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Stabilization of Recycled Concrete Aggregate Using High Calcium Fly Ash Geopolymer as Pavement Base Material

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Abstract: This research investigated high calcium fly ash geopolymer stabilized recycled concrete aggregate (RCA-FAG) as pavement base material. The effect of recycled concrete aggregate (RCA):high calcium fly ash (FA) ratios, sodium silicate (Na_2SiO_3):sodium hydroxide (NaOH) ratio, and curing time on the unconfined compressive strength (UCS) and scanning electron microscope (SEM) properties of RCA-FAG samples were evaluated. The maximum dry unit weight of the RCA-FAG sample was 20.73 kN/m^3 at RCA:FA ratio of 80:20 and Na_2SiO_3:NaOH ratio of 60:40. The 7-d UCS of RCA-FAG samples increased as the FA content and Na_2SiO_3:NaOH ratio increased. The 7-d UCS of the RCA-FAG sample was better than that of the RCA with no FA because FA particles filled in RCA particles, resulting in a dense matrix. The 7-d UCS of RCA-FAG samples passed the 7-d UCS requirement for the low-traffic road. All ingredients met the 7-d UCS requirement for the high-traffic road except the sample with RCA:FA of 100:0 and Na_2SiO_3:NaOH of 50:50 and 60:40. The 7-d SEM images indicated that spherical FA and RCA particles are bonded together, resulting in the dense matrix for all Na_2SiO_3:NaOH ratios. The proposed equation for predicting the UCS of RCA-FAG offered a good coefficient of correlation, which is useful in designing pavement base material from RCA-FAG material.

Keywords: infrastructure construction; recycled concrete aggregate; high calcium fly ash; geopolymer

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1. Introduction

Infrastructure construction tends to increase due to population growth, migration, and urbanization, which leads to growing economies and developing countries. Pavement structure (including a surface course), binder course, base course, subbase, and subgrade, is one of the transportation infrastructures that has used a massive number of natural resources and generated a large quantity of construction and demolition (C&D) materials [1,2]. Every year, 30 billion tons of C&D materials are generated worldwide [3]. The United States [4], Australia [5], China [6], and Thailand [7] produced C&D materials of 584, 19.6, 1130, and 1.1 million tons, respectively. Several researchers have explored the use of recycled concrete aggregate (RCA) in pavement construction [8–17]. They reported that RCA needs to be improved by a binder (cement, lime, and fly ash) due to low physical properties (high water absorption and porosity) and engineering properties (low strengths) [11–13]. Nonetheless, cement manufacturing emits huge quantities of carbon dioxide (CO_2) into the atmosphere [18–21].

The alternative binder material, geopolymer, has lower CO_2 emissions than cement [22,23]. For example, Tabyang et al. [15] investigated the CO_2 emissions of municipal solid waste

incineration fly ash (MSWI FA) geopolymer and cement stabilized RCA. The cement stabilized RCA was a 22.60% higher CO_2 emission than MSWI FA geopolymer stabilized RCA. However, the geopolymerization products need a temperature range between 40 °C and 80 °C in order to be promoted [24], resulting in high energy consumption [25,26]. Therefore, several researchers have reported the enhancement of properties of geopolymer material using high calcium, such as calcium carbide residue [27], slag [28], and high calcium fly ash (FA) [29]. Nuaklong et al. [30] reported that the setting time of the FA-based geopolymer sample exhibited a high rate of hardening, resulting from the rapid calcium silicates hydrate (CSH) formation [31]. In addition, high calcium in geopolymer materials created calcium aluminate silicate hydrate (CASH) products, which was a lower porosity than the sodium aluminate silicate hydrate (NASH) products [32]. Yoosuk et al. [23] examined the compressive strength of FA geopolymer mortar. They reported that the maximum compressive strength of FA geopolymer mortar was 20.94 MPa at the Na_2SiO_3:NaOH ratio of 1 and NaOH concentration of 8 M. Recently, Chindaprasirt et al. [33] investigated the effect of different binders (FA, ordinary Portland cement, basalt fiber, and silica fume) on the compressive strength of geopolymer mortar. They concluded that 10% of ordinary Portland cement offered maximum compressive strength.

