Transportation Consortium of South-Central States

Tran-SET

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Use of Rice Hull Ash (RHA) as a Sustainable Source of Construction Material

Project No.17CASU02

Lead University: Arkansas State University

Preserving the Environment

Final Report

October 2018

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16. Abstract

With the imminent shortage of natural resources, the need to find sustainable development is the highest in recent history. Therefore, this study examines the potential uses of Rice Hull Ash (RHA) as a sustainable cementitious material (SCM) in preparation of concrete. This study also assesses the use of RHA as an alternative of commonly used polymers in preparing high-grade asphalt binders. RHA is a potential sustainable solution because it is currently being treated as an agricultural waste material, yet its high silica content makes it a potential construction material. Three different sizes of RHA (600 µm, 150 µm, and 44 µm) with two different partial replacement percentages (10% and 20%) of type I Ordinary Portland Cement (OPC) were considered to prepare concrete and mortar samples. For the comparative analysis, two more SCM materials, namely, class C fly ash (CFA) and silica fume (SF), were also incorporated in this study. The results of the fresh concrete tests (slump, unit weight, air entrainment) and hardened concrete tests (e.g., compressive, tensile, flexural strength) have suggested that with a 10% replacement of OPC using finer RHA- modified concrete exhibits the improvement of concrete properties compared to the regular concrete. Based on limited test data of RHA-modified binders, RHA appears to be a viable alternative of commonly used polymers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AAS	Arkansas Academy of Science
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AFM	Atomic Force Microscope
ASCE	American Society of Civil Engineers
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
BET	Brunauer, Emmett, and Teller
CA	Coarse Aggregate
CaO	Calcium Oxide
CFA	Class C Fly Ash
CH	Calcium Hydroxide
CLSM	Controlled Low Strength Material
C-S-H	Calcium Silicate Hydrate
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
EDS	Energy-Dispersive Analysis
FA	Fine Aggregate
FHWA	Federal Highway Administration
G*	Complex Shear Modulus
NMS	Nominal Maximum Size
NPW	Net Present Worth
OCA	Optical Contact Analyzer
PG	Performance Grade
PMBs	Polymer-Modified Binders
RHA	Rice Husk Hull/Husk Ash
RTFO	Rolling Thin Film Oven

RV	Rotational Viscosity
SBR	Styrene-Butadiene-Rubber
SBS	Styrene-Butadiene-Styrene
SCM	Supplementary Cementitious Materials
SF	Silica Fume
TRB	Transportation Research Board
VTS	Viscosity Temperature Susceptibility
δ	Phase Angle

EXECUTIVE SUMMARY

Rice hull ash (RHA) is one of the most significant agricultural by-products in the United States as well as all over the world. From the chemical perspective, RHA has pozzolanic properties, which make it a potential supplementary cementitious material. In this study, three different types of RHA (RHA-1: 600 µm, RHA-2: 150 µm, and RHA-3: 44 µm) with different particle sizes were utilized to evaluate its effects on regular concrete. For comparative analysis, two supplementary cementitious materials (SCM), Class C Fly Ash (CFA) and Silica Fume (SF), were also incorporated in this study. Two different percentages of RHA (10% and 20%) were used as partial replacement of cement for producing modified concrete samples. The physical and chemical data of RHA, CFA, and SF were compared. Specific surface area (SSA) values of RHA, CFA, and SF were determined using the BET (Brunauer, Emmett, and Teller) method. Several fresh and hardened concrete tests were conducted on RHA modified concrete samples. From different hardened concrete tests, it was found that RHA-1- and RHA-2-modified concrete showed less compressive strength compared to the control sample. On the other hand, RHA-3, CFA, and SF showed a significant strength increase of modified concrete compared to the controlled sample. RHA-3 exhibited a slight increase in compressive strength compared to the controlled samples when the corresponding amounts of RHA-3 were 10% and 20%, respectively. Based on the test results, coarser RHA was found to be ineffective in mitigating the Alkali-Silica Reaction (ASR) expansion. On the other hand, finer RHA was found to mitigate the expansion of mortar bars. Similarly, the deicing durability test showed that finer RHA modified concrete caused less surface deterioration compared to the Control sample. Between the two different percentages of RHA and other SCM materials used in this study, the 10% RHA-3, CFA, and SF demonstrated the optimum beneficiary results.

The finest RHA (RHA-3) was also blended with a virgin performance grade (PG) binder (PG 64-22) at different percentages (1%, 2%, and 3%, by the weight of the binder). SF and CFA were also added at the same percentages with the virgin binder to compare the results with RHA modified asphalt binder. Superpave tests including rotational viscosity (RV) (AASHTO T 316) and dynamic shear rheometer (AASHTO T 315) were performed for the modified asphalt binders. The viscosity of RHA modified asphalt was found to be significantly higher compared to the virgin binder. Moreover, the mixing and compaction temperatures measured for the RHA-modified asphalt were also found to be significantly higher than those of the virgin binder. The dynamic shear rheometer (DSR) showed that the rutting factor ($G^*/\sin\delta$, where G^* is the complex modulus and δ is the phase angle) value was increased with the addition of RHA, CFA, and SF. The increased $G^*/\sin\delta$ values indicated higher rutting resistance of the tested RHA-modified binder. Life cycle cost analysis (LCCA) for the RHA-modified rigid pavement and asphalt binder pavement determined that modification of concrete and asphalt with RHA resulted in less net present value compared to the regular concrete and asphalt pavement, respectively. Thus, based on limited findings of the current study, the fine RHA seems to be a potential alternative of widely used polymer in modifying asphalt binders. While results are promising, further research is needed to recommend RHA as a modifier of asphalt binders.

IMPLEMENTATION STATEMENT

This is a proof-of-concept study that is limited to laboratory testing of RHA-modified concrete and asphalt binders. The implementation phase of this study includes disseminating findings of the study to the Arkansas Department of Transportation (ARDOT) and other transportation agencies in the region through participation and presentations in ARDOT-sponsored workshops, Transportation Research Council (TRC) meetings, Tran-SET-sponsored conferences, submission of technical reports, and presentation of technical articles and posters at different conferences and symposiums. Over the course of the past year, the research team has published several research articles *(28, 29, 30)*. The team also made multiple oral and poster presentations at national and regional level conferences and symposia that include the Transportation Research Board's (TRB) 97th Annual Meeting, the Tran-SET 2018 Conference, the Arkansas Academy of Science (AAS)-2018 Conference, the 2018 Create@State Research Day Symposium, and TRC meetings. A technical article has been submitted to TRB 98th Annual Meeting and additional articles are in the process of publication. The implementation and dissemination activities will continue throughout the remainder of the duration of the project. All outreach activity will be documented in the implementation report to be submitted at the end of this project.

1. INTRODUCTION

With the rapid increase in the world population, the urbanization and the construction of structures have been in a period of drastic growth. A huge impact on natural resources caused by the growing need for construction materials will eventually deplete the environmental standards and will cause an adverse effect on the natural ecosystem. About 94 million metric tons of cement was produced in 2016, and the annual growth of cement consumption for 2017 was 2.6% *(1)*. Due to the shortage of natural raw materials, the overall construction project cost has increased in recent years. To find a solution, modern technologies have resulted in sustainable construction methods and materials. Thus, rice hull ash, also called as rice husk ash, has been considered as an alternative source of cementitious material. Rice husk is an agricultural by-product from the rice milling process. The main use of rice husk is as biofuel, which generates a large volume of ashes. Currently, the rice husk ash (RHA) has no beneficial application, rather it pollutes water streams and surrounding areas.

The United States produces a significant amount of rice each year. Per the US Department of Agriculture's national agricultural statistics, about 25.1 million pounds of rice was produced all over the United States in 2016. In the process of milling rice, millions of pounds of RHA have been produced each year. Currently, the disposal of RHA as a waste material in landfills causes air and water pollution. Utilization of RHA could solve the disposal related problems. Since the RHA has pozzolanic properties, it can be used in the concrete industry. In addition, the use of RHA can also alleviate the shortage of fly ash in the cement industry. The partial replacement of cement with RHA could lower the production cost of concrete and decrease the CO_2 emission associated with the cement production. The use of RHA as a potential asphalt modifier has also been studied in this project work. On the other hand, the widely-used polymer-modified binders (PMBs) can be replaced by the low-cost RHA modified asphalt binder. Thus, the local farmers would benefit from selling the RHA and the construction industry would have an alternative source of pozzolanic material as well as an asphalt modifier.

This report discusses the use of RHA as a supplementary cementitious material (SCM) and an asphalt binder modifier. RHA contains a high percentage of silica content (SiO_2). In controlled burning chambers, RHA can be highly reactive pozzolanic material *(2)*. The combustion process creates a secondary Calcium-Silicate-Hydrate (C-S-H) gel which determines the pozzolanic activity of the RHA. Moreover, the particle size of RHA also influences the hydration process in concrete *(3)*. The presence of carbon defines varying pozzolanic properties of RHA. In cementitious products, RHA can be used as a mineral admixture. The properties of concrete of blended cementitious materials also vary with the source of RHA *(4)*. Incorporation of RHA in asphalt modification could be an alternative source of modifiers in modifying asphalt binders. The RHA-modified binder could potentially replace the currently used polymer-modified binders (PMBs) as well.

In this study, RHA has been used as a supplementary cementitious material for Ordinary Portland Cement (OPC). Two different replacement percentages of cement by weight (10% and 20%) have been utilized in the study. For the property evaluation of different RHA particle size in concrete, three different RHA sizes (RHA-1: 600 µm, RHA-2: 150 µm, and RHA-3: 44 µm) were selected in this study. Moreover, two additional supplementary cementitious materials (SCM), namely, Class C fly ash (CFA) and Silica Fume (SF), were also incorporated in this study. Different laboratory tests, both on fresh modified concrete and hardened modified concrete, were performed to evaluate their physical and mechanical properties. To evaluate the reactivity of the aggregate in presence of alkaline water, Alkali-Silica Reaction (ASR) tests were performed on the modified cement mortar bars. The surface scaling rate in adverse weather conditions was also examined through scaling resistance test. Considering the outcome of the different physical properties of modified concrete, an optimum dose of RHA was also determined.

On the other hand, asphalt binder is an adhesive material, which is an organic mixture of various chemical compositions. Usually, a small amount of asphalt binder (4–8% by weight) is used in pavement mixture. Per the natural behavior, an asphalt binder has a liquid form at high temperatures, and it becomes brittle at low temperatures. Moreover, the increasing traffic volume, load, tire pressure, and adverse weather conditions accelerate the pavement deterioration. Using a stiff, flexible, and viscoelastic asphalt binder helps to mitigate the pavement deterioration. Asphalt binder modification also helps to get the necessary properties to avoid premature pavement damages. Various types of elastomeric and plastomeric modifiers have been used in the field of asphalt modification. Currently, several mineral materials have been incorporated into the modified asphalt. For instance, SBS (Styrene–Butadiene–Styrene)/KC (Kaolinite Clay) compounds have been successfully used in the asphalt binder to improve the stability of modified asphalt. A large portion of the current usages of polymer-modified binders (PMBs) could potentially be replaced by RHA-modified binders. Moreover, RHA is very inexpensive and easily available as an agricultural by-product. The use of RHA in the asphalt modification could significantly lower the cost of the modified asphalt binder in road construction. Therefore, a proper study on the interactions between the asphalt binder and the RHA including the loading bearing capacity of RHA-modified asphalt would also be needed.

1.1. Literature Review

To understand the findings of researchers who have worked with RHA, a comprehensive literature review using pertinent sources has been completed. The literature review primarily focused on the effects of RHA, CFA, and SF on the strength properties of concrete. It also addressed durability and comparison of ASR phenomena due to the application of RHA, CFA, and SF. The effects of particle size, as well as the specific surface area of RHA on concrete properties, were also discussed. Different reputed construction and materials journals, periodicals and technical reports published by different agencies were consulted for gathering necessary information related to this study. These agencies included the American Society of Civil Engineers (ASCE), Transportation Research Board (TRB), the Federal Highway Administration (FHWA), and US Departments of Transportation (DOTs), and, the American Society for Testing and Materials (ASTM) test methods and specifications.

Researchers have studied the properties of RHA to predict the performance of RHA as pozzolana. Literature regarding RHA-modified concrete was reviewed to obtain an overview of the performance properties and chemistries behind the improved properties of RHA-modified concrete. Chemical properties of a typical RHA, reported in different studies, are presented in Table 1. As seen in Table 1, typical RHA contains over 85% of silica, but it varies from source to source.

