_2) provides 26 g of acetylene gas (C_2H_2) and 74 g of CCR in terms of $Ca(OH)_2$. Presently, the demand of CaC_2 for producing acetylene gas in Thailand is 18,500 tons/year (Tanalapsakul, 1998). This provides 21,500 tons/year of CCR and the demand is continuously increasing each year. Due to its high base, the CCR was hardly utilized in any work and all of it went to disposal area as slurry form. After being sun-dried for a few days, the slurry form is changed to dry form.

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 and 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).

The recent research works (Horpibulsuk et al., 2012 and 2013; Kampala and Horpibulsuk, 2013; and Kampala et al., 2014) on the engineering properties of CCR stabilized clay in northeast Thailand has been reviewed and is presented in this paper. The effect of influential factors such as water content, CCR content and curing time on the engineering properties of a problematic silty clay stabilized with the CCR is illustrated. The engineering properties involved are compaction, soaked and unsoaked strength, swelling behavior and durability. The w-d cycles cause tension and surface cracks, which damage the stabilized pavement structure (Dif and Bluemel, 1991; Khattab et al., 2007; Rao et al., 2001; and Sazzad et al., 2010). The wetting-drying cycle strengths were compared with the recommended values for the cement stabilized pavement material by the American Concrete Institute, ACI and the U.S. Army Corps of Engineers (ACI, 1990; and U.S. Army Corps of Engineers, 2004).

2. PROBLEMATIC SOIL IN NORTHEAST THAILAND

The upper soil in northeast Thailand is generally wind-blown and deposited for several decades. It is a silty clay with low to moderate strength ($12 < N < 20$, where N is standard penetration number). This silty clay is a problematic soil, which is sensitive to changes in water content (Horpibulsuk et al., 2008). Laboratory and field investigations on its collapse behavior due to wetting have been illustrated by Kohgo et al. (1997); and Kohgo and Horpibulsuk (1999). The lower layer is a residual soil, weathered from claystone, consisting of clay, silt and sand (Udomchoke, 1991). It possesses very high strength (generally $N > 30$) and very low compressibility.

The silty clay from the campus of Suranaree University of Technology was taken as a representative of this problematic soil in northeast Thailand. An extensively study on the engineering properties of the clay stabilized with various cementing has been undertaken in Suranaree University of Technology since 2004. The typical grain size distribution of the silty clay (Figure 1) shows that the clay is composed of 2% sand, 43% silt and 55% clay. The specific gravity is 2.72. The liquid and plastic limits are approximately 55% and 27%, respectively. Based on the Unified Soil Classification System (USCS), the clay is classified as high plasticity (CH). During sampling, the groundwater had disappeared. The natural water content was 10 percent. The free swell test proposed by Prakash and Sridharan (2004) shows that the clay is classified as low swelling with a free swell ratio (FSR) of 1.6. The Cation Exchange Capacity, CEC is 27.6 meq/100g. The chemical composition of the clay is shown in Table 1. A XRD-pattern of the clay (Figure 2) shows that main chemical composition is SiO_2. The sum of SiO_2, Al_2O_3 and Fe_2O_3 is 60.54%, which is considered as high for pozzolanic reaction.

