ROLE OF FLY ASH ON STRENGTH PROPERTIES OF REJUVENATED SOIL CEMENT FOR PAVEMENT MATERIALS

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Abstract

Stabilization with cement is the most commonly used technique for the improvement of soil physical, mechanical, and engineering properties. This research reported on the properties of the rejuvenation for recycled soil cement with incorporation of fly ash (FA). The study showed that the specific gravity of Rejuvenated Soil Cement (RSC) decreased with increasing FA. The free swell ratio and linear shrinkage of RSC were significantly decreased with the increase in FA. The maximum dry unit weight of RSC increased with increasing FA up to the optimum FA content of 20 - 25 %. The optimum water content in compaction was relatively constant with the increase in FA. Particularly, the strength improvement in active zone of FA-RSC was influenced by several factors viz., compaction, packing, rehydration, and pozzolanic reaction. As a result, the unconfined compressive strength (UCS) of RSC increased with increase in FA and curing time. This research clearly showed that the rejuvenation of soil-cement with FA as additive was successful. It was also shown that the normalized UCSs of RSC at various curing times could be used to predict the UCSs at 7 and 28 days.

Keywords:

Rejuvenated soil cement;
Pozzolanic reaction;
Rehydration effect;
Unconfined compressive strength;
Secant modulus of elasticity.

1 Introduction

Soil stabilized by cement known as "soil-cement" is the most widely used technique for soil improvement to increase the strength. Portland cement, lime mixed with fly ash (FA), and other pozzolanic materials are the commonly used ones. The techniques for soil cement stabilization are classified into two types viz., deep mixing, and shallow mixing [1]. The deep mixing improvement is done by using a blade or pressure and thus suitable for soft clay. The moisture content of soil is normally equal to or higher than the moisture of its liquid limit state. Whilst the shallow mixing is applicable for road works at shallow depth. The method of mixing is done with low moisture and the resulting soil mass typically contains air cavities. The shallow mixing of cement and soil generates the soil cement granules. The compaction moisture content is usually equal to or at 1.10 times of the optimum water content (OWC) [2].

The soil cement (SC) strength is improved by the hydration reaction. When water comes into contacted with cement; the cement mixture starts to hydrate and form several hydration products

including C-A-H (Calcium Aluminate Hydrate), C-S-H (Calcium Silicate Hydrate), and Ca(OH)_2 (Calcium Hydroxide) embedded in the soil matrix [3]. In this regard, the cement particle hydrates and creates the hardening skeleton matrix surrounding the soil particles. The hydration reaction increases the pH value due to Ca(OH)_2 dissolution and this enables the reaction with available SiO_2 (Silica) and Al_2O_3 (Alumina). In addition, silica and alumina from soil can slowly react with free lime ions and gain strength with curing time. This process is called pozzolanic reaction [4]. For shallow mixing, the compacted soil layer contains low moisture content thus a high amount of un-hydrated cement is left within the soil mass. Besides, the hydration reaction also generates Ca(OH)_2 which is also left within the soil mass. The presence of Ca(OH)_2 increases the risk of unsoundness, and could lead to excessive expansion and damage to the compacted soil [5].

The damaged soil cement road or pavement could be fixed by using the in-situ rejuvenation. The use of pozzolanic material such as FA in the recycled soil cement with re-compacting is thus a good way for the rejuvenation of soil cement pavement. This process will be called "Rejuvenated Soil Cement (RSC)" thereupon. This process also reduced Ca(OH)_2 and thus reduce the damage from the influence of unsoundness. In terms of concrete materials, several studies proposed a guideline to mitigate the Ca(OH)_2 problem [6] by mixing FA with cement. In this regard, SiO_2 , and Al_2O_3 rich in FA react with Ca(OH)_2 and form C-S-H and C-A-H. In addition, the use of FA could reduce the cement content [7-8], and increase the concrete tolerance to prevent the damage from a sulfate-chloride solution. [9-10]. In geotechnical engineering, the benefits of FA were observed in many studies such as to improve the soil property by mixing with lime and Calcium Carbide Residue [2, 5-6, 11-15], to decrease cement, and to increase soil tolerance against sulfate attack and loss of strength by wetting and drying cycles [16-17].