Table 1. Chemical properties of RHA (wt, %) *(5)*.

References	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Loss on Ignition
Mehta *(2)*	87.2	0.15	016	0.55	0.35	0.24	1.12	3.68	8.55
Zhang et al. *(9)*	87.3	0.15	0.16	0.55	0.35	0.24	1.12	3.68	8.55
Bui et al. (*31*)	86.98	0.84	0.73	1.4	0.57	0.11	2.46	-	5.14

As reported by Givi et al. *(5)*, RHA is considered as a pozzolanic material due to having high silica content and high specific surface area. Thus, RHA can be used as a partial replacement of Portland cement in lime-pozzolana mixes. The pozzolanic reactions start when the di-calcium silicate (C_2S) and tri-calcium silicate (C_3S) come into contact with water during the hydration process of cement as shown in Equations 1 and 2. These reactions result in calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). The excess ($Ca(OH)_2$) reacts with alumina and water to form calcium aluminate hydrate (C-A-H) as shown in Equation 3. Both C-S-H and C-A-H are required to produce cement gel. The presence of excess CH is harmful to concrete strength. The addition of pozzolanic material, such as RHA, in concrete causes a reaction between silica and the excess ($Ca(OH)_2$) that produces additional C-S-H gels, as shown in Equation 4. The gel fills the pores of the concrete and reduces capillary leading to stronger and more durable concrete. Givi et al. *(5)* also evaluated the properties of RHA-modified mortar and concrete samples, and it was concluded that the inclusion of RHA in concrete showed improved mechanical properties of concrete.

$$\underset{(C3S)}{2(3CaO\text{-}SiO_2)} + 6H_2O \rightarrow \underset{(C\text{-}S\text{-}H)}{3CaO.2SiO_2.3H_2O} + \underset{(CH)}{3Ca(OH)_2} \qquad [1]$$

$$\underset{(C2S)}{2(2CaO\text{-}SiO_2)} + 4H_2O \rightarrow \underset{(C\text{-}S\text{-}H)}{3CaO.2SiO_2.3H_2O} + \underset{(CH)}{Ca(OH)_2} \qquad [2]$$

$$\underset{(CH)}{Ca(OH)_2} + H_2O + Al_2O_3 \rightarrow \underset{(C\text{-}A\text{-}H)}{A1_2O_3.Ca(OH)_2.H2O} \qquad [3]$$

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.H_2O \qquad [4]$$

De sensale *(6)* studied the long-term (up to 91 days) compressive strength of RHA-modified concrete. This study used RHA from two sources: one from a local paddy milling industry of Uruguay (UY RHA) as industrial residue and another from the USA (USA RHA) obtained through controlled incineration process. The silica contents of UY RHA and USA RHA were 87.2% and 88%, respectively. Three different water-cement ratios (0.50, 0.40, and 0.32) with two different RHA contents (10% and 20%) were incorporated into this study. Local fine aggregate, coarse aggregate (crushed granite), and Type I OPC with a superplasticizer (sulfonated naphthalene formaldehyde condensate) was used in this study. Cylindrical samples of 150 mm in height and 300 mm in diameter were cast, and an external vibrator was used for compaction. The compressive strength of the cylinders at 7, 28, and 91 days was determined. It was found that the 91-day compressive strength of RHA-modified concrete was higher than the unmodified concrete (no RHA). A 20% RHA in USA RHA was found optimum. The long-term compressive strength values (at 91 days) of both USA RHA and UY RHA were higher than the base concrete (without RHA), but USA RHA exhibited a higher strength than UY RHA. This possibly occurred due to the filler effect of residual UY RHA and the long-term pozzolanic effects of USA RHA.

Habeeb and Fayyadh *(7)* investigated the mechanical properties of 20% RHA-modified concrete with three different particle sizes (i.e., 31.3, 18.3, and 11.5 µm). The RHA used in this study had the amorphous silica content of 88.32% and was obtained from burning in a Ferro-cement furnace with an incineration temperature below 700°C. The specific gravity values of the fine and coarse aggregates were 2.61 and 2.65, respectively. The measured absorption values of fine and coarse aggregates were 0.76% and 0.5%, respectively. ASTM Type I cement with a water-cement ratio of 0.53 was used to prepare the concrete mix. It was observed that the density of the RHA-modified concrete mix was smaller compared to the Control mix due to a low specific gravity of RHA. The mix with finer RHA yielded to a higher density than the coarser RHA. The 20% RHA-modified concrete showed improved mechanical properties such as compressive, tensile, flexural strength, and modulus of elasticity in comparison to the Control specimen (no RHA). This might be due to the formation of more calcium silicate hydrate (C-S-H) from the reactions of RHA with calcium hydroxides. In addition, the finer RHA (11.5 µm) yielded improved mechanical properties than the coarser RHA (31.3 µm). It was reported that the increased pozzolanic activities and packing abilities of finer RHA were responsible for the superior performance of finer RHA-modified concrete.

Rashid et al. *(8)* evaluated the durability of RHA-modified mortars. In this study, six different percentages (0%, 10%, 15%, 20%, 25%, and 30%) of OPC were replaced by RHA. River sand was incorporated in this study, and it had a specific gravity and a fineness modulus value of 2.64 and 2.73, respectively. For each percentage of RHA, 50 mm cubical mortar specimens were made with a sand to binder ratio of 1:3. The specimens were tested for compressive strength after 3, 7, 28, and 90 days of curing. From the consistency test results, it was observed that an increment in the RHA dosages increased the water demands. This happened due to the higher specific surface area and the hygroscopic nature of RHA. It was also observed that the 25% and 30% RHA concrete samples exhibited lower compressive strength than the Control. The compressive strength of the 15% and 20% RHA-modified concrete was lower than that of the Control sample at 3, 7 and 28 days, but at 90 days, these RHA-modified mortars showed a higher strength than the Control. Thus, the 20% RHA was found to be the most effective in improving concrete durability.

Zhang et al. *(9)* studied the effects of the 10% RHA and the 10% silica fume (SF) in cement (ASTM Type I) paste and concrete. This RHA had a specific surface area of 38.9m^2/g and a silica content of 87.2%. Concrete cubes and cylinders were made and tested for compressive strength. They were also analyzed with x-ray diffraction (XRD) to understand the strength development phenomena. It was reported that the compressive strength values of cement paste samples with the 10% RHA and 10% SF were about the same as that of the Control sample at 28 days, but lower than the Control at 90 and 180 days. However, the RHA- and SF-modified concrete exhibited more compressive strength than the Control. The difference in strengths between RHA-modified cement paste and RHA-modified concrete could be due to interfacial zone improvement between the aggregate and the binder in concrete. The XRD analysis showed that the main hydration products in the RHA modified paste was $Ca(OH)_2$ and calcium silicate hydrate (C-S-H). The RHA inclusion in concrete reduced the porosity and $Ca(OH)_2$ content in the interfacial zone. The SF-modified concrete exhibited better performance than the RHA-modified concrete due to SF being finer than RHA.

Alkali-silica reaction (ASR) in concrete is a common form of alkali-aggregate reaction. It occurs due to the chemical reactions of alkali oxides and silica. Generally, alkali oxides are a composition of cement and silica compounds that come from the reactive aggregate used in the concrete. The reaction between silica and alkali oxides results in ASR gel that expands in the presence of moisture, thus creating cracks in concrete. The entire process is shown in Equations 5 and 6. Findings of pertinent literature regarding the ASR problem in concrete are discussed next.

Alkali hydroxide (from cement) + Silica (from aggregate) → Alkali-silica gel [5]

Alkali-silica gel + moisture → Concrete expansion and cracking [6]

Abbas et al. (*10*) studied the use of RHA in mortar bars at our different percentages (i.e., 10%, 20%, 30% and 40% by weight) to mitigate ASR in concrete. The mortar bars were prepared with alkali-silica reactive aggregate (sand from Dolomite-limestone rock) and OPC according to ASTM C1260. Three mortar bars were made for each RHA dosage and readings were taken up to 28 days. To observe the pozzolanic activity, thermo-gravimetric analysis (TGA) and differential thermal analysis (DTA) were conducted on the 20% RHA-modified mortar cubes cured for 28 days. In addition, the chemical compositions of cement and RHA were determined by using X-ray diffraction (XRD). Moreover, cracking phenomena and the amount of CaO/SiO_2 was determined by scanning electron microscopy (SEM) imaging and energy dispersed X-ray spectroscopy (EDS), respectively. From TGA and DTA analyses, it was found that the peak of the DTA curve of the 20% RHA-modified cube between 250^0C and 350^0C attributed to the presence of calcium silicate hydrate (C-S-H). The 20% RHA-modified specimens reduced the mass loss from 29% to 26% compared to the Control specimen. It also indicated the reduction of $Ca(OH)_2$ due to the pozzolanic reaction of RHA. It was reported that the reduction of the amount of $Ca(OH)_2$ could reduce ASR expansion. Further, it was observed that the RHA in the mortar bar reduced ASR expansion, and the 40% RHA modified mortar bar showed the maximum reduction of expansion (50% of the Control). In addition, SEM images showed cracking in Control specimen, while the RHA-modified showed no cracking. Moreover, the EDS analysis exhibited lower amounts of CaO/SiO_2 in the 20% RHA-modified mortar than the control, indicating the reduction of ASR expansion.

Le et al. *(11)* assessed the performance of RHA and SF in self-compacting high-performance concrete by mitigating ASR. Both reactive (i.e., greywacke sand) and non-reactive (i.e., basalt sand) aggregates were used in preparing mortar bars with three different sizes (5.7 µm, 7.7 µm, and 15.6 µm) of RHA. It was found that SF was more effective than RHA in mitigating the ASR expansion of the mortar bars containing the reactive aggregate. Moreover, finer RHA (5.7 µm) containing mortar bars showed less expansion than the coarser RHA (15.6 µm). Finer RHA had higher pozzolanic activity than the coarser one, resulting in better refinement of pores in finer RHA containing mortar bars than coarser RHA-modified mortar bars. Both SF and RHA were found to be effective in mitigating ASR expansion of the reactive aggregate incorporating mortar bars. In the case of non-reactive aggregates, the Control specimen showed lower expansion than the RHA modified mortar bars. The mortar bar made with coarser RHA (15.6 µm) and non-reactive aggregates showed significantly more ASR expansion and substantial cracking than the control specimen. This was caused because the ASR gel produced inside the RHA particle, which was identified by EDX analysis. In this case, the ASR reaction might have happened faster than the pozzolanic reaction of RHA.

Le et al. *(11)* also evaluated the effect of pore types on the performance of the RHA- and SF-modified mortar paste. RHA used in this study contained both macroporous (> 50 nm) and mesoporous (2-50 nm) particles. Two different RHA and SF dosages (10% and 20%) were used as replacements of the OPC. The pore volume, specific surface area and water demand of RHA were greatly influenced by the pore size distribution. The rheological behavior and flowability of RHA- and SF-modified mortar were also influenced by these properties. It was found that plastic viscosity and yield strength were increased by using RHA in mortar paste. Moreover, pore volume and water demand of RHA increased with the increment of the particle size of RHA. The incorporation of finer RHA at higher content exhibited improved rheological properties of RHA mortar paste.

Akhnoukh et al. *(12)* reported premature concrete distress in pavement and barriers due to ASR in Arkansas and investigated for possible mitigations of such distresses by using local aggregates. As illustrated by these authors, the necessary components for ASR reactions are shown in Figure 1. The key factors that lead to the pavement cracking were the use of the local reactive aggregates, preparation of concrete without any supplementary cementitious material (SCM), and the presence of high moisture content in the air. It was found that the usage of 15% SF as a partial replacement of cement in concrete reduced the ASR expansion by 50% than the Control sample. Moreover, the use of the 30% CFA in concrete was found to be optimum in mitigating the ASR expansion.

