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Long-Term Mechanical Properties of Alkali-Activated Fly Ash Stabilized RAP for Pavement Base Layers

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Abstract. This research presents an interagency effort to develop cement-less alkali-activated fly ash (AAFA) stabilized reclaimed asphalt pavement (RAP) and virgin aggregate (VA) mixture as a suitable alternative to the conventional base layer in flexible pavements. This study examines the short-term, and long-term mechanical properties of AAFA stabilized RAP:VA mixes cured at ambient room temperature. After the specified curing age, all the specimens were subjected to a series of laboratory tests, including unconfined compressive strength (UCS), resilient modulus (M_r), and durability, to investigate the mechanical properties. The results showed that the alkaline activator ratio, i.e., Na_2SiO_3:NaOH, and curing age played a major role in the final mechanical strength of the mix. The 28 days UCS test results revealed that only 40 % of the ultimate UCS could be achieved with reference to the UCS obtained at 270 days of curing age. The maximum weight loss was observed to be only 4.5 % (at 28 days of curing) and 1.3 % (at 270 days of curing) when the specimens were exposed to aggressive laboratory wetting and drying cycles.

Keywords: Mechanical properties; Reclaimed asphalt pavement; Fly ash; Alkali-activation; UCS; Resilient modulus; Durability

1 Introduction

The utilization of alternative and suitable aggregate in pavement base/subbase applications has been the focus of global research. The main reasons could be preserving natural resources and cutting the overall project cost. Each year, a significant amount of natural virgin aggregates are used in India and worldwide. In many cases, the virgin aggregate material could be replaced with reclaimed pavement materials, secondary aggregate materials, and construction and demolition waste debris generally disposed of in landfills. Reclaimed materials in construction have many advantages, including a reduction in the costs of waste disposal, a reduction in the formation of landfills to prevent groundwater contamination, and finally, avoiding the amount of damage caused to natural resources. In recent times, legislations such as the National Highway Authority of India and Central Road Research Institute have been promulgating in various Indian states that removing the barriers to the productive reuse of reclaimed materials on a large scale lowers the project cost and promotes sustainability. For instance, one material that has been dealt with more often is Reclaimed Asphalt Pavement (RAP) removed from distressed or aged flexible pavements. RAP was considered a more suitable and sustainable alternative to the conventional virgin aggregate as it can be utilized in surface course, base, and subbase layers. Compared to the conventional virgin aggregate, RAP is inferior and less durable. Because of its inferior mechanical properties, RAP often has to be stabilized before it can be used as a base/subbase layer for freshly paved roads. The stabilization may be done by combining it with cement, lime, slag, and fly ash or mixing it with high-quality virgin aggregates to enhance the binding properties. Therefore, in recent times, various researchers have recommended stabilizing the RAP while using it in pavement base/subbase applications [1-6].

Ordinary Portland cement (OPC) would be a great stabilizer; however, the production of one-ton cement would often release about one ton of carbon-di-oxide into the atmosphere [7]. Therefore, given environmental sustainability, cement usage could be minimized by utilizing alternative industrial byproducts above. Over 75 % of the power generated in India comes from burning coal, which creates an ample amount of fly ash as a byproduct and offers yet another environmental concern. The use of fly ash as a fill material for constructing road embankments, dikes, retaining walls, and pavement subgrade have been done in the past [8]. In general, fly ashes have a decent amount of SiO_2, Al_2O_3, and CaO; when combined with a highly alkaline activator that consists of reactive silica (such as sodium silicate solution) could react to form cementitious compounds such as C-A-S-H and N-A-S-H gel products in the system. In high calcium fly ash (such as FA-N) stabilized mixtures, the calcium ions would form the cementitious products prevailing pozzolanic calcium-alumina-silicate-hydrates (C-A-S-H). Whereas in low calcium siliceous fly ash (such as FA-R) stabilized mixtures, the sodium ions would form the sodium-aluminosilicate-hydrate (N-A-S-H) gel [9]. In order to produce the aforementioned cementitious gel matrix, several researchers have used a mixture of sodium hydroxide (with a certain molar concentration) and sodium silicate solution in certain proportions [5,10]. Therefore, fly ash has been utilized to stabilize unconventional pavement base and subbase layers. This study investigates fly ash as a potential binder material instead of stockpiling in a landfill.