Based on the previous studies, it is evidenced that FA has been used in many applications, but there was no study on the RSC yet. Many studies presented the increase of the soil strength from the pozzolanic reaction, whereas there are also other factors which exert influence on the properties of soil cement with FA. For example, the effect of hydration reaction is also influenced by the particles, total mass, size distribution, and compaction. As a consequence, this study explored the general properties, mechanical properties, and engineering properties of RSC using FA as additive. The tested parameters included specific gravity (Gs), consistency index, linear shrinkage, swelling, compaction, and UCS. The outcome of this study should be useful in understanding the influence of FA on soil behaviors and basic properties that dominate the engineering characteristics, and the strength improvement of RSC. Especially, in country where the cementitious material, such as cement, is limited and necessarily recycled. Furthermore, it can also provide the fundamental knowledge for the extension to other pozzolans for example the use of rice husk ash for pavement improvement.

2 Materials and methods

2.1 Soil

The soil was a clayey soil from a location in Nakhon Ratchasima province, Thailand. This soil was selected as it was used for fill, subgrade material, and stabilized with cement for subbase materials. It was taken from a depth of 3 meters. The soil contained high silica and alumina contents 61.15 % SiO_2 and 18.076 % Al_2O_3 as shown in Table 1. The Gs, liquid limit, plastic limit, and grain size distribution of soil were tested in accordance with the ASTM standards as summarized in Table 2. The soil had Gs of 2.74, liquid limit of 55 % and plastic limit of 27 %. The grain size of soil is presented in Fig. 1. This soil was a high plasticity clay (CH) as per the unified soil classification system (USCS).

The free swell ratio (FSR) test of soil was done using method adopted by Prakash and Sridharan [18]. The linear shrinkage of soil was tested following ASTM standard, see Table 2. The FSR of 1.76 and linear shrinkage of 12.7 % were obtained from the tests.

Table 1: Chemical components of soil, cement, rejuvenated soil cement, and FA.

Chemical composition	Soil [%]	Cement [%]	Rejuvenated soil cement [%]	Fly ash [%]
SiO ₂	61.15	20.90	50.19	45.69
Al ₂ O ₃	18.07	4.76	15.80	24.59
Fe ₂ O ₃	6.18	3.41	7.21	11.26
CaO	2.55	65.41	14.18	12.15
MgO	5.80	1.25	4.72	2.87
SO ₃	0.05	2.71	0.72	1.57
K ₂ O	4.29	0.35	3.92	0.52
LOI	3.44	0.96	2.85	1.23

Table 2: Testing methods.

Soil grain size (sieve analysis)	ASTM D422-63(2007)e2
Soil grain size (hydrometer)	ASTM D422-63(2007)e2
Gs	ASTM D854-14
Liquid limit and plastic limit	ASTM D4318 - 17e1
Free swell ratio	Prakash and Sridharan [36]
Linear shrinkage	ASTM D423-66 (1972)
Modified proctor compaction	ASTM D1557 - 12e1
Unconfined compressive strength (UCS)	ASTM D1633 - 17

2.2 Cement and fly ash

Portland cement Type 1 was used as it was commonly used for the soil stabilization. FA was from Mae Moh Power Plant, Lampang province, Thailand. The grain size distribution is presented in Fig. 1 while the chemical compositions are shown in Table 1. This FA contained 45.69 % SiO₂, 24.59 % Al₂O₃, 11.26 % Fe₂O₃, and 12.15 % CaO; thus, the FA could be classified as class F as per ASTM C 618. The Gs of cement was 3.14 and that of FA was 2.30.

Fig. 1: Grain size distribution of clay, RSC, and FA.

2.3 Soil cement

A 4 x 10 m soil cement pavement section with 8 % cement content as required for CH by the standard of ACI 230.1R-90 [19] was prepared. The compaction was done at optimum moisture content of 18 % in 2 layers of 0.1 m thick using a reversible compactor to obtain a density of at least 95 % of maximum dry unit weight. After compaction, the compacted pavement was covered with a plastic membrane for 28 days and air-cured for 120 days.

Subsequently, the pavement section was broken, and the recycled soil cement sample was obtained. The sample was then crushed and passed through sieve No. 4. The sample before crushing

and after passing through sieve no. 4 are shown in Fig. 2. The Gs, liquid limit and plastic limit were tested in accordance with ASTM standards. The Gs of 2.74, liquid limit of 50.4 % and plastic limit of 30.4 % were obtained from the tests. Based on the Unified Soil Classification System (USCS), the RSC was classified as high plasticity (MH). The grain size distribution of soil-cement is shown in Fig. 1 and the chemical components of this soil and RSC are shown in Table 1.

Fig. 2: Recycled soil cement sample: a) before crushing, and b) crushed and passed sieve No. 4.

Fig. 3 presents the XRD patterns of soil and soil cement. The main component of soil was silica SiO_2 in a crystal form. After the improvement with 8 % cement, the XRD showed reduced amount of crystal. The important component of cement hydration product, CSH, was found at $28 - 29^\circ$ 2 Theta.

