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Effect of particle size of rice husk ash (RHA) in mitigating alkali silica reaction (ASR) in concrete pavement

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Abstract

Alkali-silica reaction (ASR) is considered as a major concern of distresses in concrete pavements and barriers in different locations across the state of Arkansas. Such premature distresses pose a significant increase in pavement life cycle cost. On the other hand, a large amount of rice husk ash (RHA) is produced in Arkansas, which is treated as an agricultural waste. In this study, different amounts (0, 10 and 20%) of three RHA samples with nominal sizes of 600 µm (600-RHA), 150 µm (150-RHA) and 44 µm (44-RHA), and a Class C fly ash (CFA) were used to observe the effect of gradation in ASR. Mortar bars were prepared and tested as per ASTM C1567. Test results revealed that finer RHA reduced the ASR expansion of the mortar bars. Both 600-RHA and 150-RHA contributed to significant expansion due to their bulk particle size. A 10% 44-RHA and a 10% CFA were found to be the optimum. In comparison to the Control, the 10% 600-RHA and 150-RHA samples expanded the bars by 101% and 40%, respectively and the 10% 44-RHA and CFA decreased the expansion of mortar bars by 81% and 95%, respectively. Furthermore, incorporation of RHA in the concrete pavement will reduce the pavement construction and maintenance cost.

Keywords: Concrete; Rice husk ash (RHA); Fly ash; Alkali-silica reaction (ASR); Supplementary cementitious material (SCM); Pavement distress

1. Introduction

Highway and pavement engineers are facing concrete pavement damages nowadays due to alkali-aggregate reaction (AAR). AAR is detrimental when it causes significant volume expansion of concrete and results in cracking. There are two types of alkali-aggregate reaction, which are the alkali-silica reaction and alkali-carbonate reaction. The most prevalent form of AAR is the alkali-silica reaction (ASR). An ASR phenomenon is a chemical reaction between the alkali hydroxide coming from hydraulic cement and silica content from aggregate used in concrete. A gel is formed during this chemical reaction, namely ASR gel [1]. When moisture comes in contact with this gel, it swells in volume and exerts pressure in concrete [1,2]. It leads to the formation of microfractures in concrete, which results in spalling and cracking [3].

Different supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag can be used to lessen ASR problem. Use of SCMs as partial replacement of cement reduces the alkali content of cement [1]. In addition, the porosity of the concrete can be enhanced by SCMs that will reduce the chances of moisture to initiate deleterious ASR expansion [1]. During pozzolanic activity of SCMs, negatively charged calcium silicate hydrate (C-S-H) is formed with a low calcium to silica ratio. This

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C-S-H reacts with alkali cations (Na^+, K^+) and reduces diffusivity of alkali cations into the concrete. In this way, ASR is mitigated by the use of SCMs [4].

About 30% rice hulls are produced during the paddy husking process [5]. It is used as biomass not only for energy production in paddy milling process but also in various power plants. When rice hull undergoes the burning process, about 20% of it converts into RHA [5,6]. About 738.2 million tons of paddies are produced in the world each year [7] of which about 70 million tons are RHA [8]. This significant amount of RHA is generally dumped in industrial premises that may cause environmental pollution. Moreover, RHA cannot be naturally degraded due to its siliceous compositions [9]. On the other hand, cement industries are responsible for about 7% of the total equivalent CO_2 emissions [9], and one ton of cement production is responsible for about one ton of equivalent CO_2 emission [8,10]. Use of RHA in substitution of cement can reduce the CO_2 footprint as well as ecological hazards [11,12,13].

Arkansas is the top of all six rice-producing states in the U.S. It contributes about 48% to the total rice production in the U.S. [14]. The largest rice miller in the world, Riceland Foods, Inc., a farmer-family based business that produces 125 million bushels of paddy annually, is situated in Arkansas [15]. Generally, Riceland Foods considers RHA as an agricultural waste product and disposes it to nearby industry premises, which may cause health hazards to the associated workers. Other SCMs such as fly ash and silica fume are expensive and may not be available locally. Hence, locally produced RHA can be used as an alternative SCM due to its high silica content [4].