Significant work has been put into using alkali-activated fly ash to stabilize the pavement base and subbase layers constructed using RAP and other secondary aggregates. Saride et al. [11] have used fly ash-treated RAP:VA mixtures to verify the feasibility as a pavement base course material. A maximum UCS of 1.6 MPa after 28 days of curing age was observed, and it was lower than the minimum UCS of 4.5 MPa, advised by the IRC:37 2012 [12] for stabilized pavement base layers. Given this, Saride et al. [13] used 20 % and 30 % (by weight) class-C fly ash activated with 0.5 molar NaOH to improve the mechanical properties of the RAP:VA mixture. It was noticed that after 28 days of curing age, the UCS and M_r of the design mixtures were found to be more than 4.5 MPa and 450 MPa, respectively, to qualify as a pavement base course layer as per the IRC:37 2012 [12] standards. Similar observations were made by Hoy et al. [5] when class-C fly ash was stabilized using 50%NaOH:50%Na_2SiO_3 to stabilize 100 % RAP to use as pavement base material. It was noticed that the UCS of the proposed design mix after 28 days of curing at room temperature was 5.9 MPa, which is sufficient as per the Thailand National Road Authorities. According to Sakai et al. [14], when two distinct fly ashes were evaluated, the total reactive phases remained for up to 270 days. Similarly, Avirneni et al. [15] examined the UCS of 0.5M NaOH-activated fly ash stabilized RAP:VA blends cured up to 224 days and found higher UCS and denser matrix than the short-term cured samples.

Based on the current findings, there is a perceived lack of information on the mechanical strength and durability properties of the long-term curing conditions for alkali-activated fly ash stabilized RAP and RAP:VA mixtures. In addition, the maturity age of alkali-activated fly ash is not similar to that of cement, which is 28 days. The formation of cementitious gels, resulting from the pozzolanic activity of fly ash, is assumed to be partially responsible for these mechanisms. Thus, the long-term mechanical properties are essential in understanding the mixture behavior when adopting alkali activation.

2 Materials Mix Design and Test Methods

2.1 Materials

The RAP material was collected from an ongoing National Highway project near Rajahmundry, Andhra Pradesh. The RAP material was oven dried at 70^{o}C for 24 hours, and then sieve analysis was performed. Based on the particle size distribution, the material could be classified as well-graded gravel (GW) as per the USCS classification (Fig. 1). In this present study, fly ashes were collected from two different thermal power plants located in Ramagundam, Telangana, and Neyveli, Tamilnadu in India. The chemical oxide composition of these fly ashes was determined using X-ray fluorescence spectroscopy (XRF) analysis, and the corresponding data is listed in Table 1. As per the ASTM C618 [16], Ramagundam fly ash (labeled as FA-R) was classified as Class-F, where the $SiO_2+Al_2O_3+Fe_2O_3 > 70$ % and Cao < 10 % and the Neyveli fly ash (FA-N) was classified as Class-C, where the $SiO_2+Al_2O_3+Fe_2O_3 >50$ % and Cao > 10%. After that, particle size distribution was carried out using a Microtrac's optical particle analyzer, and it was found that both the fly ashes come under the silty sand (SM) category as per the USCS classification (Fig. 1).

Table 1. FA and RAP oxide composition (% by mass)

Oxide Composition (%)	FA-R	FA-N
SiO_2	53.79	38.18
Al_2O_3	26.82	33.11
Fe_2O_3	5.4	8.4
CaO	5.8	10.54
TiO_2	2.26	2.76
K_2O	2.13	0.29
MgO	1.68	2.3
P_2O_5	0.82	0.33
SO_3	0.66	2.69

In order to activate the fly ashes used in this study, a mixture of NaOH and Na_2SiO_3 solution was used, and it is termed as a liquid alkaline activator. Based on the previous studies by Saride and Jallu [10], the NaOH solution with 0.5 M and 3 M was used to activate the FA-R and FA-N-based RAP:VA mixtures, respectively. Similarly, the sodium silicate (Na_2SiO_3) in the solution form was used, and the chemical oxide composition was found to be 10 % Na_2O, 38 % SiO_2, and 52 % H_2O.