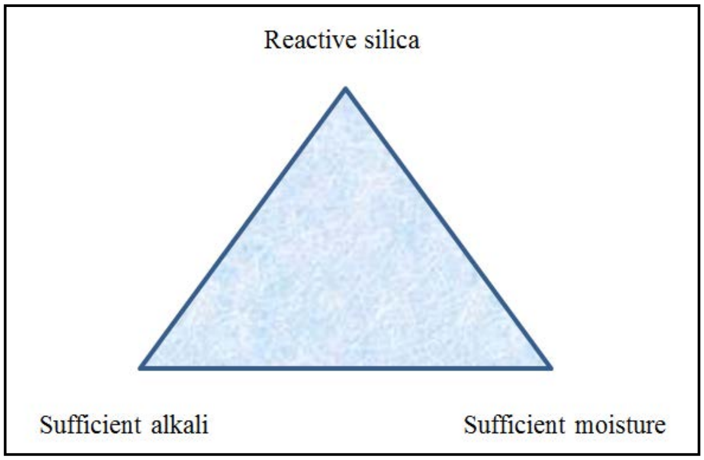

Figure 1. Necessary components for ASR reaction *(12)*.

Venkatanarayanan and Rangaraju *(13)* studied the performance of the cement concrete incorporating both unground RHA (URHA) and ground RHA (GRHA) having low carbon contents. The strength and durability of RHA-modified concrete along with properties such as the flow behavior, the setting time of RHA mortar paste, and depletion of calcium hydroxide of RHA were evaluated in this study. It was found that both URHA and GRHA showed improved properties than the Control except the setting time. However, GRHA showed better results in terms of the aforementioned properties compare to URHA. It might happen due to the internal porosity and incomplete pozzolanic reaction of the coarse URHA. Therefore, improved concrete properties were observed due to the grinding of the coarse URHA.

Preliminary data of the current study was published in the literature *(e.g., 14)*. The RHA used in this study had a particle size of 600 µm, which was thirteen times coarser than the cement particles. This RHA was used as a partial replacement of Type I OPC to prepare concrete cylinders (150 mm × 300 mm) and beams (600 mm × 150 mm × 150 mm). Two different percentages (i.e., 10% and 20% by weight) of RHA were used in replacement of Type I OPC in this study. The RHA-modified concrete was tested for mix properties of the fresh concrete (i.e., slump, air content and unit weight) and mechanical properties of hardened concrete (i.e., compressive, tensile, flexural strength, modulus of elasticity and Poisson's ratio). A significant amount of strength reduction of the RHA-modified concrete was reported due to the use of coarse RHA. The 10% RHA-modified concrete exhibited 56% more compressive strength than the control sample. The tensile and flexural strength of the 10% RHA-modified concrete were 76% and 96% of the control sample, respectively. A similar pattern of strength reduction was found for the 20% RHA-modified concrete. Even still, the coarse RHA had the potential to be used in the controlled low strength material (CLSM) as flowable fill and backfills. It was suggested that the coarse RHA be further ground to a finer particle to get improved concrete properties.

In the presence of deicing chemicals, concrete experiences significant distresses during the freezing and thawing cycle. Deicing chemicals also creates osmotic and crystallization pressure in concrete that increases the potential of frost damage. The freezing point of the concrete pore solution can be decreased by the presence of salts in the deicing solution resulting in developing hydraulic pressure in concrete. Thus, the surface of concrete exposed to deicing chemicals undergoes scaling due to the combined effect of osmotic, crystallization and hydraulic pressure.

Wang et al. *(15)* investigated concrete distresses due to the different deicing chemicals under various exposure conditions. Five deicing chemicals (i.e., calcium chloride ($CaCl_2$), sodium chloride (NaCl), potassium acetate, calcium chloride with a corrosion inhibitor, and an agricultural deicing product) were used in this study. The authors tested fifteen paste samples and twelve concrete cube samples for each of the two different exposure conditions (i.e., freezing-thawing and wetting-drying). Freezing-thawing was continued for 60 cycles and the wetting-drying process continued up to 130 cycles. The properties of concrete such as mass loss, scaling, compressive strength, chemical penetration, and microstructure were evaluated. It was found that the calcium chloride, with and without a corrosion inhibitor, showed the most severe concrete distresses among the five deicing chemicals. The use of potassium acetate and the agricultural deicing product showed few cracks and no chemical damages. Significant concrete damages were identified in both freezing-thawing and wetting-drying exposure conditions.

Yongjie et al. *(16)* reported that RHA can be used in improving physical properties of modified asphalt binder. They also pointed out that the asphalt binder modified with RHA is more stable when RHA content is less than 20%. The addition of RHA to the asphalt binder increases the viscosity, complex modulus and rutting factor ($G^*/\sin\delta$) at a high temperature. Because of this RHA addition, the deformation resistance of modified binders at a high temperature is greatly improved.

2. OBJECTIVES

The main objective of this study is to evaluate the usage of RHA as a construction material for concrete and asphalt. Specific technical objectives are given as follows:

- Evaluate chemical, physical, and strength properties of RHA modified concrete and asphalt;
- Evaluate the effect of curing time and environmental conditions on strength properties and durability of RHA-modified concrete and asphalt;
- Evaluate the optimum dosage of RHA in concrete;
- Assess the effectiveness of RHA in modifying asphalt binders; and
- Perform life-cycle cost analysis of RHA modified concrete and asphalt.

3. SCOPE

As mentioned earlier, the main goal of this proof-of-concept study is to assess the viability of RHA as an alternative cementitious material in preparing concrete and as an additive for modifying asphalt binders. To accomplish the goals of this study, limited laboratory tests and analyses have been conducted to find the workability and strength of RHA-modified concrete. RHA samples of three different sizes and two selected amounts were considered in the laboratory test plan. For comparison purposes, two other cementitious materials, namely, CF and SF were considered. With the application of RHA in concrete, the strength properties of concrete will vary based on the particle size and chemical composition of RHA. Various ASTM test methods and specifications were followed to evaluate properties of fresh and hardened concrete. Moreover, several Superpave tests following the AASHTO standards were conducted to evaluate the viability of RHA as a modifier of asphalt binders.

4. METHODOLOGY

In this study, unmodified and modified concrete samples were prepared and tested to observe the effects of RHA, CFA, and SF as pozzolanic materials. Properties of coarse aggregate (CA), fine aggregate (FA), RHA, CFA, and SF were also determined prior to the mix preparation. A concrete mix design was developed using the measured properties of CA, FA, and Type I OPC. Concrete cylinders and beams were then made and tested to evaluate mechanical properties such as compressive, tensile, flexural strength, modulus of elasticity, and Poisson's ratio of CFA-, SF-, and RHA-modified concrete. To examine the adverse effects of alkaline water on concrete, ASR tests were conducted on the mortar bars. Adverse effects of deicing agents were also evaluated in this study.

4.1. Material Selection and Collection

The CA and FA were collected from a local concrete ready-mix plant, Nettleton Concrete, Inc., of Jonesboro, Arkansas. The CA was crushed stone and the FA was stone sand. The ASTM Type I OPC was also collected from the same plant to continue the experiments in this study.

Three different types of RHA (RHA-1, RHA-2, and RHA-3) were incorporated into this study (Figure 2). To conduct a comparative analysis, CFA and SF samples were collected from a supplier approved by the ARDOT. The sources of the RHA, CFA, and SF along with their detailed information are shown in Table 2.

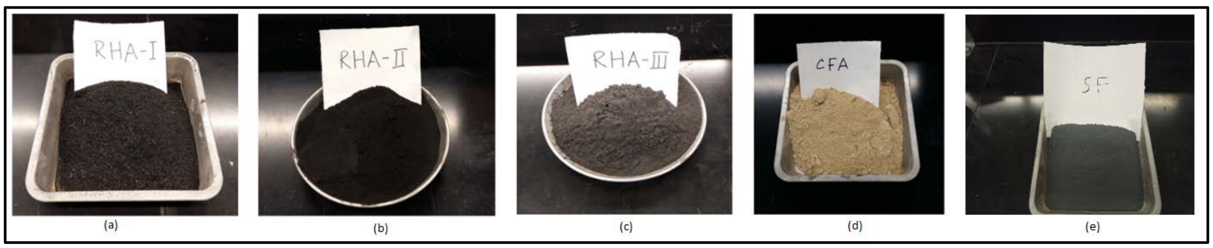

Figure 2. (a) 600-RHA, (b) 150-RHA, (c) 44-RHA, (d) CFA, and SF.

Table 2. Source information of RHA, CFA, and SF used in this study

Material	Description	Source of Material
RHA-1	Coarse RHA with particle size of 600 μm	Riceland Food, Inc., Stuttgart, AR
RHA-2	Finer RHA with particle size of 150 μm	Riceland Food, Inc., Stuttgart, AR
RHA-3	Finer RHA with particle size of 44 μm	Agrilectric, Lake Charles, LA
CFA	Particle size of 44 μm	Charah Inc., Louisville, KY
SF	Particle size of 45 μm	Norchem, Inc – NY

4.2. Data Collection of RHA, CFA, and SF

Physical and chemical data of RHA, CFA, and SF were collected from the suppliers and are presented in Table 3. These properties were compared with AASHTO M 321-04 (Standard Specification for High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete, Mortar, and Grout) and ASTM C 618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolana for Use in Concrete) specifications.

Table 3. Chemical properties of RHA, CFA, and SF.

Chemical Properties	RHA-1	RHA-2	RHA-3	CFA	SF	AASHTO M 321-04
Reactive oxides (SiO2+Al2O3+ Fe2O3)	95.50%	95.50%	86.80%	60.02%	93.47%	75% (minimum)
Loss on ignition (LOI)	8.98%	8.98%	5.40%	0.22%	3.55%	6% (maximum)
Moisture content	3-5%	3-5%	2.60%	0.04%	0.25%	3% (minimum)

From Table 3, it is seen that all RHA and SF samples met the AASHTO M 321-04 specifications for reactive oxides, whereas CFA did not meet the AASHTO M 321-04 specification. CFA met ASTM C618 specifications for fly ash or natural pozzolan. The AASHTO M 321-04 specification is given for all high-reactive pozzolans, whereas ASTM C618 is given for fly ash or natural pozzolan. Therefore, CFA can be still considered as pozzolanic material. It is also seen that RHA-1 and RHA-2 did not meet the specifications for moisture content and loss on ignition. However, SF used in this study met all the specifications.

RHA-1 was treated mechanically to obtain RHA-2, and it was further treated with the application of heat to obtain RHA-3. The mechanical treatment was done at the Riceland Facility at Stuttgart, AR and the heat treatment was done at the commercial laboratory of Agrilectric at Lake Charles, LA. The research team also attempted to apply heat treatment (below 700^{o}C) using a small furnace and pottery kilns available at the A-State laboratory. Due to the production of a small quantity of fine RHA using the small furnace and non-uniform burring in the pottery kilns, these in-house treatments were discontinued. Therefore, treated RHA samples obtained from Riceland and Agrilectric were used in this study.

4.3. Mix Design

To prepare the test samples, a mix design was developed per ACI 211.1-91 (Absolute Volume Method). The properties required for the mix design are presented in Table 4. The concrete structure, which can be exposed to freezing and thawing in a moist condition, was chosen for the mix design. For this study, a locally available Type I OPC was considered, and it had a specific gravity of 3.15. The design water-cement ratio for this study was 0.45. A slump value of 75 mm was considered to prepare the mix design. Using the ACI provided charts, the amounts of CA, FA, water, and cement were determined per cubic yard of concrete. Later, using the properties of CA and FA, moisture correction was applied. The mix ratio of Type I OPC, FA, and CA was determined as 1.0:1.42:2.90. The mix ratio was followed during the batching process in the lab.

Table 4. Properties of materials required for mix design.

Material	Required Properties
Cement	1. Type of cement 2. Specific gravity
Coarse Aggregate (CA)	1. Nominal maximum size 2. Bulk specific gravity 3. Percent absorption 4. Dry-rodded density
Fine Aggregate (FA)	1. Fineness modulus 2. Bulk specific gravity 3. Percent absorption

4.4. Tests on RHA-Modified Concrete

Various ASTM test methods were followed to determine the properties of CA and FA required for the concrete mixes. Afterward, mix properties of fresh concrete, as well as mechanical properties of hardened concrete, were estimated in accordance with the ASTM guidelines. The test methods followed in this study are summarized as follows:

4.4.1. Properties of CA and FA

The ASTM C136 method was followed to perform a sieve analysis of CA and FA with the ASTM standard sieves. The fineness modulus of FA and the nominal maximum size of CA were determined from the sieve analysis. The specific gravity and absorption values of CA and FA were determined per ASTM C127 and ASTM C128, respectively.

4.4.2. Gradation of RHA

The grain size distribution of each type of RHA was determined by using ASTM standard sieves. The gradation curves of RHA-1, RHA-2, and RHA-3 can be seen in Appendix A. The gradations of these RHA samples were used to measure their average particle sizes.