Akhnoukh et al. [3] reported that Arkansas Department of Transportation (ARDOT) faced concrete pavement and barrier damages at various places across Arkansas in recent years. It may incur ARDOT extra maintenance cost, leading to inflation in the life cycle cost of the project. The factors that contribute to the concrete pavement distress due to ASR in Arkansas are the use of reactive aggregates, the trend of not using SCM in cement and availability of high moisture content in the air. It is suggested to incorporate SCM in highway projects to lessen ASR-related concrete pavement deterioration.

Abbas et al. studied the mitigation of ASR in their corresponding study by incorporating RHA [1]. These researchers used Ordinary Portland Cement (OPC), four different percentages (i.e., 10%, 20%, 30% and 40% by weight of OPC) of RHA and reactive aggregate (sand from Dolomite-limestone rock) in their study. The cracking phenomena and the amount of CaO/SiO2 in the tested concrete samples were examined using scanning electron microscopy (SEM) technology and energy disperse X-ray spectroscopy (EDS) analysis, respectively. Reductions in ASR expansion were observed in the case of mortar bars containing RHA and a 40% replacement of OPC by RHA was found optimum. Additionally, SEM images showed no cracks in RHA modified mortar bars while cracks were found in the control specimen (0% RHA). The EDS analysis revealed that the presence of low CaO/SiO2 correlated to the reduction of ASR expansion.

Le et al. [2] studied the effect of different types of pores in the performance of the RHA- and SF-modified mortar paste. Both macroporous (particle size: >50 nm) and mesoporous (particle size: 2–50 nm) RHA particles were used in this study. It was observed that the pore size distribution of RHA significantly influenced the pore volume, specific surface area, and water demand of RHA-modified concrete. The authors reported the improved rheological properties of RHA mortar paste due to the incorporation of finer RHA at higher content.

A follow-up study by Le et al. [4] attempted to assess the performance and ASR mitigation capability of RHA and SF in self-compacting high-performance concrete. The authors used both reactive (i.e., greywacke sand) and non-reactive (i.e., basalt sand) aggregates in preparing mortar bars. Three different sizes (5.7 μm, 7.7 μm, and 15.6 μm) of RHA samples were incorporated into this study. It was reported that the finer RHA had higher pozzolanic activity than the coarser one since the finer RHA containing mortar bars exhibited better refinement of pores than the coarser RHA-modified mortar bars. Higher ASR expansion and substantial cracking were observed in the case of mortar bars containing coarser RHA (15.6 μm) and non-reactive aggregates compared to the control specimen. The authors suspected that the excessive expansion was due to the formation of ASR gel inside the RHA particle, which was identified in the energy-dispersive X-ray (EDX) spectroscopy analysis. It was also mentioned that the ASR reactions occurred in mortar bars faster than the pozzolanic reaction of RHA.

Venkatanarayanan and Rangaraju studied the performance of the concrete prepared with both unground RHA (URHA) and ground RHA (GRHA) having low carbon contents. GRHA showed preferable rheological properties of concrete compared to the URHA-modified concrete. The authors suggested that the reason behind this phenomenon could be due to the internal porosity and incomplete pozzolanic reaction of the coarse URHA.

Based on the findings of the studies conducted around the world and preliminary performance data of RHA-modified concrete of the current study, the authors believe that RHA can be used in concrete to mitigate ASR expansion. However, the performance of concrete with local RHA in mitigating ASR is still unknown to the agencies and contractors in Arkansas. Using waste materials like RHA, in addition to lowering the material costs, the concrete industries and agencies in the region can achieve their sustainability goals. Moreover, local farmers can be benefitted by selling RHA as well as getting rid of landfilling problems caused by the disposal of RHA.