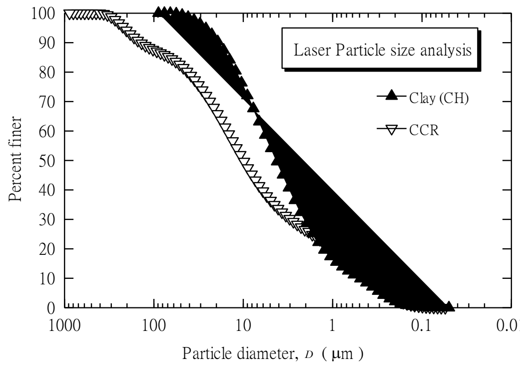
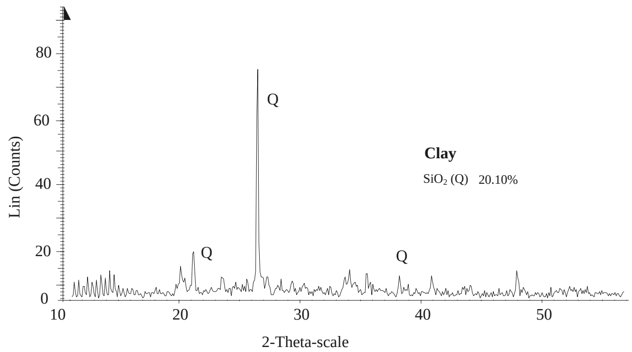
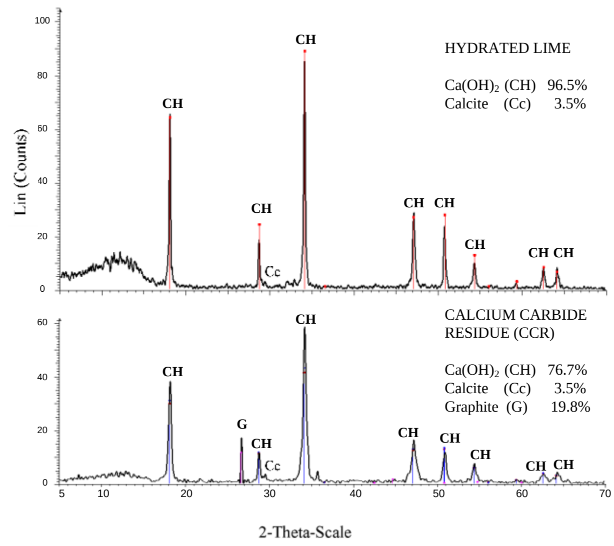


Figure 1 Grain size distribution of the silty clay and the CCR (Kampala and Horpibulsuk 2013).



a) Sitly clay



b) Hydrated lime and CCR

Figure 2 XRD pattern of (a) the clay and (b) the hydrated lime and the CCR (Kampala and Horpibulsuk 2013).

3. CALCIUM CARBIDE RESIDUAL

Calcium Carbide Residue (CCR) was obtained from the Sai 5 Gas Product Co., Ltd. The CCR was oven-dried at 200^{o}C for 3 hours and ground in a Los Angeles abrasion machine. The CCR was passed through a sieve No. 40 (425 μm). The specific gravity is 2.25. Table 1 shows the chemical composition of the CCR compared with that of a hydrated lime. The chemical composition shows the CaO contents of 90.13% and 70.78% for the hydrated lime and the CCR, respectively. The CCR contains pozzolanic materials (SiO_2, Al_2O_3 and Fe_2O_3) of about 12.3% while the hydrated lime contains very few of about 2%. The XRD pattern of the CCR is similar to that of the hydrated lime, showing the $Ca(OH)_2$ as a main composition (*vide* Figure 2). The $Ca(OH)_2$ contents are about 96.5% and 76.7% for the hydrated lime and the CCR, respectively. The high $Ca(OH)_2$ and CaO contents of the CCR indicate that it can react with pozzolanic materials and produce a cementitious material.

Table 1 Chemical composition of clay, CCR and hydrate lime

Chemical Composition	Clay	CCR	Hydrated lime	FA
CaO	26.15	70.78	90.13	1.03
SiO_2	20.10	6.49	1.29	49.04
Al_2O_3	7.55	2.55	0.24	37.91
Fe_2O_3	32.89	3.25	0.49	2.75
MgO	0.47	0.69	0.22	0.39
SO_3	4.92	0.66	0.45	0.18
Na_2O	ND	ND	ND	0.38
K_2O	3.17	7.93	3.3	0.52
LOI	3.44	1.35	1.21	4.70

The grain size distribution of the CCR compared with that of the clay is shown in Figure 1. The curves were obtained from the laser particle size analysis. The D_{50} of the CCR and the clay are 0.01 and 0.006 mm, respectively. From the grain size distribution, it is found that the clay particles are smaller than the CCR particles.