4.4.3. Specific Surface Area of RHA, CFA, and Cement

The specific surface areas of RHA, CFA, SF, and Type I OPC were determined by following the BET (Brunauer, Emmett, and Teller) method. The BET analysis was done with the help of a NOVA 2200e analyzer (Figure 3). The BET equation, representing an adsorption isotherm, is shown in Equation 7.

$$\frac{1}{W(\frac{P}{P_0})^{-1}} = \frac{1}{W_m C} + \frac{C-1}{W_m C}\left(\frac{P}{P_0}\right) \quad [7]$$

where:
W = weight of gas adsorbed,
P/P_0 = relative pressure,
P = equilibrium adsorption pressure,
P_0 = saturation vapor pressure,
Wm = weight of adsorbate as monolayer, and
C = BET constant.

In this study, the multi-point BET mode of NOVA 2200e analyzer was used to determine the specific surface area within the relative pressure range of 0.05 to 0.30, per the ASTM D1993-03 method. To maintain a constant temperature of 77^{o}K during the test, liquid nitrogen was used to achieve adsorption isotherms during the test. Since nitrogen is an inert gas and its molecular size is known, it is used as the adsorbate gas in this study. Many other researchers *(e.g., 17, 18)* also used nitrogen as the adsorbate gas in their corresponding BET analyses in the test. The sample cell was calibrated before conducting the actual BET test.

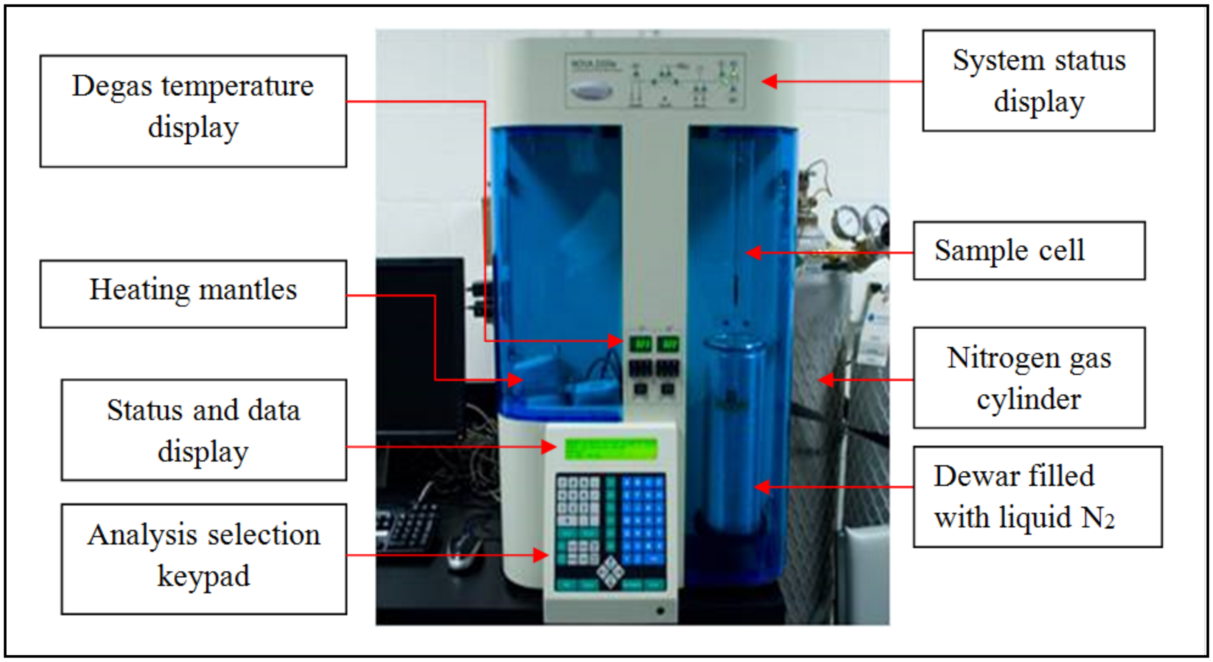

Figure 3. NOVA 2200e analyzer.

4.4.4. Properties of Fresh Concrete

The properties of the fresh concrete mix such as the slump, unit weight, and air content were determined by following ASTM methods. The slump, unit weight and air content of the concrete mix were estimated per ASTM C143, ASTM C138, and ASTM C231, respectively.

Devices used in the temperature measurement of fresh concrete are shown in Figure 4 (a). A300-mm long slump cone with a 100-mm diameter at the top and a 200-mm diameter at the bottom was used to assess the workability of concrete (Figure 4(b)). In this process, a fresh concrete was poured into the slump cone at three layers. Each layer was tamped 25 times with a tamping rod of 16 mm diameter. Then the slump cone was lifted vertically upward and the slump value was measured with the help of a ruler. The air content of the concrete mix was determined by using the pressure method, as shown in Figure 4 (c). To measure the unit weight of the concrete, a 0.25ft^{3} cylindrical mold was used (Figure 4 (d)).

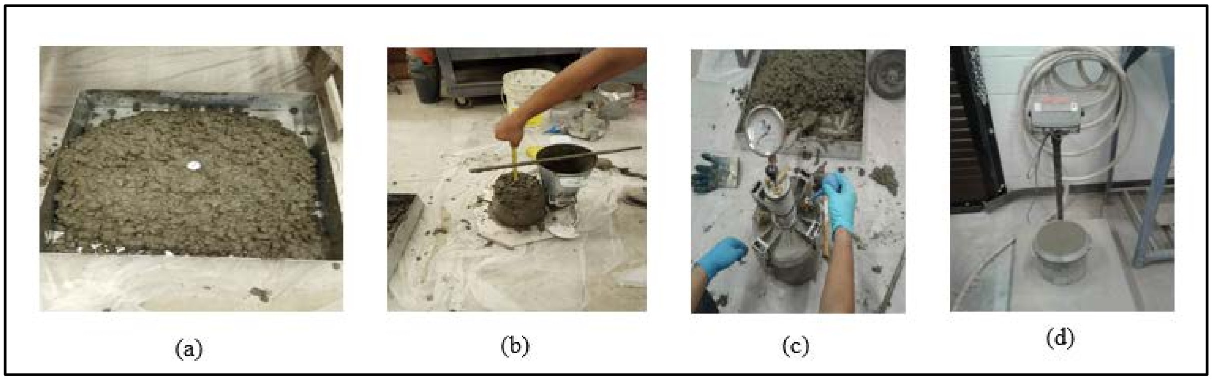

Figure 4. (a) Temperature test, (b) Slump test, (c) Air content test, and (d) Unit weight test.

4.4.5. Curing of the Test Samples

The fresh concrete mix was used to cast cylinders (150-mm diameter and 300-mm height) and beams (600-mm long with a cross-section of 150-mm by 150-mm). Plastic cylindrical molds and steel beam molds were used to cast cylinders and beam samples, respectively. After 24 hours of casting, cylinders and beams were demolded and placed in a water bath for curing at a room temperature of 23^{o}C per ASTM C31. Tap water was used for curing the test samples. Test samples were kept in the water bath until the age of testing, as shown in Figure 5.

Figure 5. Curing process of concrete cylinder and beam samples.

4.4.6. Compressive Strength Test

Per the ASTM C39-04a method, cured cylindrical samples were removed from the water bath, and loaded with the aid of a Forney compression machine. The compressive strength was measured at 7, 14, 21, and 28 days. For each test condition, two samples were tested and the average of the two test results was reported. A typical compressive strength test setup is shown in Figure 6.

Figure 6. Compressive strength test.

4.4.7. Tensile Strength Test

Splitting tensile strength of cylindrical samples was measured in accordance with the ASTM C496 method. In this test, 28 days of cured samples were used as shown in Figure 7. Like the compressive strength tests, two samples were tested for each test condition and the average value was reported.

Figure 7. Tensile strength test.

4.4.8. Flexural Strength Test

The beam samples were tested according to the ASTM C293 method to determine the flexural strength of concrete (Figure 8). As mentioned earlier, beam samples were cured for 28 days in a moist cabinet before testing. For each test condition, one beam sample was prepared and tested. The two-point loading method was followed during the test.

Figure 8. Flexural strength test with two-point loading set up.

4.4.9. Modulus of Elasticity and Poisson's Ratio Test

Modulus of elasticity and Poisson's ratio values of hardened concrete samples were calculated per the ASTM C469 method. To determine the modulus of elasticity, a Universal Testing Machine (UTM) was used to apply the load corresponding to 40% of the 28-day compressive strength of the cylindrical sample (Figure 9). Generally, concrete samples of 28-day compressive strength test samples were used for the determination of the modulus of elasticity.

A compressometer and two strain gages were used to measure Poisson's ratio of the concrete (Figure 10). Longitudinal and lateral strains were determined from the data of the compressometer and strain gages mounted on the surface of the test sample, respectively. A portable strain indicator was used to get the readings from the mounted strain gages.

Figure 9. Modulus of elasticity test.

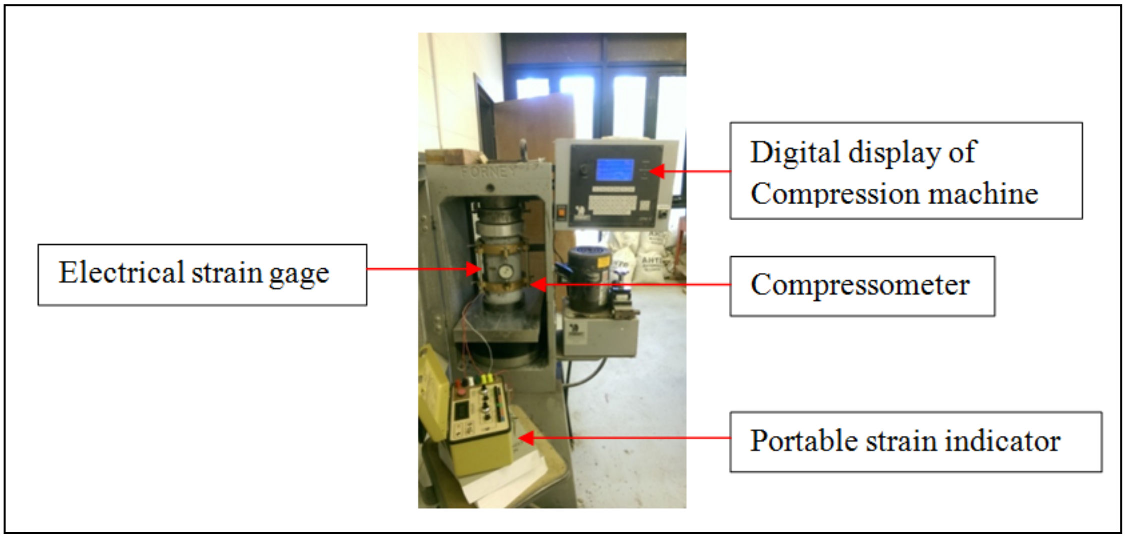

Figure 10. Measurement of Poisson's ratio of concrete.

4.4.10. Alkali-silica Reaction (ASR) Test

Alkali-silica reaction (ASR) test was conducted to predict the expansion of concrete in the presence of alkaline water and reactive aggregate. To conduct the test, 285-mm by 25-mm by 25-mm mortar bars were prepared (Figure 11(a)). Type I OPC was used in the preparation of mortar bars with cement to the aggregate ratio of 1:2.25 and with a water to cement ratio of 0.47. Mortar bars were mixed per the ASTM C 305 method and molded within 2 minutes and 15 seconds. Molds were filled in two equal layers and each layer was compacted with a tamper until obtaining a homogenous mix. Three samples for each test condition were prepared and kept in the moist room for 24 hours. Afterward, mortar bars were demolded and placed in water at 80°C for another 24 hours. Mortar bars were then removed from the water and initial reading was taken. The mortar bars were then placed in 1N NaOH solution for next 14 days (Figure 11(b)) and intermediate readings (expansion) were taken at 4, 8, 12, and 14 days, respectively. A linear variable differential transducer (LVDT) was used to take the readings with the help of a data storage unit (Figure 11).