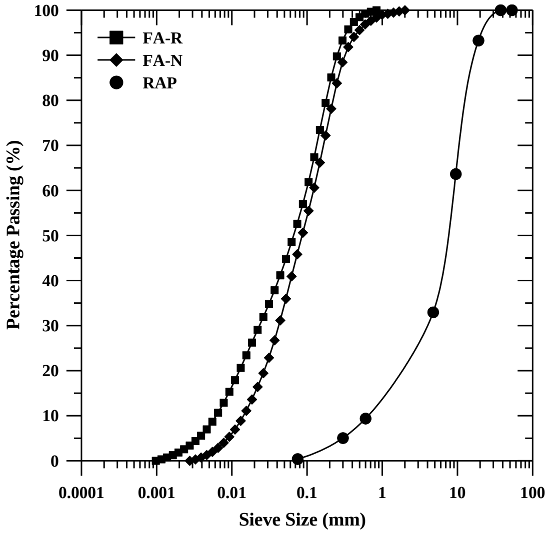

Fig. 1. Sieve analysis of FA-R, FA-N, and RAP

2.2 Mixing, Specimen Casting, and Curing

Initially, the LAA solution was prepared based on the calculated weights of NaOH and Na_2SiO_3 Solution. In this present study, $50Na_2SiO_3$:50NaOH and $70Na_2SiO_3$:30NaOH LAA combinations were prepared to mobilize the FA-R and FA-N based RAP:VA mixtures. Both LAA 50:50 and 70:30 solutions were prepared 24 hours before to attain the uniformity of the solution. Based on the mix maximum dry density (MDD) and optimum moisture content (OMC), the calculated amount of 60RAP:40VA+20FA dried mixtures were taken and thoroughly mixed with LAA solution and prepared 100 mm (diameter) x 200 mm (length) cylindrical specimens to carry out the short-term and long-term UCS, M_r, and durability studies in laboratory conditions. After the specimen casting, all the samples were left in the moulds and demoulded after 24 hours. All the specimens were wrapped using a cling wrap to avoid any moisture loss and placed in a humidity chamber at ambient curing conditions.

2.3 Test Methods

A set of compaction tests were performed on 60RAP:40VA+20FA mixtures in accordance with ASTM D1557 [17]. The optimum moisture content (OMC) of FA-R and FA-N based RAP:VA mixtures were found to be 6.5 %, 6.9 %, and the maximum dry density (MDD) was found to be 22.6 kN/m^3, 21.75 kN/m^3, respectively. Based on the mix OMC and MDD, the UCS specimens were prepared as per the ASTM D 1633 [18]. For this purpose, samples were subjected to modified compaction effort, and the cured specimens were tested using the universal compression testing machine at a strain rate of 1.25 mm/min until the specimen failed. In the same way, 100 mm x 200 mm specimens were made for testing the resilient modulus according to AASHTO T307-99 [19], and then the wrapped specimens were placed under ambient curing conditions until the testing. In order to carry out the M_r testing, a cyclic triaxial test setup procured from Wille

Geotechnik, Germany, was used. In this present study, durability studies were also conducted per ASTM D559 [20]. For this purpose, all the cured samples were subjected to 5 hours of wetting followed by 42 hours of drying and then air drying for one hour. After this, the specimens were tapped using a hammer with a stroke approximately equal to 18 N and then rubbed using a wire brush to remove any loose material in the sample will be removed. The whole procedure of 48 hours consists of one cycle like that 12 cycles were required to determine the final weight loss of the specimen.

3 Results and Discussion

3.1 Unconfined Compressive Strength (UCS) Tests

Fig. 2 details the UCS of 28 days and 270 days cured RAP:VA specimens under ambient curing conditions. In order to activate the 60RAP:40VA mixtures, FA-R, and FA-N based mixtures were activated with LAA 50:50 and LAA 70:30 and cured for 28- and 270-day intervals. It is worth noting that the LAA 50:50-based specimens cured for 28 days had exhibited the highest UCS of 6.5 MPa, which is 5 % higher than specimens activated with LAA 70:30. The possible reason could be due to the presence of water in LAA 70:30 is higher than the LAA 50:50. Therefore, presence of excess water impedes the formation of cementitious gels in the matrix. On the other hand, RAP:VA stabilized using LAA 70:30 activated FA-N mixtures exhibited the highest UCS of 5.8 MPa, which is 8.5 % higher than LAA 50:50 activated specimens. This might be due to the presence of lower silica, i.e., 38.18 % in FA-N (Table 1), which demands higher silica content to enhance the mechanical strength of the mix.