4. ENGINEERING PROPERTIES OF CCR STABILIZED CLAY

4.1 CCR Fixation Point

Figure 3 shows the effect of CCR content on the index properties of the CCR stabilized clay. As the CCR content increases, the plastic limit, *PL* of the stabilized clay significantly increases while the liquid limit, *LL* tends to change with small magnitude, resulting in a decrease in the plasticity index, *PI*. However, when the CCR content is greater than 7%, the change in *PI* is minimal. The CCR content of 7% is thus designated as the "CCR fixation point" (Horpibulsuk et al., 2012). The decrease in *PI* indicates the flocculation and the coagulate aggregation of the clay particles, which are caused by the absorption of Ca^{2+} ions. The CCR fixation point has been proved as a prime parameter governing the engineering properties of CCR stabilized clay (Horpibulsuk et al, 2012 and 2013 and Kampala and Horpibulsuk, 2013) and is illustrated in the following sections.

4.2 Compaction Curves

Figure 4 shows the compaction curves of the clay and the CCR stabilized clay. The *OWC* tends to increase as the CCR content increases up to the CCR fixation point. The reduction in maximum dry unit weight is associated with the increase in *OWC*. The reduction in the maximum dry unit weight could be due to the lower specific gravity of CCR and an immediate formation of cementitious products, which reduce the compatibility (Lees et al., 1982). The compaction characteristics (*OWC*, $\gamma_{d,\max}$) are practically constant when the CCR content is higher than the CCR fixation point.

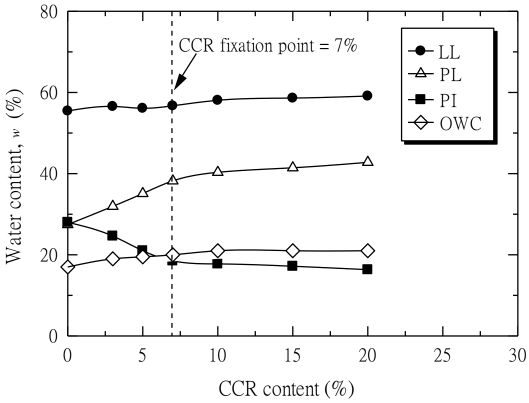


Figure 3 Fixation point (Kampala and Horpibulsuk, 2013).

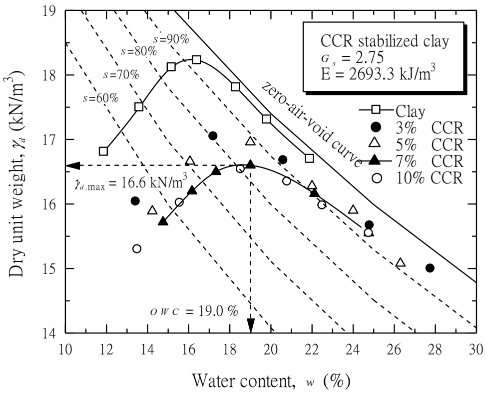


Figure 4 Compaction curves of CCR stabilized clay (Kampala and Horpibulsuk, 2013).

4.3 Compressive Strength

Previous research (Kampala and Horpibulsuk, 2013) shows that samples compacted at OWC possesses the highest strength compared to samples compacted on dry and wet sides of optimum. The strength development with the CCR contents of the stabilized clay at the *OWC* (maximum dry unit weight) under unsoaked and soaked conditions is shown in Figure 5. The stabilizer contents were designed to be the same for both conditions. The compaction enhances the interparticle forces (effective stress). Consequently, the unsoaked strength of the compacted clay (without CCR) is very high with the compressive strength of 824 kPa. However, the water absorption induces the swell pressure (reduces the effective stress). The soaked strength becomes null after soaking for few minutes. This significant strength reduction causes severe damages of earth structures and pavements in the northeast Thailand during periods of high rainfall. This undesirable characteristic can be improved by the CCR as shown by the high soaked strength of the CCR stabilized clay. The strength improvement of the stabilized clay under soaked and unsoaked conditions is classified into three zones (*vide* Figure 5). As the CCR content increases, the strength significantly increases. This zone is designated as the active zone. Beyond this zone, the strength development slows down. The incremental gradient becomes nearly zero and does not make any further significant improvement. This zone is referred to as the inert zone (CCR content = 7-12%). The strength decrease appears when the CCR content is higher than 12%. This zone is identified as the deterioration zone. Even though the same pattern of strength development is found for both unsoaked and soaked conditions, the unsoaked strength is higher. It is interesting that the optimal CCR content providing the highest unsoaked and soaked strengths is 7%, which is the CCR fixation point. The soaked strength of the hydrated lime stabilized clay is also presented in the figure. For all the stabilizer contents, the soaked strengths of the CCR stabilized clay are higher than those of the lime stabilized clay. Kumpala and Horpibulsuk (2012) postulated that the higher strength of CCR stabilized clay is possibly because the CCR contains more pozzolanic materials (SiO_2, $Al_2O_3$and Fe_2O_3) of about 12.3%.