Fig. 3: X-Ray diffraction of soil and RSC.

2.4 UCS test

The UCS test was done in accordance with ASTM D1633-17. This test gives a quick result and is timesaving for the compressive strength estimation. The clay and RSC samples mixed with various FA contents cured for 0, 7, and 28 days as shown in Table 3 were tested. The cylindrical sample of 71 mm in diameter and 142 mm in height was used. The compaction was done with Modified Proctor compaction as per ASTM D1557 - 12e1 at optimum water content 18 %. After the compaction, the sample with mold was wrapped with plastic membrane to prevent loss of moisture. Before testing, the sample was soaked in water for 2 hours so that it was in a saturated state. The displacement rate of 0.16 mm/minute was used for testing. The secant Young's modulus E_{50} was determined from the UCS test.

Table 3: Summary of testing programs.

Test	Sample	Curing time [days]	FA [%]
Particle size	Soil	0	0
	Recycled soil cement	120	0
	FA	0	100
Compaction	Soil	0	0, 5, 10, 15, 20, 25, 30
	Rejuvenated soil cement	0	0, 5, 10, 15, 20, 25, 30
Gs	Soil	0	0, 5, 7, 10, 15, 20, 25, 30
	Rejuvenated soil cement	28	0, 5, 7, 10, 15, 20, 25, 30
Index properties	Soil	0	0, 5, 7, 10, 15, 20, 25, 30
	Rejuvenated soil cement	28	0, 5, 7, 10, 15, 20, 25, 30
Free swell	Soil	0	0, 5, 7, 10, 15, 20, 25, 30
	Rejuvenated soil cement	28	0, 5, 7, 10, 15, 20, 25, 30
Linear shrinkage	Soil	0	0, 5, 7, 10, 15, 20, 25, 30
	Rejuvenated soil cement	28	0, 5, 7, 10, 15, 20, 25, 30
UCS	Rejuvenated soil cement	0, 7, 28	0, 5, 10, 15, 20, 25, 30, 40, 50

3 Results

The results on the change in Gs of soil and RSC with FA after 28 days curing are shown in Fig. 4. The Gs of clay mixed with FA decreased slightly with increasing FA content while the Gs of RSC with FA decreased more significantly. Nevertheless, the reduction in Gs was quite small when the FA content was higher than 25 % by weight of dry soil.

Fig. 4: Influence of FA on Gs of the clay and RSC samples with FA at 28-day curing.

The results of plasticity index of clay and RSC with FA after curing for 28 days curing are shown in Fig. 5. The liquid limits (LL) of clay and RSC were similar 54 - 55 %. The LL of clay was relatively constant. While the plastic limits (PL) of clay and RSC with FA slightly decreased with increase in FA content. The decrease in PL resulted in the increase in plasticity index (PI). Fig. 5 showed that the PI of RSC with FA was lower than that of clay with FA.

Fig. 5: Influence of FA on plasticity index of a) clay, and b) RSC with FA samples at 28-day curing.

Fig. 6 presents the result on the swelling behavior in terms of free swell ratio (FSR) of the clay and RSC stabilized with FA at 28-day curing. The FSR of clay and RSC (without FA) were 1.76 and 1.30 respectively. The FSR of both samples clearly decreased with the increase in FA. The FSR of RSC tended to decline when the FA content decreased. The FSR of clay with FA also decreased with the increase in FA content until FA content was about 15 % and remained constant at 1.10 thereafter. However, the FSR of RSC was significantly lower than that of clay and the FA content of 25 % was appropriate to stabilize the FSR in terms of the swelling.

Fig. 7 shows the results of linear shrinkage of clay and RSC stabilized with FA at 28-day curing. The linear shrinkages of clay and SC (without FA) were 12.7 % and 5.2 %, respectively. The linear shrinkage of the two samples decreased with the increase in FA. It was also shown that the linear shrinkage of RSC was lower than that of clay.

Figs. 8 and 9 describe the dry unit weight and water content relationship under the compaction test by modified compaction test method for clay, SC (without FA), and RSC stabilized with FA. From Fig. 8 the maximum dry unit weight of RSC is slightly higher than that of clay while the optimum moisture contents are similar. When mixing RSC with FA, the maximum dry unit weight of RSC increased with the increase in FA content up to 15 % by weight of dry soil. However, beyond the FA content of 15 %, the maximum dry unit weight of samples was considerably reduced. However, the optimum water content did not change with the increasing of FA content. The influence of FA on maximum dry unit weight and optimum water content of RSC stabilized with FA are shown in Figs. 10 and 11.

Fig. 6: Influence of FA on free swell ratio of clay and RSC with FA tested with remolded samples after 28 days curing.