Several research studies have already been conducted on geopolymer-stabilized RCA. For example, Mohammadinia et al. [8] investigated the unconfined compressive strength of fly ash and cement kiln dust stabilized RCA. The highest UCS of the sample was found at FA:cement kiln dust ratio of 50:50. Arulrajah et al. [9] examined RCA stabilized by calcium carbide residue (CCR) and class F FA geopolymer. The UCS of CCR-FA geopolymer stabilized RCA was higher than that of FA geopolymer stabilized RCA because Ca from FA and RCA was not enough to react with silica [34]. Furthermore, FA-rice husk ash (RHA)geopolymer improved RCA was investigated by Poltue et al. [35]. The higher RHA resulted in a decrease in UCS because high Si gels from RHA hinder water evaporation. The 60RHA:40FA ratio and 50NaOH:50Na_2SiO_3 ratio of FA-RHA geopolymer stabilized RCA provided the optimum ingredient. Based on the strength requirement given by the national road authority of Thailand [36,37], Tabyang et al. [15] reported the optimum liquid content, 90RCA:10MSWI FA ratio, and 60Na_2SiO_3:40NaOH of RCA-MSWI FA geopolymer samples passed the 7-d UCS requirement for the high traffic road.

Although several studies have been undertaken to evaluate the mechanical behavior of class F FA geopolymer stabilized RCA, the mechanical properties of the RCA-high calcium fly ash geopolymer under ambient room temperature have never been investigated. This study evaluated the properties of recycled concrete aggregate using high calcium fly ash geopolymer (RCA-FAG) as pavement base material. The studied influence factors included RCA:FA ratios, Na_2SiO_3:NaOH ratio and curing time. The unconfined compressive strength (UCS) and scanning electron microscope (SEM) tests were used to examine the strength development and microstructure in the RCA-FAG samples. The proposed equation for predicting the UCS of RCA-FAG should be very useful for designing pavement base material.

2. Materials and Methods

2.1. Materials

The RCA was sourced from the Rajamangala University of Technology Isan in Nakhon Ratchasima, Thailand. Based on ASTM C128-15 [38], the specific gravity was 2.61. Figure 1 illustrates the grain size of the RCA based on the Department of highway standard. The RCA had a median grain size of 10 mm and was categorized as well-graded gravel (GW) by the Unified Soil Classification System. The modified Proctor compaction evaluated by ASTM D1557 [39] of RCA yielded the maximum dry unit weight of 19.95 kN/m^3 and the optimal water content of 9.8%.

Fly ash (FA) was collected from the Mae Moh power plant in Thailand. The specific gravity of FA was 2.46. The chemical properties according to ASTM E1621 [40] are indicated in Table 1. The CaO content was 31.41% and SiO_2 + Al_2O_3 + Fe_2O_3 was 63.41%. It was

classified as class C following the standard ASTM C618-19 [41]. The median grain size was 0.02 mm as indicated in Figure 1.