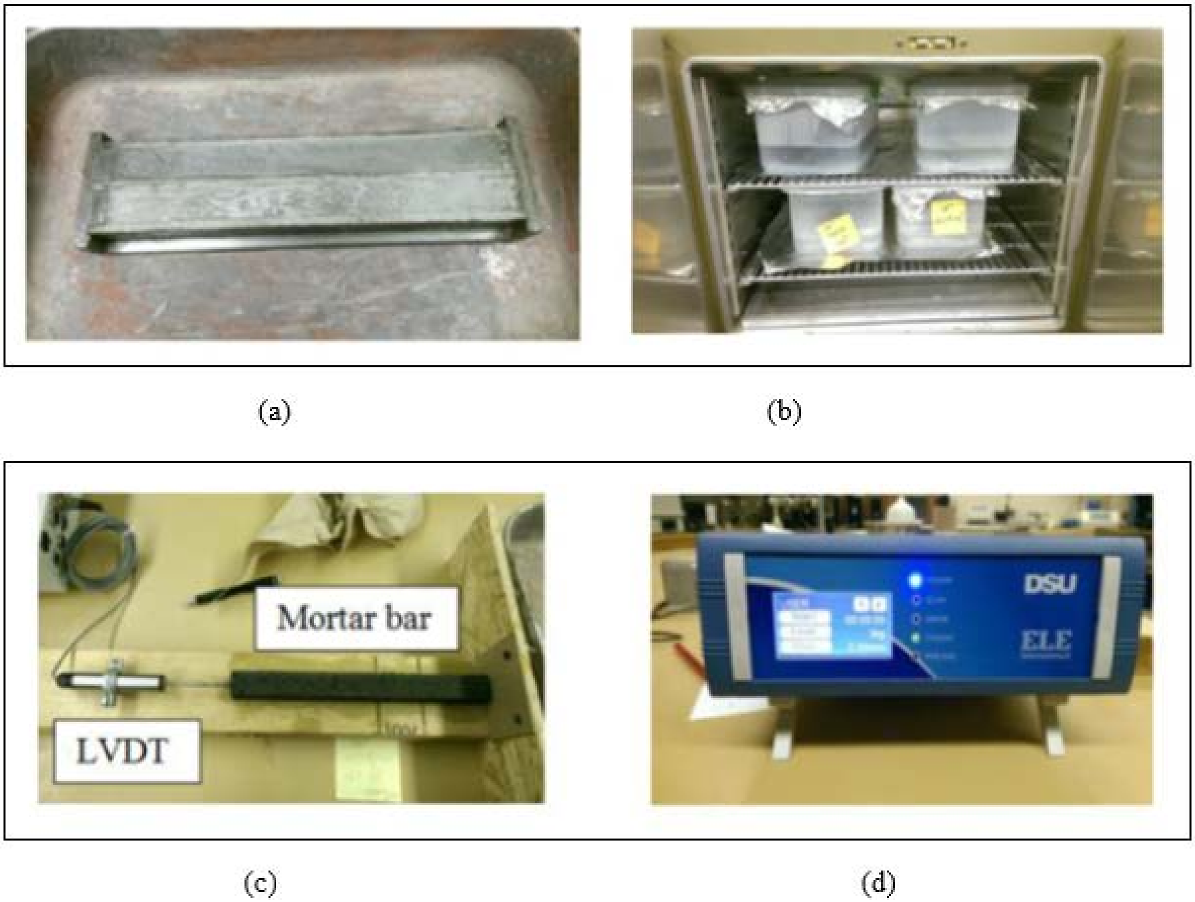

Figure 11. (a) Mortar bar casting mold, (b) Curing mortar bar in 1N NaOH at 80ºC, (c) Use of LVDT to take readings, and (d) Data storage unit.

4.4.11. Scaling Resistance Test

This test was conducted to evaluate the effect of a deicing chemical on CFA-, SF-, and RHA-modified concrete. Concrete mortar bars of 285-mm × 25-mm × 25-mm dimensions were prepared using 10% RHA (i.e. RHA-1, RHA-2, and RHA-3), 10% CFA and 10% SF as partial replacement of Type I OPC. Anhydrous calcium chloride was used as the deicing chemical. After preparing the mortar bars per ASTM C305, they were submerged in a solution containing 40g of anhydrous calcium chloride per liter of water. The freezing and thawing cycle procedures were followed per the ASTM C672 method. Mortar bars were placed in a freezing environment of -12ºC for 16 hours. Afterward, mortar bars were removed from the freezer and placed in the laboratory at an air temperature of 23±2ºC with 55% relative humidity. The mortar bars were left drying in the air for 8 hours to complete one cycle. This cycle was repeated daily and continued for 10 cycles. At the end of the 10th cycle, mortar bars were visually examined, and surface conditions were rated from 0 to 5, with “0” for no scaling and “5” for severe scaling in accordance with the ASTM C672 method.

4.5. Tests on RHA-Modified Asphalt

The collected RHA were blended with virgin performance grade (PG) binders (PG 64-22) obtained from local suppliers at different amounts (1%, 2% and 3%) and the blended binders were tested for determining workability and PG grading. The optimum dosage of RHA was estimated based on the performance test results. Workability and high-temperature properties were investigated in this study. The virgin blends underwent a round of rotational thin film oven (RTFO) and pressure aging vessel (PAV) aging since they experience aging while in production and in service. Thus, Superpave tests included rotational viscosity (RV) (AASHTO T 316), dynamic shear rheometer (DSR) (AASHTO T 315), RTFO (AASHTO T 240), and PAV (AASHTO R 28). These test methods are summarized next.

4.5.1. Rotational Viscosity (RV)

By following AASHTO T 316, a Rotational Viscometer (RV) (Figure 12) was used to conduct the viscosity test at temperatures from 135°C to 180°C in increments of 15°C. The viscosity test results were used to estimate the mixing and the compaction temperatures of the modified asphalt binders. A constant rotational speed and torque of a cylindrical spindle submersed in the asphalt binder was maintained during the test. Three measurements of viscosity were taken one minute apart at each temperature.

4.5.2. Rotational Thin Film Oven (RTFO)

Per AAASHTO T 240, a Rolling Thin Film Oven (RTFO) was used to simulate short-term aging of the binder. In this method, asphalt binders filled in glass bottles were left to age for 85 minutes by maintaining a constant temperature (163°C) and air flow (4 liters/min). The short-term aged modified asphalt binder was tested later for the long-term aging as well as for the other mechanistic tests. A pictorial view of the RTFO used in this study is shown in Figure 13.

Figure 12. Rotational viscometer.

Figure 13. Rolling thin film oven.

4.5.3. Pressure Aging Vessel (PAV)

A pressure aging vessel (PAV) apparatus (Figure 14) was used to simulate asphalt binder aging that occurs during 5-10 years of in-service pavements. Following the specification of AASHTO R 28, the short-term aged residue was exposed to 20 hours at 100°C and 2.1 MPa of pressure in the PAV chamber. After the PAV aging, the samples were collected for further testing.

Figure 14. Pressure aging vessel (PAV).

4.5.4. Dynamic Shear Rheometer (DSR)

Dynamic shear rheometer (DSR) test was conducted for the RHA-modified asphalt for characterizing the high-temperature viscoelastic properties of the asphalt binder. Two specific properties of asphalt binder, namely, complex shear modulus (G^*) and phase angle (δ), at desire temperatures, were obtained from this test. AASHTO T 315 specification was followed to perform the test. Figure 15 shows major components of a DSR device used in this study.

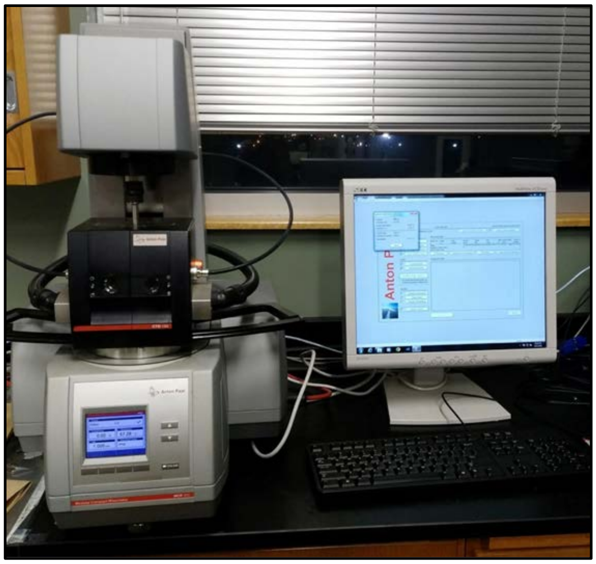

Figure 15. Dynamic shear rheometer (DSR).

4.5.5. Bending Beam Rheometer (BBR)

The RHA-modified samples were tested in a bending beam rheometer following the AASHTO T313 specification. The mid-point deflection of a simply supported beam subjected to a constant loading was measured to find the low-temperature stress-strain-time response within the viscoelastic range. A pictorial view of a BBR device is shown in Figure 16.

Figure 16. Bending beam rheometer (BBR).

5. FINDINGS

In this section, the findings of different test results are discussed. Several tests were conducted to evaluate different workability and performance properties of modified concrete and asphalt binder. Properties of fresh concrete, mechanical properties (compressive, tensile, flexural strength, modulus of elasticity, and Poisson's ratio) of hardened concrete, and results from ASR and deicing chemical tests are discussed in this section. Test results of rotational viscosity and dynamic shear rheometer tests of RHA-modified asphalt binder have also been discussed in this section.

5.1. Mix Design Properties

Different physical properties such as specific gravity, absorption, fineness modulus (FM), and nominal maximum size (NMS) of collected CA and FA were determined. The FM of FA was found to be 2.6, indicating a fine to medium sand. The NMS of CA was determined as 25-mm. The bulk specific gravity values of the CA and FA were found to be 2.61 and 2.58, respectively. The absorption of the CA and FA were determined as 0.9% and 0.3%, respectively, indicating that both aggregates are less absorptive to water. In this study, a Type I OPC was used as the binding material, and it had a specific gravity of 3.15.

5.2. Specific Surface Area of RHA, CFA, and Cement

For the development of the desired strength properties of concrete, the specific surface area of the cementitious material plays a vital role. It is directly correlated with the particle size and fineness of the materials *(5, 19, 20, 21)*. The measured BET surface areas of all tested materials are presented in Table 5. It was observed that the specific surface area increased with the decreasing particle sizes for different types of RHA. Therefore, finer RHA exhibited higher specific surface area. A similar observation was made by Habeeb and Mahmud *(19)*. These researchers conducted tests on three different RHA samples having average particle sizes of 31.3 µm, 18.3 µm, and 11.5 µm. The BET surface areas of these RHAs were found to be 27.4 m^2/g, 29.1 m^2/g, and 30.4 m^2/g, respectively. It was also observed that the BET specific surface area decreased by the increment of the particle size of RHA. Habeeb and Fayyadh (7) also reported that the specific surface area and particle size of the cementitious material affected the pozzolanic reactivity in concrete. The specific surface areas of the Type I OPC, CFA, and SF of the current study were found to be 47.178 m^2/g, 42.270 m^2/g, and 22.24m^2/g, respectively.

Table 5. Multi-point BET surface area (m^2/g).

RHA-1	RHA-2	RHA-3	CFA	SF	Type-I OPC
18.038	22.114	39.78	42.27	22.24	47.178

5.3. Fresh Concrete Properties

Properties of fresh concrete mixes are presented in Table 6. All RHA-1 modified concrete mixes had a slump greater than 3 inches (75 mm), but all RHA-2 and RHA-3 mixes showed slump values of less than 3 inches (75 mm). Concrete mixes with 10% and 20% RHA-1 showed slump values of 3.5 inches(88mm) and 4.5 inches (113mm), respectively. The slump of the Control mix was 3.5 inches (88 mm). Both 10% and 20% RHA-2 modified mixes had a very low slump of 1 inch (25 mm), indicating low workable mix. The slump values of the 10% and 20% RHA-3 modified concrete mixes were found as 1.5 inches (38 mm) and 2.0 inches (50 mm), respectively. Thus, the fine RHA modified mixes (RHA-2 and RHA-3) were stiffer than the coarse RHA mix (RHA-1). Therefore, finer RHA modified mix should be compacted by a vibrator per the ACI recommendation. However, low slump values of RHA-2 and RHA-3 indicated that the finer RHA modified mix required more water to get the same consistency as the Control mix. The adsorptive character of finer RHA and the non-spherical shape of the RHA are mainly responsible for the water demanding character of the finer RHA *(22, 23)*. However, the slump values of both the 10% and 20% CFA modified concrete mixes were found to be 5.0 inches (125 mm), indicating them as good workable mixes. For the 10% SF modified concrete, the slump value was found to be 5.0 inches (125 mm), and 3 inches (75 mm) slump value was determined for 20% SF modified concrete.