Fig. 7: Influence of FA on linear shrinkage of clay and RSC with FA at 28-day curing.

Fig. 8: Dry unit weight and water content of clay and RSC with modified compaction.

Fig. 9: Dry unit weight and water content of clay and RSC with FA with modified compaction.

Fig. 10: Maximum dry unit weight of RSC with FA with modified compaction.

Fig. 11: Water content of RSC with FA compacted with modified compaction.

From the results of UCS of RSC stabilized with 0 - 50 % FA by weight of dry soil tested at 7 and 28 days of curing, it was found that the maximum UCS of RSC stabilized with FA increased with the increase in FA. The suitable FA content (at the maximum UCS) of samples after 7 and 28 days curing were 20 % and 25 % as shown in Fig. 12. Therefore, the content of FA with the increase in strength of RSC was called “active zone”, whereas “deterioration zone” was the zone for the strength decline.

Fig. 12: Relationship between UCS and FA content of RSC after 7 days and 28 days of curing.

4 Analysis and discussion

The effect of rehydration and pozzolanic reaction between FA and free lime significantly influenced the Gs, index properties and swelling properties of soil treated by FA see Fig. 4 – Fig. 7 which were clearly observed by the difference of the results from samples with and without curing.

The decrease in Gs with increasing FA content as shown in Fig. 4 was affected by the increase of void ratio of RSC. The decrease in Gs of RSC stabilized with FA was due to the low Gs of FA 2.30 compared with that of clay 2.74 and the associated expansion as the result of rehydration of RSC and pozzolanic reaction between FA and free lime [20].

From the compaction graph, the maximum dry unit weight of RSC was higher than that of natural clay with the same optimum water content, Fig. 8. The presence of cement and free lime in RSC resulted in the Ca^{2+} absorption onto the surface of particles and led to a reduction in the soil particles attractive force and created edge-to-face arrangement [21-22].

From Figs. 9 and 10, the use of FA resulted in increased RSC maximum dry unit weight initially. Further increase in the FA content resulted in a suitable FA content with maximum dry unit weight whereby the soil particles in RSC were assembled together coinciding with forming a larger lump and notably increasing the plasticity index, Fig. 5, which therefore reduced the swelling and shrinkage, Figs. 6 and 7.

The same optimum water content of RSC was observed with increasing FA content. This mechanism was associated with a low plasticity of clay. The test results were in line with the previously reported work on the silty clay mixed with cement [23]. Since the liquid limit controlled the OWC of the low plasticity of clay [24], therefore, the optimum water contents of RSC stabilized with FA were similar, Fig. 11.

The USC of RSC stabilized with FA increased with the increase in FA and curing period, Fig. 12. This was the result from the influences of several components viz., compaction effect, filling effect of FA in voids amongst the soil grains, rehydration effect of un-hydrated cement due to shallow mixing with very low water to soil-cement ratio, and pozzolanic reaction. The results of USC test of RSC stabilized with FA are presented in Fig. 13. The pozzolanic reaction and rehydration reaction were the key factors for the strength improvement of RSC stabilized with FA resulting in the increasing of compressive strength with curing. The others were the compaction effect (the soil particle arrangement by compaction) and packing effect from FA small particles. Similar finding was reported by Kampala et al. [9].

The role of FA on strength development of RSC stabilized with FA could be described by SEM (Scanning Electron Microscope) photos as illustrated in Figs. 14a-14d. The result from packing effect was due to filling or packing of the fine FA particles into the void between the soil grain as shown in Fig. 14a. With curing time, the pozzolanic reaction between Ca(OH)_2 and FA increased, and the products were deposited on the surface of FA particles as shown in Figs. 14b-14d. The increase in pozzolanic reaction with curing time was also reported by Horpibulsuk [2] and Massazza [25].

Fig. 13: Influences on unconfined compressive strength of RSC stabilized with FA.

Fig. 15 illustrates the compressive strength improvement of clay and RSC stabilized with FA. The natural clay with FA alone did not show any strength suggesting that the compaction effect and packing effect alone was not sufficient in stabilizing natural soil. The soil sample collapsed with no strength after being soaked in water for only a few minutes. While the UCS of RSC stabilized with FA in active zone 0 - 25 % were considerable and increased with the increase in FA content and curing time which indicated the rehydration effect and pozzolanic effect. The FA content over 25 % (30 - 50 %) resulted in deterioration zone and thus was not taken into account. Presenting this result with curing time in a semi-logarithm scale, the relationship of strength and curing time showed a linear relationship as shown in Fig. 16.