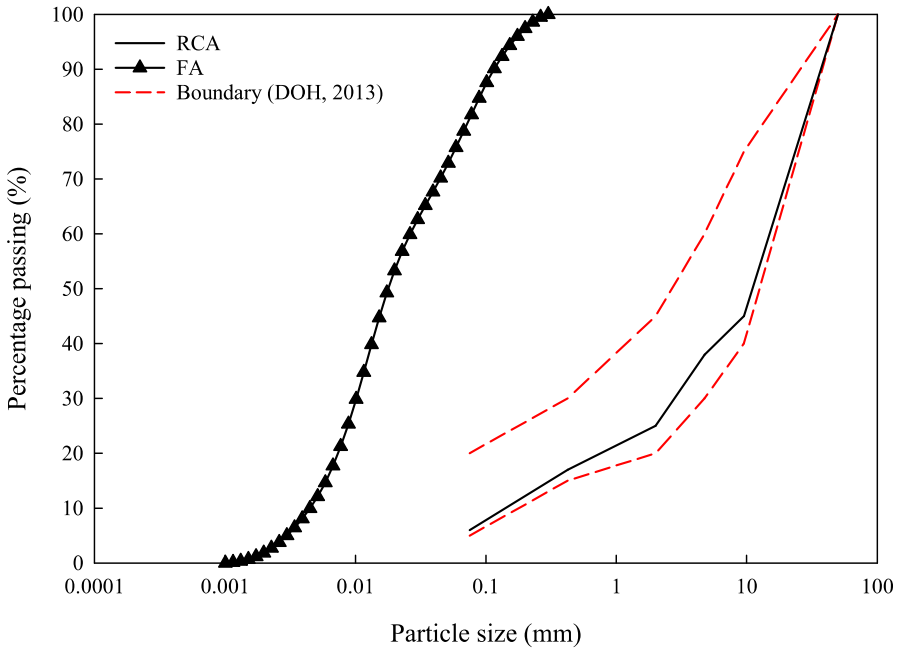

Figure 1. The particle size of RCA and FA.

Table 1. Chemical composition of FA.

Chemical Compositions	FA (%)
SiO_2	45.44
Al_2O_3	10.53
Fe_2O_3	7.44
CaO	31.41
SO_3	2.02
K_2O	2.20
LOI	0.96

Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used as liquid alkaline activators (L). The Na_2SiO_3 with 9% Na_2O and 30% SiO_2 by weight and 98% purity of NaOH were used.

2.2. Sample Preparation and Testing

RCA, FA, and L (Na_2SiO_3 and NaOH) were used to prepare RCA-FAG samples. In this study, the ratios of RCA:FA were 100:0, 90:10, 80:20, and 70:30, while the ratios of Na_2SiO_3:NaOH were 80:20, 60:40, 70:30, and 50:50. The NaOH concentration of 8 molars was fixed. Mix proportions of RCA-FAG samples are shown in Table 2.

Table 2. Mix proportions of RCA-FAG samples.

Item	Compaction Test	UCS Test
RCA:FA	100:0, 90:10, 80:20, 70:30	100:0, 90:10, 80:20, 70:30
L content (% by weight of total)	Between 5–14	Optimum liquid content
Na_2SiO_3:NaOH ratios	80:20, 60:40, 70:30, 50:50	80:20, 60:40, 70:30, 50:50
NaOH concentration (molars)	8	8
Curing time (days)	-	7, 14, 28, 60

RCA and FA were mixed for 5 min in order to prepare a sample for this investigation. Following the addition of L, the sample was mixed for 10 min to guarantee its homogeneity. Modified Proctor compaction was used to compact the RCA-FAG samples. Different L contents were used to establish the optimal liquid content (OLC) for each RCA:FA ratio. After acquiring the OLC, the specimens were made with a diameter of 101.6 mm and a height of 116.4 mm. The samples were then plastic-wrapped. After 7, 14, 28, and 60 days of curing at room temperature (27–30 °C), the unconfined compressive strength (UCS) according to ASTM D4318-00 [42] of samples was measured by using a universal testing machine (UTM). Small RCA-FAG samples were collected from the center and their scanning electron microscope (SEM) analysis was assessed [43,44].