The main objective of the present study is to observe the effect of RHA size (gradation) and percentage of dosage of local RHA as SCM in concrete to mitigate ASR. The ASR test was conducted according to ASTM C1260 and ASTM C1567 method to observe the expansion phenomenon of

RHA modified mortar bars. Three types of graded RHA along with Class C fly ash (CFA) were used throughout the research. CFA and each type of RHA were used separately in mortar bars at two different replacement levels (10% and 20%) by weight of cement for the same curing period of 14 days.

2. Material and methods

Type-I Ordinary Portland Cement (OPC) and stone sand of fineness modulus (FM) 2.6 were used to prepare mortar bars. Three types of RHA of different gradation were used separately that have particle size 600 μm, 150 μm and 44 μm, respectively (Fig. C.1). None of the SCMs were mixed with each other since they were used independently in preparing mortar bars. The mortar bars prepared using 600 μm RHA, 150 μm RHA, 44 μm RHA and CFA would be termed as 600-RHA, 150-RHA, 44-RHA, and CFA modified mortar bars, respectively in this study. The 600-RHA and 150-RHA were collected from Riceland Food, Inc. Usually, they produce 600-RHA as a by-product of the milling process. It is black in color and very coarse in size. It was further ground to produce 150-RHA. It is finer than 600-RHA and also black in color. But none of these meet AASHTO 321-04 specifications. However, 44-RHA was collected from a commercial industry, Agrilectric, California, and it is gray in color and meets AASHTO M 321–04 specifications. CFA was collected from a local supplier, Charah, Inc. (Fig. C.1.d). The chemical properties of RHA and CFA are shown in Table B.1.

In this study, the ASTM C1260 and ASTM C1567 test methods were followed to conduct the ASR tests. Three mortar bars were prepared using three types of RHA (600-RHA, 150-RHA, and 44-RHA) and CFA. To prepare the mortar bars, the OPC was replaced by each type of RHA for 10% and 20%, respectively by weight and compared with control mortar bars (0% RHA). During the test, the length change of each mortar bar was determined by taking intermediate readings at 4, 8, 12 and 14 days. A linear variable differential transducer (LVDT) was used to take measurements with the help of a data storage unit (Fig. C.2).

Routine test results (e.g., workability, air contents, compressive strength, tensile strength) of tested RHA- and CF-modified concrete of the current study have been reported elsewhere in the literature [17,19]. Slump values of fresh concrete were about the same for the control and 10% RHA-modified concrete, whereas 20% RHA-modified concrete exhibited a higher slump value. An increment of the RHA percentage also increased the air voids, but it decreased the unit weight. It happened as the OPC was significantly finer than the RHA. Coarser particles of RHA created additional air voids in the concrete, which eventually decreased the unit weight of the fresh concrete.

At 28 days, 600-RHA- and 150-RHA-modified concrete showed less compressive strength (e.g., 20 MPa for 600-RHA and 22.5 MPa for 150-RHA with a 10% replacement of OPC) compared to the control sample (36 MPa). On the other hand, 44-RHA- and CFA-modified concrete exhibited more compressive strength values compared to the control sample. Also, a 10% replacement of cement showed a greater increase in compressive strength than a 20% cement replacement.

Regarding flexural strength, the RHA-modified concrete sample followed a similar trend of the compressive strength. 44-RHA-modified concrete showed a significant increase in flexural strength compared to the control sample. On the other hand, CFA (e.g., with 10% and 20% CFA the flexural strength values were 3.45 MPa, and 2.69 MPa, respectively) showed less flexural strength than that (4.17 MPa) of the control sample.