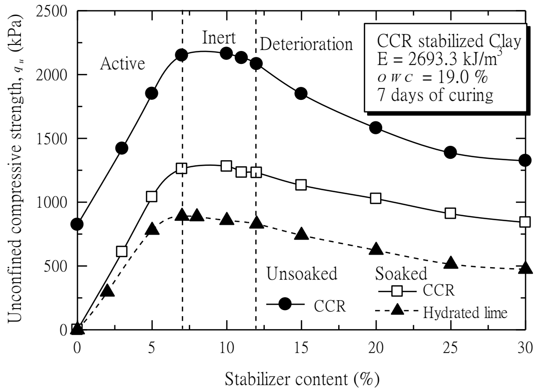


Figure 5 Strength versus stabilizer content relationship (Kampala and Horpibulsuk, 2013).

4.4 Vertical Swell

Figure 6 shows the vertical swell versus the CCR content relationship of the CCR stabilized clay at 7 days of curing. The vertical swell of the compacted clay (without CCR) strongly depends on the state of water content. The vertical swell of compacted clay is about 6% at the optimum water content (maximum dry unit weight). The soil stabilization by CCR greatly reduces the vertical swell due to the increase of the cementation bonding among the clay particles. For all water contents, the vertical swell decreases as the CCR content increases. The CCR stabilized samples on the dry side of optimum exhibit highest vertical swell and those compacted at *OWC* yields the lowest vertical swell. This characteristic is the same as that of the compacted clay but the CCR stabilized clay possesses much lower vertical swell. The optimal CCR content for improving the swell behavior ranges from 5 to 10%. The effect of the state of water content is significant when the CCR content is less than 5%. The vertical swell is less than 1% and insignificantly changed with the CCR content when the CCR content is higher than the fixation point.

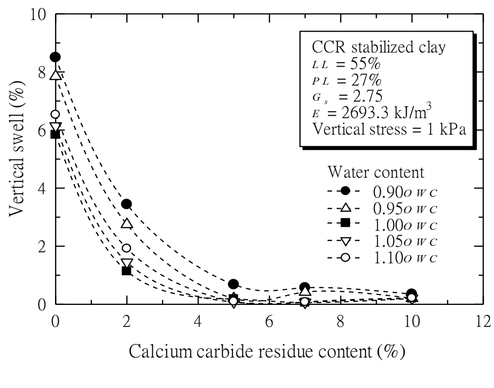


Figure 6 Vertical swell of the CCR stabilized clay at different water contents (Kampala and Horpibulsuk, 2013).

4.5 Durability

The water absorption induces the repulsive forces among clay particles (Kumpala and Horpibulsuk, 2012) and causes the expansion of the diffuse double layer (Herrin and Mitchell, 1961). The drying process makes the CCR stabilized samples to shrink due to the reduction of the pore volumes and causes tension and surface cracks on the samples (Tang et al., 2011). The repulsive forces and the tension and surface cracks upon the wetting and drying cycles reduce the strength of the CCR-FA stabilized clay.