3. Results and Discussion

3.1. Compaction of RCA-FAG

Figure 2 indicates the relationship between FA content and maximum dry unit weight of RCA-FAG samples at different RCA:FA and Na_2SiO_3:NaOH ratios. The optimum liquid content of RCA-FAG samples was 8.46–11.75% for all RCA:FA and Na_2SiO_3:NaOH ratios. Poltue et al., 2019 [35] reported a similar result when investigating compaction curves of FA geopolymer stabilized RCA. The RCA-FAG sample had the maximum dry unit weight of 20.73 kN/m^3 at an RCA:FA ratio of 80:20 and Na_2SiO_3:NaOH ratio of 60:40. In contrast, the minimum dry unit weight of an RCA-FAG sample was an RCA:FA ratio of 100:0 and Na_2SiO_3:NaOH ratio of 70:30, which was 19.26 kN/m^3. When the FA content increased, the maximum dry unit weight increased. For example, maximum dry unit weight values of RCA-FAG samples with Na_2SiO_3:NaOH ratio of 60:40 were 19.58, 20.43, 20.73, and 20.35 kN/m^3 for RCA:FA ratios of 100:0, 90:10, 80:20, and 70:30, respectively. For FA contents more than 20%, the maximum dry unit weight of RCA-FAG samples dropped due to FA's lower specific gravity [18,19].

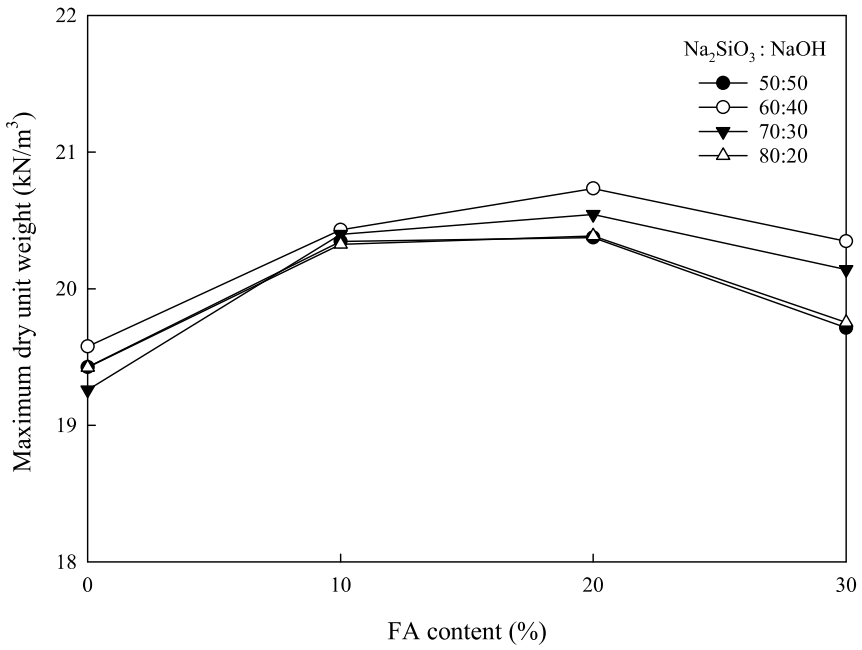

Figure 2. The relationship between FA content and maximum dry unit weight of RCA-FAG samples.

3.2. Unconfined Compressive Strength of RCA-FAG

Figure 3 indicates the 7-d UCS of RCA-FAG samples at different RCA:FA and Na_2SiO_3:NaOH ratios. The 7-d UCS of RCA-FAG samples increased as FA content increased. For example, the 7-d UCS of RCA-FAG samples at Na_2SiO_3:NaOH ratio of 70:30 were 2.50, 9.55, 11.92, and 15.37 MPa for FA content of 0, 10, 20, and 30, respectively. This is because silica and alumina from FA can react with calcium, which results in pozzolan

and geopolymerization products [33]. The 7-d UCS of the RCA-FAG sample was better than that of the RCA with no FA because FA particles filled in RCA particles, resulting in a dense matrix [15].