3. Result and discussion

3.1. Effect of grain size distribution

The effects of RHA and CFA in mortar bars to mitigate ASR expansion are shown in Figs. C3 to C6. It is observed that the expansion of the control mortar bar is 0.129% in 14 days, which is more than 0.10%. According to ASTM C1567, if the expansion of mortar bars is greater than 0.1%, the expansion is considered potentially deleterious. Thus, it can be concluded that the tested aggregate source is potentially alkali-silica reactive. It is seen that the 600-RHA mortar bars showed expansion of 0.26% and 0.33%, respectively at 14 days for the 10% and 20% replacement level (Fig. C.3). For 150-RHA, 10% and 20% RHA modified mortar bars displayed an expansion of 0.18% and 0.22%, respectively. The coarse RHA sample (600-RHA) contributed to the ASR expansion instead of mitigating the ASR expansion as shown in the Fig. C.3. The similar phenomenon was also observed in case of ground 150-RHA (Fig. C.4). The 600-RHA modified mortar bars showed more expansion than the 150-RHA mortar bars. The dark color of the 600-RHA indicated the presence of high amount of unburnt carbon [17,18]. This type of coarse RHA is hydrophilic in nature. Thus, mix prepared with the 600-RHA resulted in a comparatively dry inhomogeneous mix than finer RHA modified mix. Thus, this inhomogeneity causes increased expansion in 600-RHA mortar bars due to the formation of voids having more interparticle distance than the 150-RHA mortar bars. Thus, the total pore volume in the 600-RHA mortar bars is greater than the 150-RHA mortar bars. Hence, moisture can access easily to the porous structure of 600-RHA and react with the ASR gel. That's why the 600-RHA mortar bars exhibited greater expansion than 150-RHA mortar bars. Another possible explanation for the expansion of the 600-RHA mortar might be the presence of higher alkali/reactive silica ratio. Furthermore, there is a high expansion potential when large sized particles are used in the mix as there is an increased amount of bound potential reactive silica within the large particle, which is sometimes coupled by some delayed ASR due to the time taken for the excess silica to leach out. The scanning electron microscopy (SEM) technique in collaboration with the X-ray diffraction (XRD) can be used in future to do a micro-level study to better understand the ASR gel formation and expansion phenomena in the mortar bars. The authors also suggest that for mitigating the ASR, both 600-RHA and 150-RHA should be grounded further to meet AASHTO specifications and their chemical composition should be analyzed before using as SCM.

The 44-RHA is finest RHA among all the RHA that have been studied in this research study. The particle size of this RHA is similar to OPC and also it meets the AASHTO specification M 312-04. The ASR test result for 44-RHA mortar bars is shown in Fig. C.5. From Fig. C.5, it is seen that the expansions of 10% and 20% incorporating 44-RHA mortar bars were 0.02% and 0.08% at 14 days that are less than the expansion of control mortar bars. A similar trend was found using CFA in mortar bars as shown in Fig. C.6. Thus, the 44-RHA and CFA were found effective in mitigating ASR. The 44-RHA produced homogeneous mix due to having the similar particle size of OPC. It leads to less porous mortar bars in which moisture cannot easily access and react with the ASR gel to expand. A homogeneous mix of 44-RHA enhances the porosity of the mortar bars that restricts the moisture access into the pores, reducing the potential of the diffusivity of alkaline ions in concrete. Moreover, 44-RHA has finer particles that have a higher specific surface area. Le et al. [4] reported that the finer RHA exhibits higher pozzolanic activity than coarser RHA and effective in controlling ASR.

3.2. Effect of RHA dosage

From Fig. C.3, it is seen that the 14 day expansions of the control, 10% 600-RHA, and 20% 600-RHA mortar bar were 0.129%, 0.26%, and 0.33%, respectively. Thus, the 10% and 20% incorporating 600-RHA mortar bars expanded 101% and 156%, respectively in comparison to the control bars. A similar phenomenon was observed in the case of 150-RHA mortar bars (Fig. C.4). The 14 day expansions of the mortar bars modified with 10% and 20% 150-RHA were 0.18% and 0.22%, respectively. Therefore, the 10% and 20% 150-RHA incorporated mortar bars exhibited 40% and 71% expansion, respectively compared to the control bars. The use of unground coarse RHA in concrete increases inter-particle distance, leading to the less homogeneous mixture. Thus, coarse RHAs are also responsible for producing a high amount of alkali-silica expansion in mortar bars with visible cracks [16]. Moreover, coarse RHA has a low bulk density that affects mortar mix when used as partial replacement of cement [8]. Use of more percentage of coarser RHA contributes to the more ASR expansion exaggerating concrete distress.