Table 6. Properties of fresh concrete

Type of RHA/Fly Ash	Percentage of Replacement	Slump (in)	Air Content (%)	Unit Weight (kg/m^3)
Control	0%	3.5	1.3	2435
RHA-1	10%	3.5	2.1	2259
RHA-1	20%	4.5	3.2	2179
RHA-2	10%	1.0	3.4	2323
RHA-2	20%	1.0	3.5	2275
RHA-3	10%	1.5	1.4	2371
RHA-3	20%	2.0	2.3	2323
CFA	10%	5.0	5.5	2355
CFA	20%	5.0	5.8	2355
SF	10%	5.0	5.0	2387
SF	20%	3.0	5.5	2291

Another important property of the fresh concrete mix is air content. In this study, the Control mix had an air content of 1.3%. It was seen that all modified concrete mixes had higher air contents than the Control mix. The air contents of the 10% and 20% RHA-1 modified mix were 2.1% and 3.2%, respectively. For RHA-2, the air contents for 10% and 20% RHA were 3.4% and 3.5%, respectively. In the case of RHA-3, the corresponding slump values for 10% and 20% RHA were 1.4% and 2.3%, respectively. It was also observed that the air content of the RHA, CFA, and SF modified mixes increased with the increment of RHA, CFA, and SF amounts. Alternatively, the concrete mix with 20% CFA, SF, and RHA exhibited higher air content than that with 10% CFA, SF, and RHA.

Following the ASTM C138 method, unit weights of all modified concrete mixes along with the Control mix were measured. From Table 6, it is seen that the unit weights of the 10% and 20% RHA-1 mixes were found to be 2259 kg/m^3 and 2179 kg/m^3, respectively. The Control mix exhibited a unit weight of 2435 kg/m^3. The unit weights of the 10% RHA-2, 20% RHA-2, 10% RHA-3, and 20% RHA-3 were determined as 2323 kg/m^3, 2275 kg/m^3, 2371 kg/m^3, and 2323 kg/m^3, respectively. Incorporation of RHA in concrete reduced the unit weight of the concrete mix since RHA is lighter than cement. A similar pattern was also observed for the CFA and SF modified concrete mixes. Both 10% and 20% CFA modified concrete mixes exhibited a unit weight of 2355 kg/m^3. On the other hand, 10% and 20% SF modified concrete mixtures showed unit weights of 2387 kg/m^3 and 2291 kg/m^3, respectively.

5.4. Compressive Strength

The quality of any concrete is determined based upon its mechanical strengths. This includes compressive strength. The modified concrete cylinders were cured up to 28 days to observe the effects of curing on the strength development of concrete. Figure 17 represents the effects of curing on the development of compressive strength of different modified concretes. Detailed results of the compressive strength tests of all modified concrete samples are provided in Appendix B. It was also observed that all modified concrete samples along with the Control mix showed a similar trend in the development of strength over the 28-day curing period.

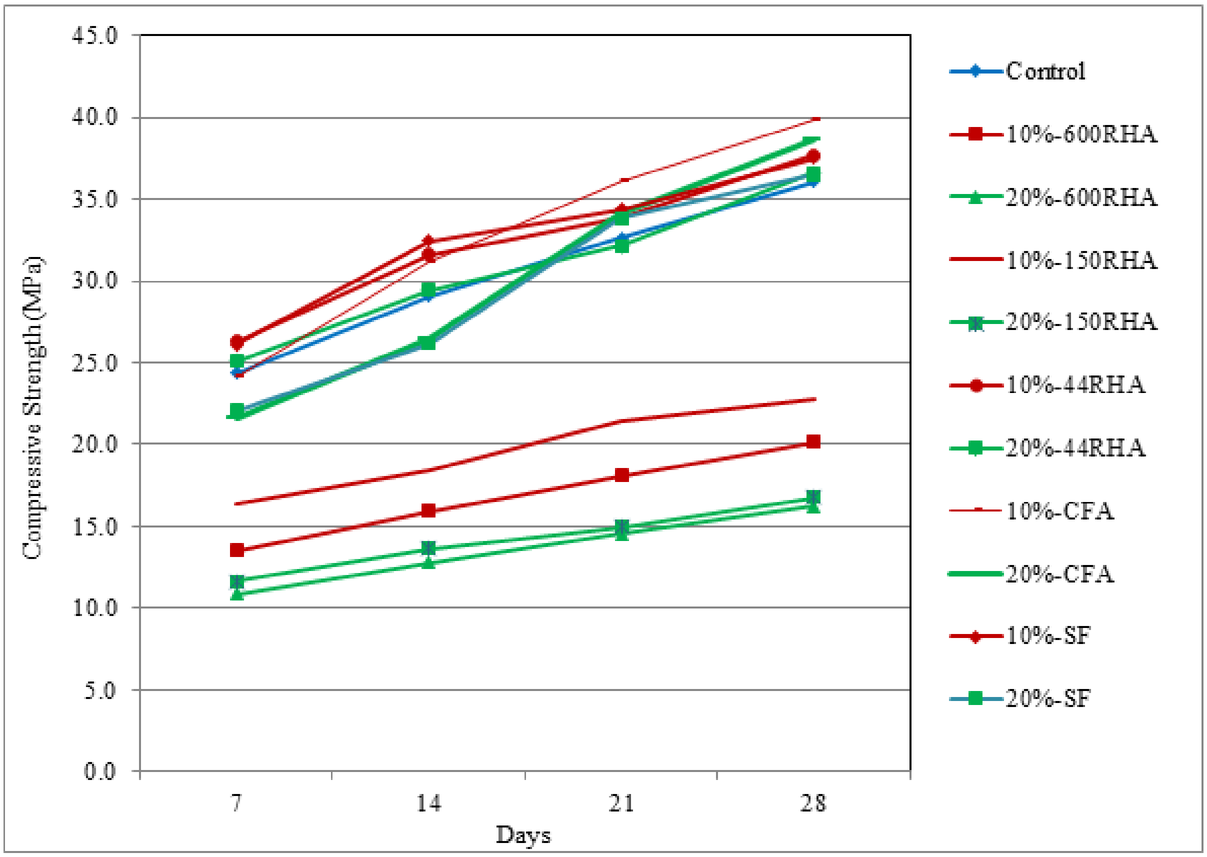

Figure 17. Compressive strength of different types of modified concrete.

The compressive strengths of all the modified concrete samples at 28 days are given in Figure 18. It was observed that the RHA-1 and RHA-2-modified concrete showed reduced strength compared to the Control sample. The 28-day compressive strengths of the 10% RHA-1, 20% RHA-1, 10% RHA-2 and 20% RHA-2-modified concrete were determined as 20.1 MPa, 16.2 MPa, 22.8 MPa, and 16.8 MPa, respectively. On the other hand, the Control mix sample showed a compressive strength of 36.1 MPa. The 10% RHA-1 and 10% RHA-2 modified concrete samples exhibited about 56% and 63%, respectively, of the compressive strength of the Control sample. In addition, 20% of RHA-1 and 20% of RHA-2 samples yielded 45% and 47%, respectively, of the compressive strength of the Control sample. Thus, a 10% replacement of both RHA-1 and RHA-2 showed the optimum strength. Moreover, RHA-2 showed more compressive strength than RHA-1. This was because RHA-2 was finer than the RHA-1, indicating finer RHA was more effective in filling the voids in the concrete.

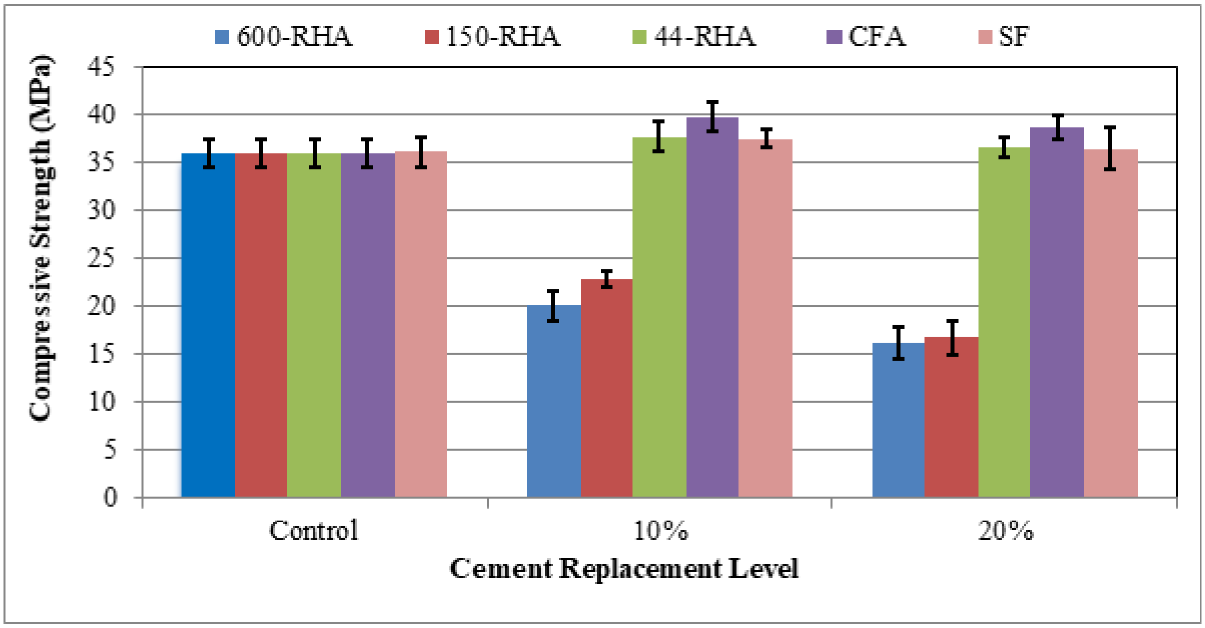

Figure 18. Comparison of compressive strengths of modified concrete.

The incorporation of coarse RHA in concrete might not generate enough cement gel to develop strength compared to the Control sample. Moreover, presence of the unburnt carbon content of RHA-1 and RHA-2 could have contributed to the reduction of strength in the concrete. Because of the low strength property, RHA-1 and RHA-2 could be used to prepare concrete in backfill and flowable fill projects that require a compressive strength of 8.3 MPa (1,200 psi) *(24, 25)*. Moreover, the 10% RHA-2 can be used in concrete sidewalk projects that need a compressive strength of20.6 MPa (3000 psi). Additional burning, grinding, or a combination of both burning and grinding of RHA-1 and RHA-2 is expected to help attain an improved compressive strength of concrete. In contrast, RHA-3 modified concrete showed more compressive strength than the Control sample. The 10% and 20% RHA-3 samples exhibited compressive strength values of 37.7 MPa (5,470 psi) and 36.6 MPa (5,310 psi), respectively, which are 4.4% and 1.4% higher in compressive strength compared to the corresponding strength of the Control sample. Thus, the incorporation of finer RHA that had a similar particle size of cement showed better strength development in concrete. Among all types of RHA samples, 10% RHA-3 showed the highest strength in this study. A similar trend was found in the case of CFA- and SF-modified concrete. The CFA-modified concrete yielded a compressive strength of 39.8 MPa (5,770 psi) and 38.7 MPa (5,610 psi), whereas SF- modified concrete resulted in a compressive strength of 37.54 MPa (5,445 psi) and 36.47 MPa (5,290 psi) for 10% and 20% replacement levels, respectively. Between the two CFA and SF dosages, the 10% CFA and SF was found to be the optimum based on the finding of the current study. The 10% replacement level of RHA-3, CFA, and SF modified concrete samples possibly generated more cement gel to fill the internal voids of concrete leading to formation of stronger concrete compared to the Control sample. Therefore, like CFA and SF, fine RHA can also be used as a partial replacement of cement in producing paving concrete or vertical structures.

5.5. Tensile Strength

Figure 19 represents the splitting tensile strengths of different modified concretes. Raw data of tensile strength tests can be found in Appendix C. It was seen that both RHA-1 and RHA-2 modified concrete samples showed a reduction of tensile strength compared to the Controlled sample. The 10% dosage level of both RHA-1 and RHA-2 modified concrete yielded tensile strengths of 2.69 MPa (390 psi) and 2.10 MPa (305 psi), respectively, whereas the Control had a tensile strength of 2.79 MPa (405 psi). In the case of 20% of RHA-1 and RHA-2, concrete samples showed tensile strength values of 2.72 MPa (395 psi) and 2.45 MPa (355 psi), respectively. Thus, concrete samples with 10% RHA-1, 10% RHA-2, 20% RHA-1, and 20% RHA-2 yielded about 96%, 97%, 75% and 88% of the tensile strength of the Control sample.