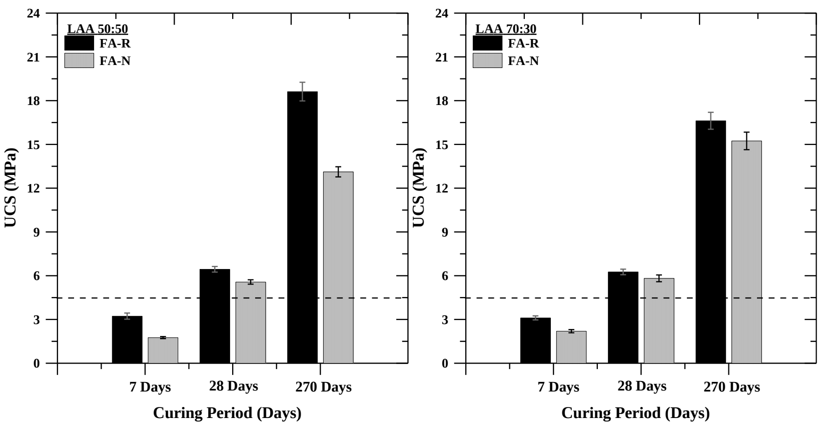

Fig. 2. Variation of UCS with curing time (a) LAA 5:50 activation (b) LAA 70:30 activation

To verify the long-term UCS of the proposed design mixtures, the curing age was selected as 270 days based on the studies conducted by Sakai et al. [13] on the hydration of fly ash. The UCS trend observed in Fig. 2, pertaining to LAA type and long-term curing, is similar to the observations made on short-term cured samples. In addition, the percentage gain in the UCS of 7 days and 28 days cured specimens with respect to its ultimate UCS was observed to be only 12 % and 40 %, respectively. This observation implies that the remaining 60 % of the UCS was attained after 242 days, indicating a total curing period of 270 days. Therefore, it can be concluded that the maturity age of alkali-activated fly ash stabilized RAP:VA mixtures continue after 28 days. Both short-term and long-term cured samples showed that the UCS was more than 4.5 MPa, which is required by IRC:37 2018 [21] to qualify as a pavement base material for stabilized mixtures.

3.2 Resilient Modulus (M_r) Tests

Resilient modulus is an accurate representation of vehicle movement and one of the essential design parameters in flexible pavements. In this study, Fig. 3 illustrates the variation of M_r of LAA 50:50 and 70:30 based FA-R, and FA-N stabilized 60RAP:40VA mixtures cured for 28 days and 270days. It can be observed that LAA 50:50 activated FA-R samples showed the highest M_r of 1200 MPa, which is 20 % higher than LAA 70:30 based samples. The decline in M_r in LAA 70:30 activated specimens was due to more water presented in LAA 70:30 compared to LAA 50:50, and the excess water would inhibit the formation of cementitious gels in the system. However, FA-N samples activated with LAA 70:30 showed the maximum M_r, similar to the trends observed in the UCS results. This is because inadequate silica in FA-N demands additional reactive silica to gain the M_r. Like the UCS results, the samples that have been cured for a long time have the highest M_r values, with a maximum of 1600 MPa. This is 60 % higher than the maximum M_r seen in samples cured for a short time. Therefore, it can be concluded that the extended curing time plays a significant role in enhancing the M_r, in addition to the UCS.

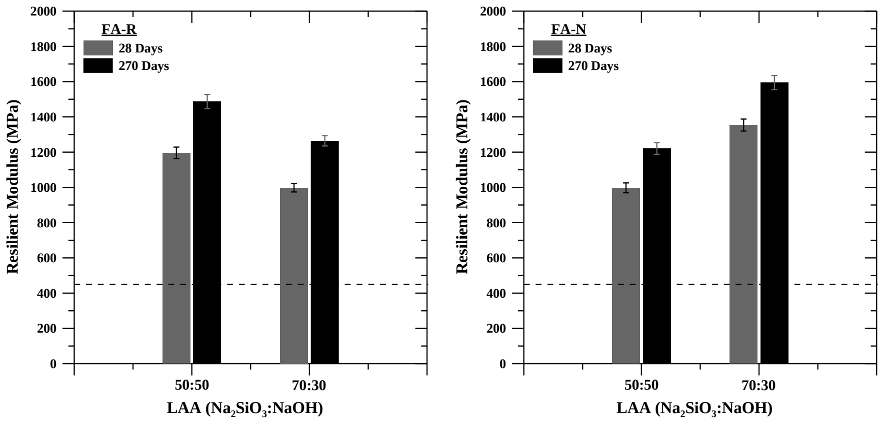

Fig. 3. Variation of M_r with curing time (a) LAA 5:50 activation (b) LAA 70:30 activation