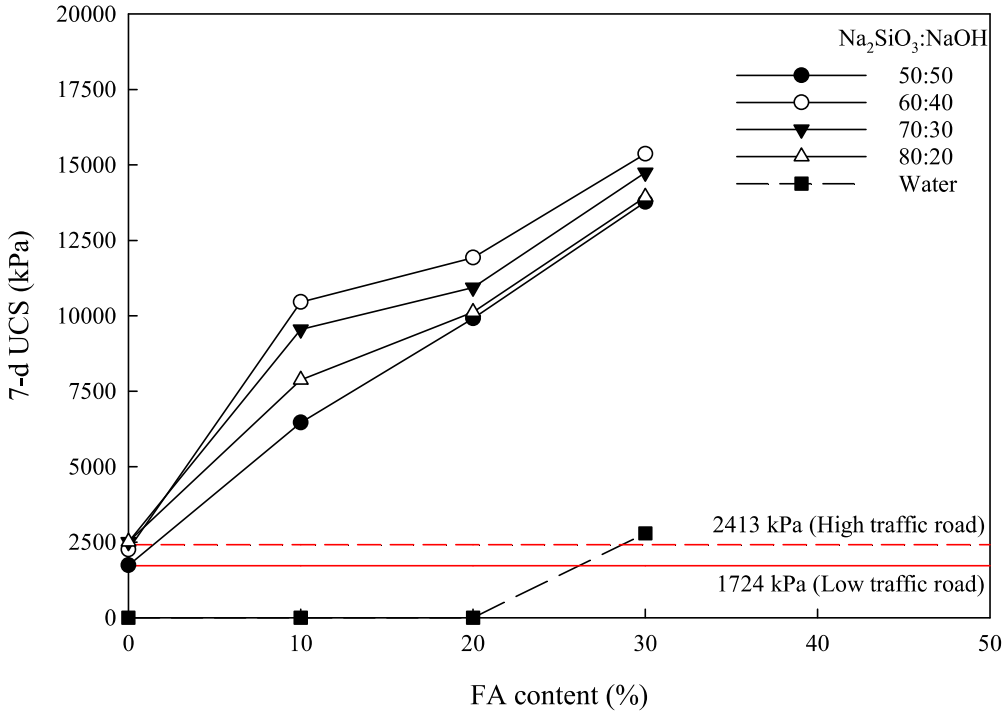

Figure 3. The 7-d UCS of RCA-FAG samples.

The effect of the Na_2SiO_3:NaOH ratio on 7-d UCS of RCA-FAG samples is shown in Figure 3. The 7-d UCS of RCA-FAG samples increased with the Na_2SiO_3:NaOH ratio because calcium silicate hydrate (CSH) and sodium aluminosilicate gels [8,26] resulted from a silicate reaction with calcium from FA and RCA. Until the Na_2SiO_3:NaOH ratio was 60:40, the 7-d UCS of RCA-FAG samples decreased as the Na_2SiO_3:NaOH ratio increased. A similar result was reported by Tabyang et al. [15], who concluded that the addition of Na_2SiO_3 caused UCS reduction because the packing effect resulted from the high viscosity of Na_2SiO_3. The RCA:FA ratio of 70:30 and Na_2SiO_3:NaOH ratio of 70:30 of RCA-FAG sample exhibited the maximum 7-d UCS of 15.37 MPa.

Figure 3 indicates red lines as the 7-d UCS requirement for specified low traffic and high traffic roads of pavement base material [36,37]. The 7-d UCS of RCA-FAG samples passed the 7-d UCS requirement for the low-traffic road. For the high-traffic road, all ingredients met the 7-d UCS requirement except the sample with RCA:FA of 100:0 and Na_2SiO_3:NaOH of 50:50 and 60:40.

3.3. UCS Development in RCA-FAG

Figure 4 indicates the UCS development in RCA-FAG samples at different RCA:FA ratios and Na_2SiO_3:NaOH ratios. For RCA-FAG samples, the UCS increased with an increase in curing time. For example, the UCS of RCA-FAG samples with RCA:FA ratios of 70:30 and Na_2SiO_3:NaOH ratios of 60:40 were 15.37, 20.32, 22.41, and 23.91 MPa for curing times of 7, 14, 28, and 60 days, respectively. The increased UCS because the coexistence of calcium silicate hydrate (CSH) and geopolymerization products resulted from NaOH continually leached silica and alumina from FA [15]. On the other hand, for samples with no FA, the UCS of the sample was slightly increased with an increase in curing time due to insufficient silica and alumina from FA for geopolymerization reaction [34].