On the other hand, 10% and 20% 44-RHA modified mortar bars showed 0.02% and 0.08% expansions, respectively at 14 days of curing. Thus, 44-RHA modified mortar bars having 10% and 20% dosages decreased the expansion by 85% and 38%, respectively compared to the control. (Fig. C.5). It is assumed that the pozzolanic activity occurs on the surface of the RHA at first and later inside the pores of RHA particles [4]. The finest 44-RHA exhibited more pozzolanic activity due to a higher specific surface area, resulting in ASR mitigation to a great extent. Use of 44-RHA may produce sufficient C-S-H that react with alkali cations, leading to lower alkali to silica ratio [1]. This reduces ASR expansion and concrete cracking. CFA also showed similar test results. The 14 day expansions of the 10% and 20% CFA incorporating mortar bars were 0.006% and 0.0022%, respectively. Therefore, the 10% and 20% CFA mortar bars reduced the ASR expansion by 95% and 98%, respectively, compared to the control mortar bars (Fig. C.6). In this study, 10% 44-RHA and 10% CFA were found optimum to mitigate ASR expansion.

It can be noted that the expansion tests for mortar bars of this study did not separate the effect of shrinkage on the volumetric variations of the specimens. In other words, for the specimens with different mixture designs, different amounts of shrinkage could occur due to chemical reactions and drying processes and they might have affected the ASR test results. The specimen with finer RHA of reactive substances may exhibit larger shrinkage, and thus they compensate a portion of expansion induced by the ASR phenomenon. Moreover, the specimens with different porosities may also cause various shrinkages during ASR expansion tests. Such types of measurements separating shrinkage from ASR expansion can be undertaken in a future study.

4. Conclusion

The ASR test was conducted using CFA and three types of RHA at two levels of cement replacement. It is found that coarser RHA (600-RHA and 150-RHA) was ineffective in mitigating ASR while finer RHA (44-RHA) and CFA mitigated ASR expansion. RHA should be grounded to have the particle size less than or equal to 44 μm to lessen ASR expansion. Use of coarse RHA increases ASR expansion rather than controlling. Increase in the percentage of coarse RHA also increases ASR expansion. The 20% 600-RHA mortar bars exhibited most ASR expansion by 156% compared to the control mortar bar due to the formation of excess pores. It is recommended not to use unground coarse RHA as SCM to mitigate ASR. It is also concluded that RHA can be used as SCM to control ASR expansion. The 10% 44-RHA and 10% CFA were found optimum for mitigating ASR expansion in this study.

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Appendix A

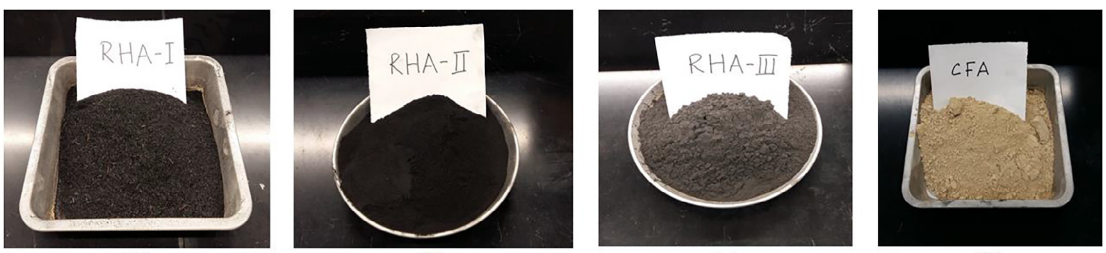
Table B.1

Table B.1
Chemical properties of RHA and CFA.