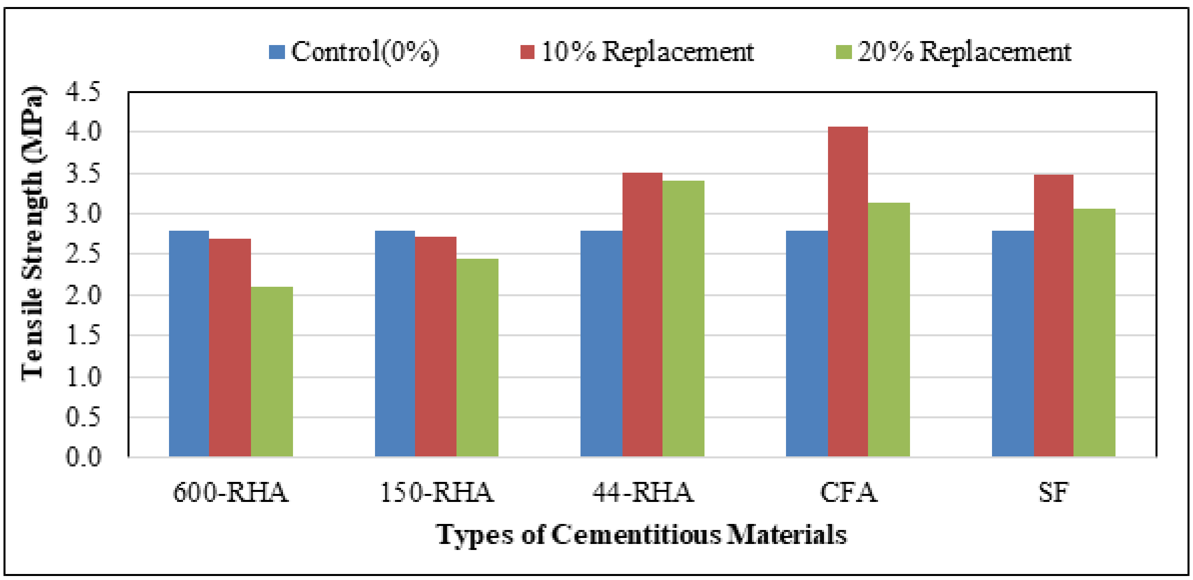

Figure 19. Comparison of tensile strengths of modified concrete.

RHA-3, CFA, and SF modified concrete samples showed more tensile strength values than the unmodified concrete. The 10% RHA-3 modified concrete sample showed a tensile strength of 26% more than the Control samples. The improved tensile strength of RHA-modified concrete was also reported by Givi et al. *(5)*. Moreover, the 10% dose of CFA in concrete yielded 45% more tensile strength than the Control, and the 10% SF modified concrete showed 25% more tensile strength than the unmodified concrete. Thus, the 10% dose of bothRHA-3, CFA, and SF was found to be the optimum amount regarding the tensile strength of concrete. The ACI suggested that the tensile strength of concrete would be 10% of the corresponding compressive strength of that concrete. It was also observed that 10%-RHA-3, 20%-RHA-3,10%-CFA and 10% SF-modified concrete showed tensile strengths of about 10% of their corresponding compressive strength.

5.6. Flexural Strength

The bending resistance of the concrete beam samples was determined by the flexural strength test. Flexural strength data of different types of concrete are presented in Figure 20 and raw data is provided in Appendix D. The flexural strength values of RHA-1 and RHA-2 concrete samples with the 10% RHA were found to be3.14 MPa and 3.62 MPa, respectively. For the 20% replacement level, the RHA-1 and RHA-2 modified concrete samples exhibited flexural strength values of 2.69 MPa (390 psi) and 2.79 MPa (405 psi), respectively. The corresponding flexural strength values of 10% RHA-1, 10% RHA-2, 20% RHA-1, and 20% RHA-2 were found to be 75%, 87%, 65% and 67% of the Control sample, respectively. RHA-3andCFA modified concrete samples showed significantly higher flexural strength than the Control sample. On the contrary, SF- modified concrete showed less flexural strength than the control sample. With a 10% replacement of cement RHA-3, CFA, and SF samples showed flexural strength values of 4.72 MPa, 5.03 MPa, and 3.45 MPa, respectively. Givi et al. *(5)* also reported that RHA-modified concrete could exhibit improved flexural strength. Regarding flexural strength, a 10% replacement of cement by CFA, SF, and RHAs was found to be the optimum dose in this study.

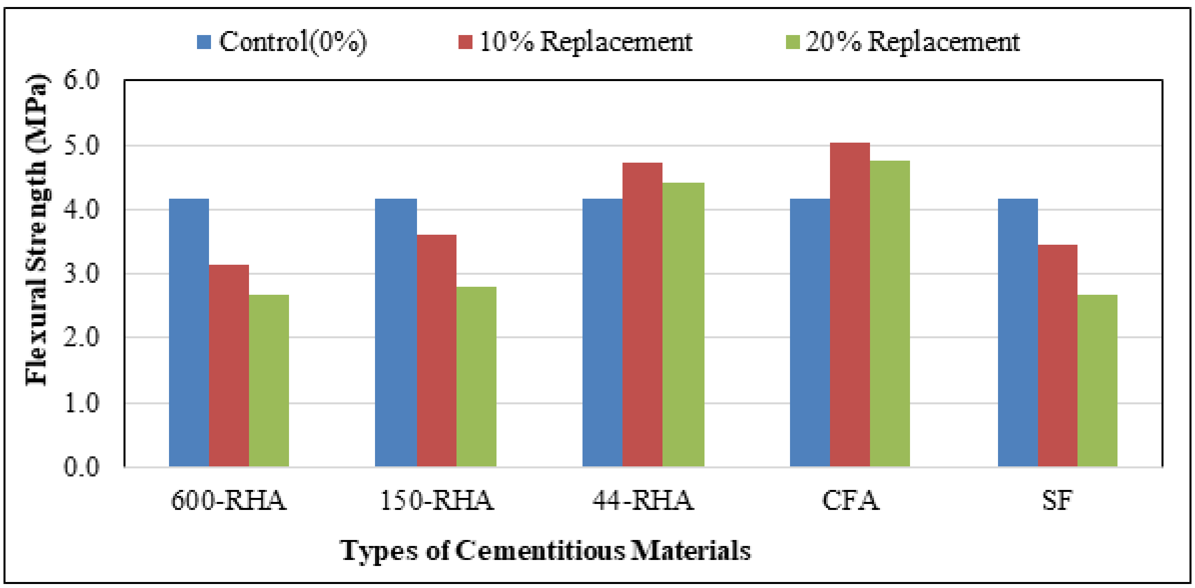

Figure 20. Comparison of flexural strength of modified concrete.

5.7. Modulus of Elasticity

Modulus of elasticity is an important parameter of the structural designs of concrete. After determining the elastic moduli of RHA- and CFA-modified concrete beam samples, they were compared with the estimated value using the ACI formula. The modulus of elasticity data of the tested samples is presented in Table 7. It was observed that RHA-1 and RHA-2 showed smaller moduli of elasticity compared to the Control, but an opposite phenomenon occurred for the RHA-3, CFA and SF modified concrete samples. The Control sample showed the modulus of elasticity of 3.12×10^4 MPa, but the 10% and 20% RHA-3 samples exhibited 3.19×10^4 MPa and 3.15×10^4 MPa, respectively. From Table 7 it is also seen that the 10% dose for CFA and all types of RHA yielded a higher modulus of elasticity than the 20% replacement level.

Table 7. Modulus of Elasticity of modified concrete.

Type of RHA/Fly Ash	Percentage of Replacement	Measured in the Laboratory (MPa)	Estimated from ACI formula: Ec=4700√f'c (MPa)
Control	0%	$3.12x10^4$	$2.83x10^4$
RHA-1	10%	$2.56x10^4$	$2.10x10^4$
	20%	$1.65x10^4$	$1.89x10^4$
RHA-2	10%	$2.60x10^4$	$2.24x10^4$
	20%	$2.03x10^4$	$1.92x10^4$
RHA-3	10%	$3.19x10^4$	$2.89x10^4$
	20%	$3.15x10^4$	$2.84x10^4$
CFA	10%	$3.35x10^4$	$2.96x10^4$
	20%	$3.27x10^4$	$2.92x10^4$
SF	10%	$3.95x10^4$	$1.82x10^4$
	20%	$4.9x10^4$	$1.8x10^4$

5.8. Poisson's Ratio

The Poisson's ratios of all modified concrete along with the Control sample are presented in Table 8. It is seen that 10% RHA-1, 10% RHA-2, 20% RHA-1 and 20% RHA-2 modified concrete showed Poisson's ratio values of 0.40, 0.35, 0.55 and 0.47, respectively. On the other hand, the Control sample had a Poisson's ratio of 0.28. The coarse RHA (RHA-1 and RHA-2) modified concrete samples exhibited higher Poisson's ratio than the regular unmodified concrete. RHA-3, CFA, and SF modified concrete showed a lower Poisson's ratios than the Control. Thus, Poisson's ratio of the modified concrete increased with the incorporation of coarser RHA (RHA-1 and RHA-2).

Table 8. Poisson's Ratio of modified concrete.

Control	RHA-1	RHA-1	RHA-2	RHA-2	RHA-3	RHA-3	CFA	CFA	SF	SF
0%	10%	20%	10%	20%	10%	20%	10%	20%	10%	20%
0.28	0.40	0.55	0.35	0.47	0.25	0.31	0.20	0.23	0.24	0.27

5.9. Alkali-silica Reaction (ASR) Tests

Concrete resistance to adverse weather, such as in the presence of alkaline water, can be measured by performing ASR testing. The ASR data for all modified concretes are presented in Figure 21. Figures 22 to 26 represent the ASR data for RHA-1, RHA-2, RHA-3, CFA, and SF, respectively.

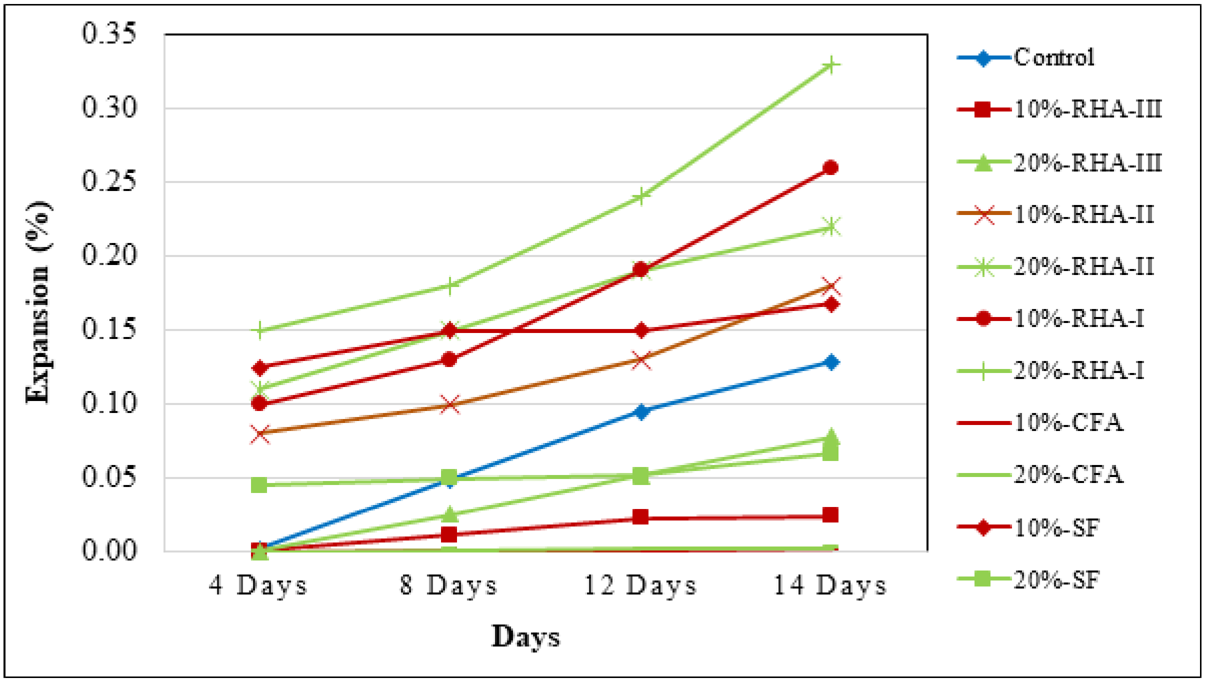

Figure 21. Effect of ASR on modified mortar bars.