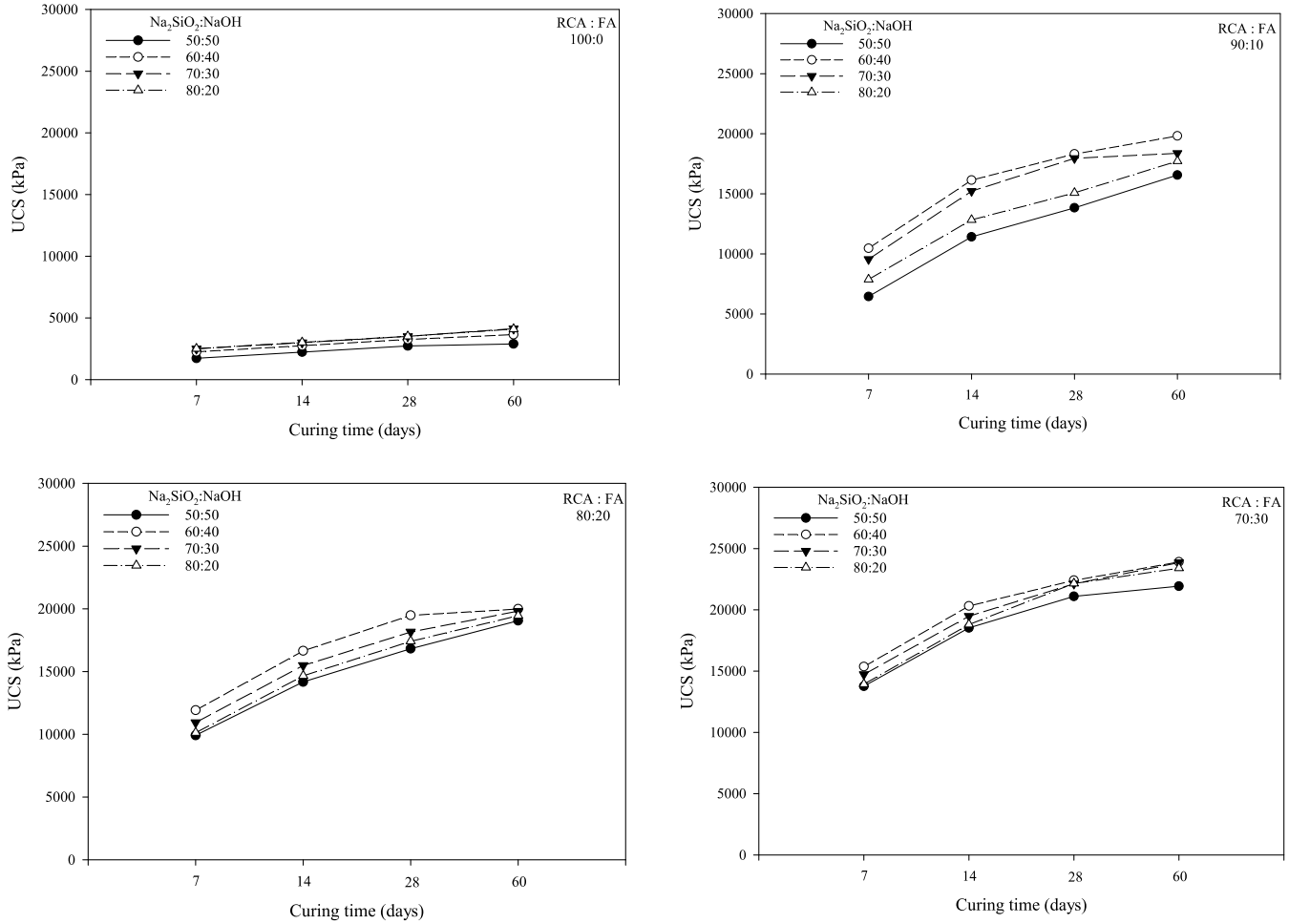

Figure 4. The UCS development in RCA-FAG samples.