Figure 7 shows the influence of w-d cycles on the unconfined compressive strengths of the 5%, 7%, and 12% CCR samples cured for 7, 14 and 28 days, represented active, inert and deterioration zones, respectively. For all the CCR contents, the compressive strength of the CCR stabilized samples without w-d cycle increases with increasing CCR content and curing time. The strength of 7% and 12% CCR samples are essentially the same because the CCR contents are in the inert zone where the natural pozzolanic reaction in the clay is not sufficient to react with $Ca(OH)_2$ in the CCR. Compared with the recommended strengths by the ACI and the U.S. Army Corps of Engineers, the CCR stabilized clay without w-d cycles passes the recommendation. Both institutes recommend the 7-day and 28-day strengths not lower than 1723 and 2068 kPa, respectively. However, the strengths reduce significantly with number of cycles. All samples cured for 7 days cannot pass the recommendation after being subjected to only 1st cycle. The same is found for the 5% CCR sample cured for 28 days. The 7 and 12% CCR samples cured for 28 days can resist up to the 2nd w-d cycle. In other words, the service life of this material is short and its durability against w-d cycles must be improved. The 7-day criterion is more critical than the 28-day one because the rate of strength development with time of this material is relatively high and close to that of the cement stabilized clay (Horpibulsuk et al., 2013).

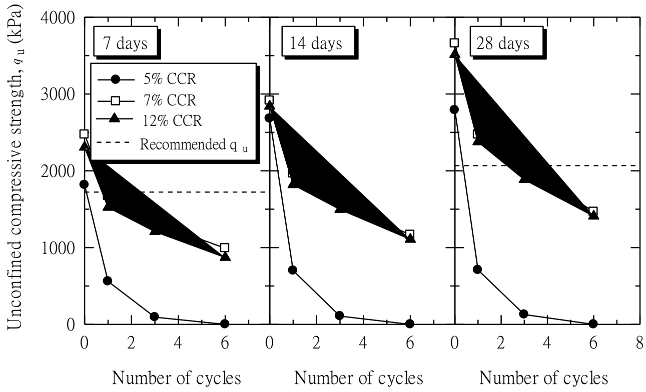


Figure 7 durability of CCR stabilized clay (Kampala et al., 2013).

Horpibulsuk et al. (2103) suggested a method to further enhance the strength of the CCR stabilized clay is to input the pozzolanic materials such as fly ash (FA) and biomass ash in the inert zone. 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. Figures 8 and 9 show the strength development in the CCR-FA stabilized samples compacted at *OWC* under 1, 3, and 6 w-d cycles for various FA contents. The advantage of the input FA is evident; the w-d cycle strengths increase remarkably with the increase in FA content for all curing times tested. Compared with the unsoaked strength (prior to the cyclic wetting-drying test), the highest strengths for different w-d cycles are at the same FA content (about 20%) and the strength development pattern is similar. This result indicates that the w-d cycle strength is dependent upon the unsoaked strength. It is also noted that for the same input of FA, the 12% CCR samples show slightly higher strength than the 7% CCR samples. In other words, the CCR fixation point is the most appropriate content for strength and durability improvement with FA.

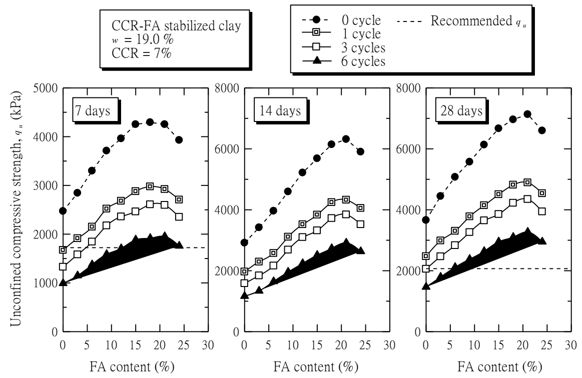


Figure 8 Influence of fly ash on durability in inert zone (Kampala et al., 2014).

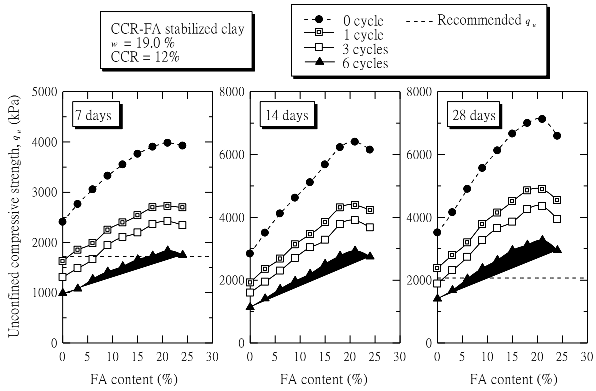


Figure 9 Influence of fly ash on durability in deterioration zone (Kampala et al., 2014).