In general, the compressive strength of pavement should be tested at 7 and 28 days of curing. The curing period for the designed strength for sub-base layer of soil cement according to ACI230.1R-90 [19] the compressive strength at 7 and 28 days which are 1724 kPa and 2068 kPa respectively.

When the compressive strength at any curing period was normalized against the compressive strength at 7 and 28 days of curing, the relationship of compressive strength and curing period plotted in a semi-logarithm scale was linear as shown in Fig. 16. This established relationship could then be

used to estimate the compressive strengths at 7 and 28 days of curing. From the tests, Eq. (1) and (2) for the compressive strengths at 7 days and 28 days of curing were established as follows:

Equation (1) is for the compressive strength estimation at 7 days of curing.

$$\frac{q_D}{q_7} = 0.0615 + 1.127 \log(D), \quad (1)$$

where $D = 1 - 7$ days of curing.

Equation (2) is for the compressive strength estimation at 28 days of curing.

$$\frac{q_D}{q_{28}} = 0.0355 + 0.649 \log(D), \quad (2)$$

where $D = 1 - 14$ days of curing.

Fig. 14: SEM photos of 25 % FA stabilized RSC at: a) 1 day, b) 7 days, c) 14 days, and d) 28 days of curing.

Fig. 15: Soaked strength of clay and RSC with FA.

Fig. 16: Development of strength with time of FA stabilized RSC and normalization.

Generally, this relationship could be used to estimate the compressive strength of clay with lime and FA at 28 days of curing from the compressive strength test result at 7 days [14] and estimate the strength of silty clay with calcium carbide residue and FA at 28 days curing [15]. The result of compressive strength test at 7 and 28 days curing and the strength calculated from Eq. (1) and (2) were comparable and presented in Fig. 17. This confirmed that the equations gained from the compressive strength tests at 7 days and 28 days of curing could be used for the pavement work design. The knowledge obtained from the results of compressive stress and axial strain which is the relationship of modulus of elasticity, E_{50} and unconfined compressive strength q_u of FA stabilized RSC at 7 and 28 days curing time could also be established as illustrated in Fig. 18. This could also be used to estimate the elastic of deformation on pavement structure or embankment in soil rejuvenated pavement application.

Fig. 17: Measured and predicted soaked strengths at 28 days curing.

Fig. 18: Relationship between secant modulus of elasticity, E_{50} and UCS, q_u of FA stabilized RSC at 7 and 28 days curing.

5 Conclusions

Based on the study on the influences of FA on basic and strength properties of the RSC with FA, the findings could be summarized as follows:

- 1) The decrease of Gs of RSC is due to the low Gs of FA 2.30 compared to that of clay 2.74, and the expansion due to rehydration and pozzolanic reaction between FA and free lime.
- 2) The liquid limit indices of clay and RSC are similar (approximately 54 - 55 %) and the liquid limit of clay is relatively constant and does not change with FA content. Whereas the plastic limit of clay and RSC stabilized with FA slightly decreased with the increase in FA. Consequently, the decrease in PL resulted in the increase in plasticity index (PI) of both samples. In most cases, the PI of RSC mixed with FA was lower than that of clay with FA.
- 3) The free swell ratio (FSR) and linear shrinkage of clay and SC (without FA) were 1.76 and 1.30 respectively. Whereas the linear shrinkage of clay and RSC (with FA) were 12.7 % and 5.2 % respectively. Thus, the FSR and linear shrinkage of RSC were significantly lower than those of clay. Additionally, the FSR and linear shrinkage of both samples tended to decrease by the increasing FA content.
- 4) The maximum dry unit weight of RSC was slightly higher than that of clay while the optimum moisture contents of both were similar. When mixing RSC with FA, the maximum dry unit weight of RSC increased with the increasing FA up to 15 %. After that, the maximum dry unit weight decreased with the increase in FA. However, the optimum water content is quite stable and does not change with the increasing FA.
- 5) The strength improvement of FA stabilized RSC was influenced by four mechanisms viz., compaction effect, packing effect, rehydration effect, and pozzolanic reaction effect.
- 6) The compressive strength of RSC stabilization with FA increased with increase in FA up to 25 %. The relation between compressive strength and curing time is linear when plotted in a semi-logarithm form. When the compressive strength at any curing period is normalized against the compressive strengths at 7 and 28 days of curing, the relationship became linear. This established relationship can be used to estimate the compressive strengths at 7 days and 28 days of any curing period.
- 7) The relationship between secant modulus of elasticity, E_{50} and UCS of FA stabilized RSC at 7 days and 28 days curing time can also be established. This established relationship can also be used to estimate the modulus of elasticity on pavement structure or embankment in soil recycled pavement application.

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