Figure 5 shows the relationship between UCS/28-d UCS and the curing time of RCA-FAG samples. It can be seen that the UCS development in RCA-FAG samples can be normalized by 28-d UCS. The correlation of normalized UCS/28-d UCS of RCA-FAG samples at different RCA:FA ratios and Na_2SiO_3:NaOH ratios was expressed by a logarithmic function as follows:

$$\text{UCS/28-d UCS} = 0.219 + \ln(d)0.237 \qquad \text{for } 7 < d < 60 \text{ days} \tag{1}$$

with a coefficient of correlation of 0.89. The proposed equation is useful for predicting the UCS of RCA-FAG samples when 28-d UCS is known.

3.4. SEM Images of RCA-FAG

Figure 6 illustrates 7-d SEM images of RCA-FAG samples at RCA:FA = 80:20 and Na_2SiO_3:NaOH = 50:50, 60:40, 70:30, and 80:20. It can be observed that spherical FA and RCA particles are bonded together, resulting in the dense matrix for all Na_2SiO_3:NaOH ratios. At optimum Na_2SiO_3:NaOH of 60:40, the products with etched holes were found on the FA surface, indicating the complete degree of a chemical reaction [25] and associating with the highest 7-d UCS of 15.37 MPa. For Na_2SiO_3:NaOH of 70:30 and 80:20, the high Na_2SiO_3 content resulted in voids due to the high viscosity of Na_2SiO_3 and some unreacted FA particles were observed, which were 7-d UCS of 14.74 and 13.94 MPa, respectively.

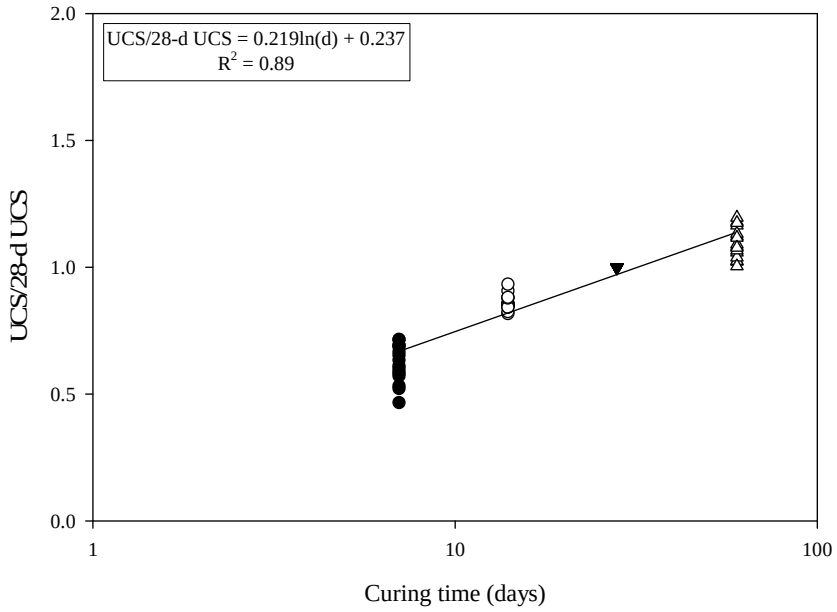

Figure 5. The relationship between UCS/28-d UCS and curing time of RCA-FAG samples.