Chemical Properties	600-RHA	150-RHA	44-RHA	CFA	AASHTO M 321-04
Reactive oxides ($SiO_2 + Al_2O_3 + Fe_2O_3$)	95.5%	95.5%	86.8%	60.02% (ASTM C 618: Min 50%)	75% (minimum)
Loss on ignition (LOI)	8.98%	8.98%	5.4%	0.22%	6% (maximum)
Moisture content (MC)	3–5%	3–5%	2.6%	0.04%	3% (maximum)

Appendix B

Figs. C.1–C.6.



(a) (b) (c) (d)

Fig. C.1. (a) 600-RHA, (b) 150-RHA, (c) 44-RHA, and (d) CFA.

(a) (b)

Fig. C.2. (a) Use of LVDT to measure expansion, (b) data storage unit.

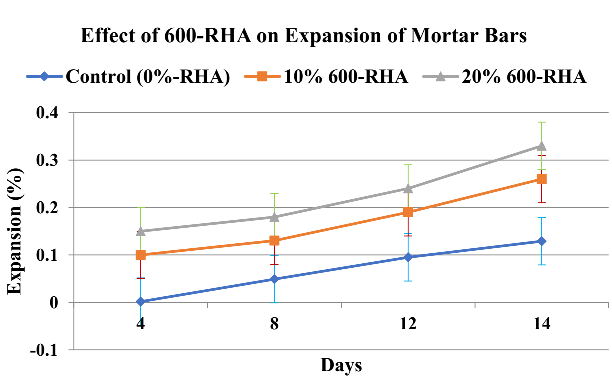


Fig. C.3. ASR test result of 600-RHA mortar bars.

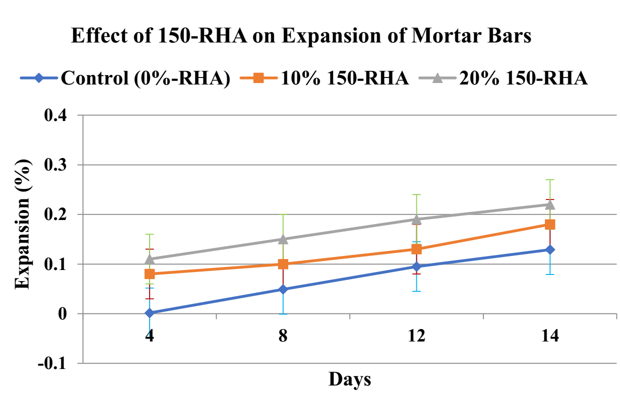


Fig. C.4. ASR test result of 150-RHA mortar bars.

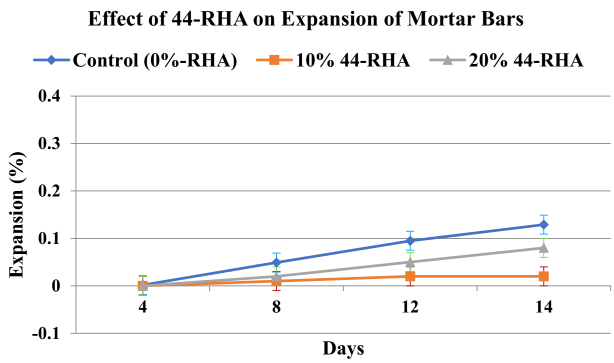


Fig. C.5. ASR test result of 44-RHA mortar bars.

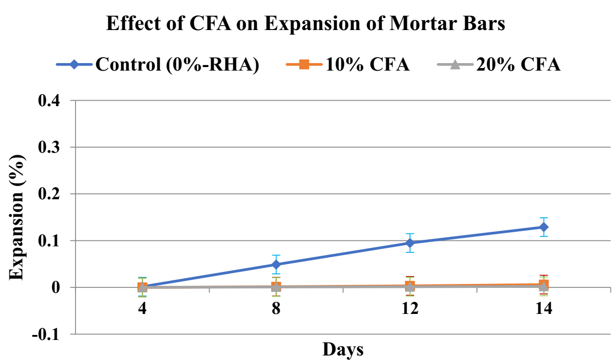


Fig. C.6. ASR test result of CFA mortar bars.

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