The input FA enhances not only the strength development but also the durability against w-d cycles. It is logical to relate the durability to the strength because they are mainly governed by the pozzolanic reaction. It is of interest to note that the strength at any number of w-d cycle is directly related to the unsoaked strength, irrespective of the CCR and FA contents. Consequently, it is possible to develop a relationship between generalized strength and number of w-d cycles, *c* (*vide* Figure 10) in the following form:

$$\frac{q_{u(w-d)}}{q_{u(unsoaked)}} = 0.73 - 0.05c \qquad \text{for } 1 \le c \le 6 \tag{2}$$

The relationship between the generalized strength and number of w-d cycles might not be linear. However, the linear relationship exists for the number of w-d cycles between 1 and 6. The number of wet-dry cycles may be different according to the type of road or type of soil, as 1 to 12 cycles for soil cement stabilized base course (PCA, 1992 and Davidson, 1961) or 1 to 4 cycles for silty or clay (expansion or collapsible) (Tripathy, 2009; Soni and Jain, 2008; Rao et al., 2001 and Rao and Revanasiddappa, 2006). For this study, the 6 w-d cycles are considered as sufficient because the 6 w-d cycled strengths of some CCR stabilized samples are lower than and of some samples are very close to the recommended values (ACI, 1990; and U.S. Army Corps of Engineers, 2004). This relationship can be used for quick approximation of the w-d cycle strength of the stabilized clay to ascertain the serviceability of the pavement material. The development of this relationship is on sound principle. More test data of different stabilized soils (coarse and fine-grained) are required for the future researches to develop a generalized relationship. Based on the equation, the required $q_{u(unsoaked)}$ values are 4006 and 4809 kPa for 7 and 28 days of curing to pass the recommendations by the ACI and US Army Corps of Engineers at the sixth w-d cycle.

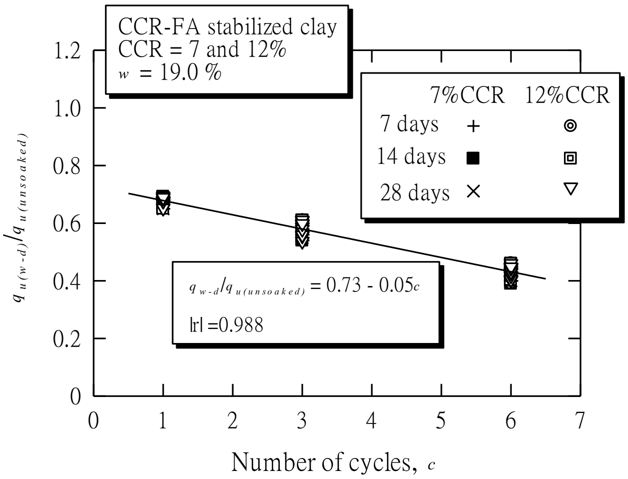


Figure 10. Relationship between the normalized strength and number of cycles (Kampala et al., 2014).

4. CONCLUSIONS

Research on the engineering properties of clay stabilized with CCR, a sustainable cementing agent, has been reviewed and is presented in this paper. The engineering properties reported are compaction curves, unconfined compressive strength, swelling and durability. 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.

2) Soil improvement with CCR can be classified into three zones: active, inert and deterioration. The CCR fixation point, which is simply obtained from the laboratory test can be used to identify the active zone. The CCR fixation point indicates the capacity of the clay to absorb Ca^{2+} ions and react with $Ca(OH)_2$.

3) The CCR enhances the chemical bonding among the clay particles. The *OWC* is the suitable mixing state, providing the best engineering properties (highest strength and durability and lowest swelling).

4) In the inert zone, the input FA enhances strength. 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.

5) The strength test results show that the durability against wetting and drying cycles for all curing times tested is strongly dependent upon the unsoaked strength (prior to the wetting and drying test). It is logical to develop a relationship between the normalized strength and number of cycles. This relationship is useful for a quick determination of strengths under different number of wetting and drying cycles to ascertain the service life of the stabilized material.

5. ACKNOWLEDGEMENTS

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