3.3 Durability Studies

Fig. 4 depicts the variation in weight loss concerning the wetting–drying (w–d) cycles of the RAP:VA mixtures stabilized with alkali-activated low calcium and high calcium fly ashes cured for 28 and 270 days. It was noticed that, for all wetting-and drying cycles, the weight loss was increased up to 1.75 % for FA-N based specimens activated with LAA 50:50 and cured for 28 days.

In the same way, Fig. 4 shows that weight loss rises as the number of the first seven wetting and drying cycles increases. After that, the weight loss was almost constant for all the mixtures. The samples cured for 270 days of curing age had the lowest weight loss, about 1.2 %, in FA-R stabilized RAP:VA mixtures. This can be attributed to the improved mechanical strength during the extended curing period. To note, the weight loss in all the mixture combinations is less than 14 %, which is the maximum allowed limit as per the IRC:37 2018 [21] for stabilized mixtures.

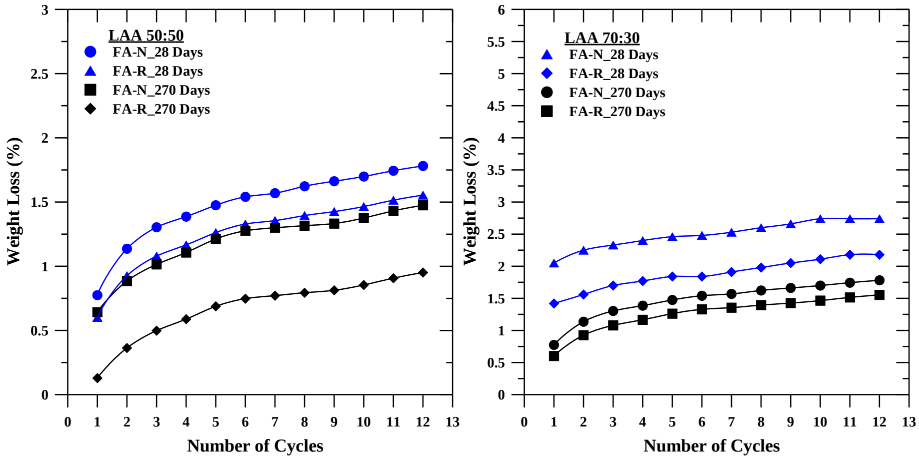

Fig. 4. Variation of weight loss for wet-dry cycles with curing age (a) LAA 5:50 activation (b) LAA 70:30 activation

Conclusions

In this present study, 60%RAP:40%VA+20%FA mixtures were used as an alternative to the conventional pavement base material. In order to improve the mechanical properties of the proposed mixtures, alkali-activation has been proposed. For that purpose, the liquid alkaline activator consisting of Na_2SiO_3:NaOH solution with 50:50 and 70:30 proportions was used to activate the fly ashes collected from Ramagundam (Class-F) and Neyveli (Class-C). The influence of short-term and long-term curing age on the mechanical strength of the proposed mixtures was evaluated using UCS, M_r, and durability studies. Based on the laboratory test results, the following conclusions were drawn.

- As recommended by the IRC 37 2018 for stabilized mixtures, the UCS of the proposed design mixtures has qualified the minimum requirement of 4.5 MPa after 28 days of curing age.
- High calcium fly ash-based RAP:VA mixtures exhibited the maximum UCS at LAA 50:50, whereas the low-calcium based RAP:VA mixtures shown with LAA 70:30 activated RAP:VA mixtures.
- After 28 days of curing age, the short-term curing samples exhibited only 40 % of their ultimate UCS, and the remaining UCS was achieved at 270 days.

- The M_r of both short-term and long-term cured samples has qualified the minimum baseline requirement of 450 MPa after 28 days of curing age specified by the IRC:37 2018.
- The weight loss after aggressive durability wetting and drying cycles was observed to be a maximum of 1.75 % for short-term cured samples and 1.2 % for long-term cured samples. It is less than the allowable limit of 14 %, as specified by the IRC:37 2018.

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