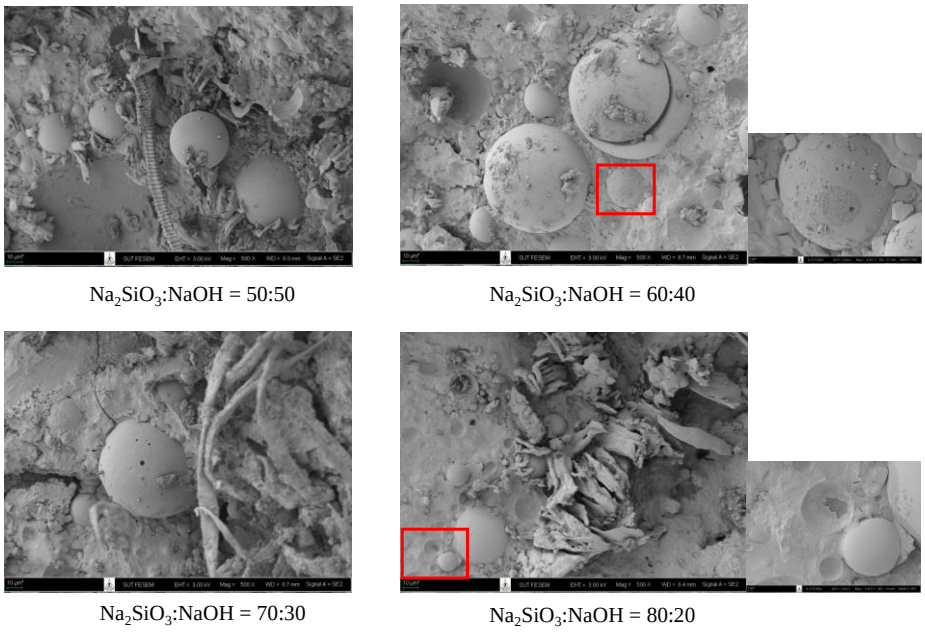

Figure 6. 7-d SEM images of RCA-FAG samples at RCA:FA = 80:20 and Na_2SiO_3:NaOH = 50:50, 60:40, 70:30, and 80:20.

4. Conclusions

The effect of RCA:FA ratios, Na_2SiO_3:NaOH ratio, and curing time on the UCS of RCA-FAG samples can be concluded as follows:

1. The optimum liquid content of RCA-FAG samples was 8.46–11.75% for all RCA:FA and Na_2SiO_3:NaOH ratios. The maximum dry unit weight of the RCA-FAG sample was 20.73 kN/m^3 at RCA:FA ratio of 80:20 and Na_2SiO_3:NaOH ratio of 60:40.

2. The 7-d UCS of RCA-FAG samples increased as FA content raised because FA silica and alumina from FA can react with calcium, resulting in pozzolan and geopolymerization products. The 7-d UCS of RCA-FAG sample was better than that of the RCA with no FA because FA particles filled in RCA particles, resulting in a dense matrix.

3. The 7-d UCS of RCA-FAG samples increased with the Na_2SiO_3:NaOH ratio because calcium silicate hydrate (CSH) and sodium aluminosilicate gels resulted from a silicate reaction with calcium from FA and RCA.

4. The 7-d UCS of RCA-FAG samples passed the 7-d UCS requirement for the low-traffic road. All ingredients met the 7-d UCS requirement for the high-traffic road, except the sample with RCA:FA of 100:0 and Na_2SiO_3:NaOH of 50:50 and 60:40.

5. The UCS of RCA-FAG samples increased as curing time increased because the coexistence of calcium silicate hydrate (CSH) and geopolymerization products resulted from NaOH continually leached silica and alumina from FA. The proposed equation for predicting UCS of RCA-FAG offered a good coefficient of correlation, which is useful in designing pavement base material from RCA-FAG material.

6. The 7-d SEM images indicated that spherical FA and RCA particles are bonded together, resulting in the dense matrix for all Na_2SiO_3:NaOH ratios. Recommendations for further research on the RCA-FAG include the evaluation of flexural strength and indirect tensile strength tests, the effect of water absorption of RCA, and durability against wetting–drying cycles.

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