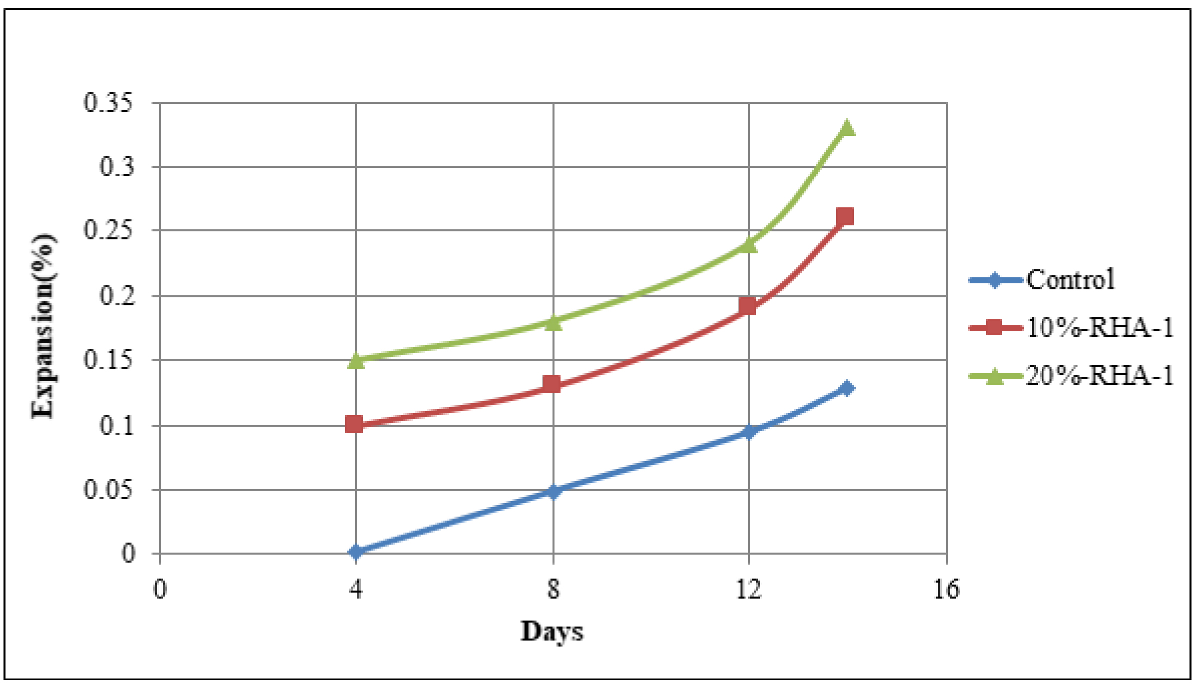

Figure 22. Effect of RHA-1 on ASR.

From Figure 22, it is observed that both the 10% and the 20% RHA-1 modified mortar bars exhibited expansion higher than the ASTM C1567 recommended a limit of 0.20%. Moreover, the expansions of 10% and 20% RHA-1 modified mortar bars were about 102% and 156% of the Control bar, respectively. Thus, RHA-1 failed to reduce the expansion of mortar bar due to ASR.

In the case of RHA-2, 20% RHAs also exhibited expansion more than the ASTM recommended a limit of 0.20% (Figure 23). Moreover, the 10% RHA-2 modified mortar bar showed expansion of less than 0.20%, but it was greater than the expansion of the Control bar. This phenomenon could be explained by the particle size and bulk density of the RHA. Use of coarse RHA created more inter-particle distance than the finer RHA resulting in the expansion of the mortar bars. In addition, the coarse RHA had a low bulk density that affected the RHA modified mix *(13)*. Thus, incorporation of the coarse RHA into concrete was found to be ineffective in producing a sufficient homogeneous mix and ASR gel to mitigate the ASR problem. SEM imaging along with the EDX analysis could be incorporated in the future to explain the ASR gel production phenomena inside the mortar bars.

In this study, RHA-3 not only met the ASTM specified limit but also showed less expansion compared to the Control bar. The RHA-3 mortar bar mitigated ASR expansion by 81% and 40% for the 10% and 20% replacement levels, respectively, compared to the Control sample (Figure 24). The finer RHA possessed higher surface area and lower pore volume. The pozzolanic activity initiated in the outer surface and later continued inside the pores of the RHA particles *(11)*. Thus, finer RHA-3 exhibited more pozzolanic reactivity due to the presence of more specific surface area and contributed to reducing the ASR expansion.

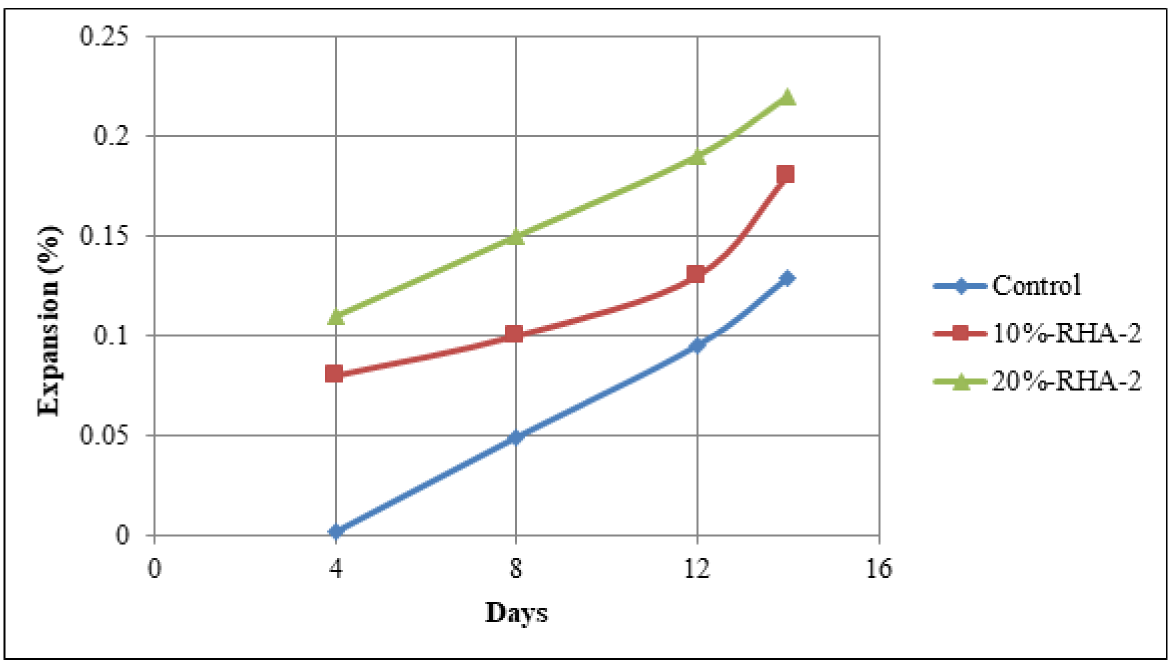

Figure 23. Effect of RHA-2 on ASR.

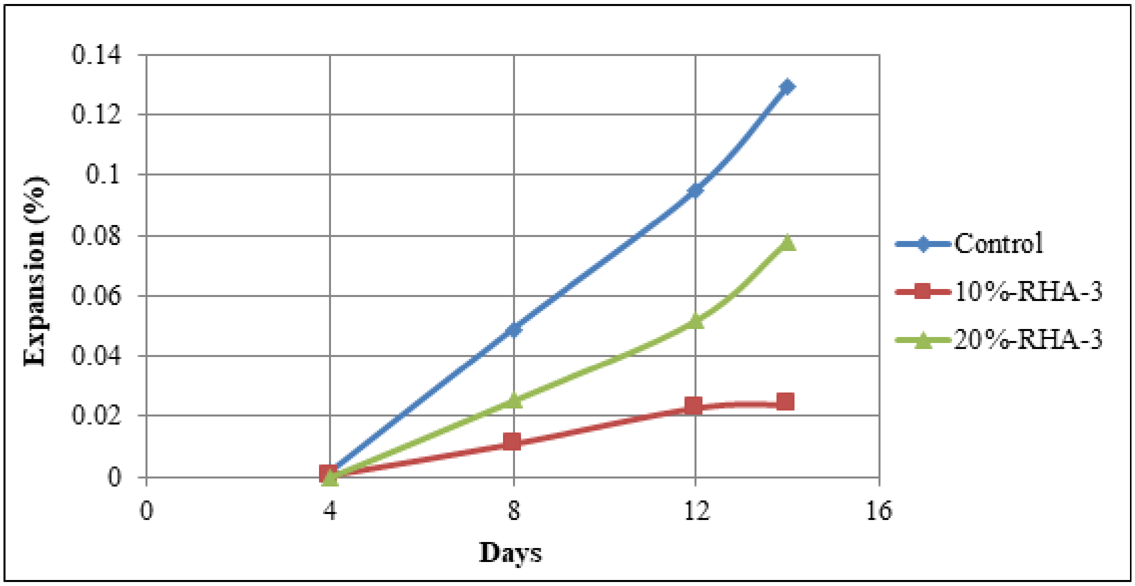

Figure 24. Effect of RHA-3 on ASR.

The use of RHA-3 might generate sufficient C-S-H gel to react with the alkali cations. Thus, the alkali to silica reaction might have been reduced and mortar bar showed less expansion than the Control bar. This phenomenon was supported by a recent study *(10)*. Therefore, incorporation of RHA-3 could reduce premature concrete distress due to ASR. The CFA modified concrete also mitigated the ASR expansion in a similar way (Figure 25). The 10% and the 20% CFA modified mortar bars mitigated ASR expansion by 99% and 98%, respectively, in comparison to the Control sample. From Figure 26, it is seen that the 20% SF modified concrete showed lower ASR expansion where the 10% SF concrete showed higher expansion compared to the Control samples. Therefore, the 10% dose of RHA-3 among all other types of RHA doses was found effective to reduce ASR expansion. The CFA and 20% SF used in this study were also found to be very effective in mitigating the ASR problem.

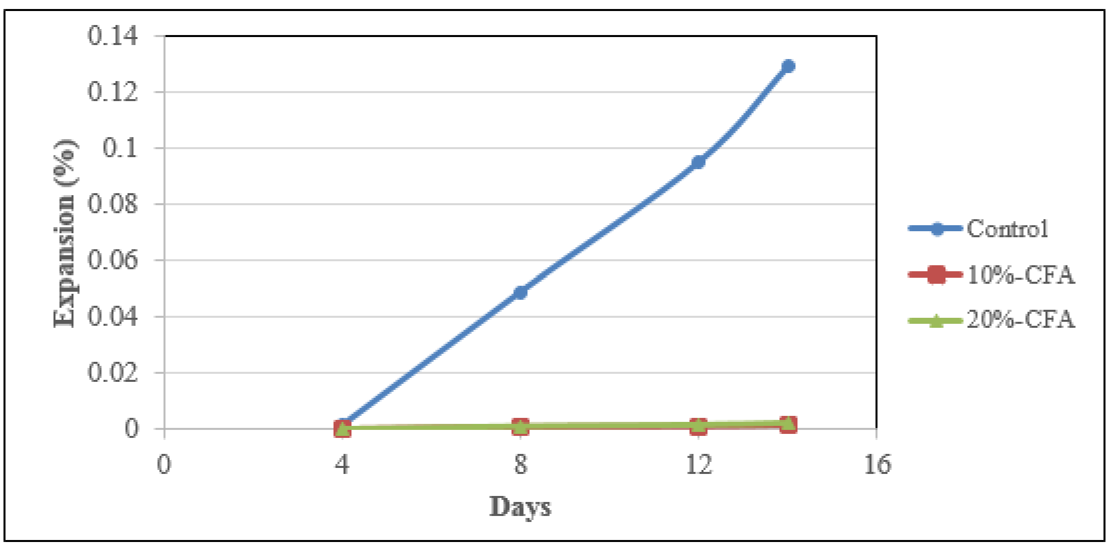

Figure 25. Effect of CFA on ASR.

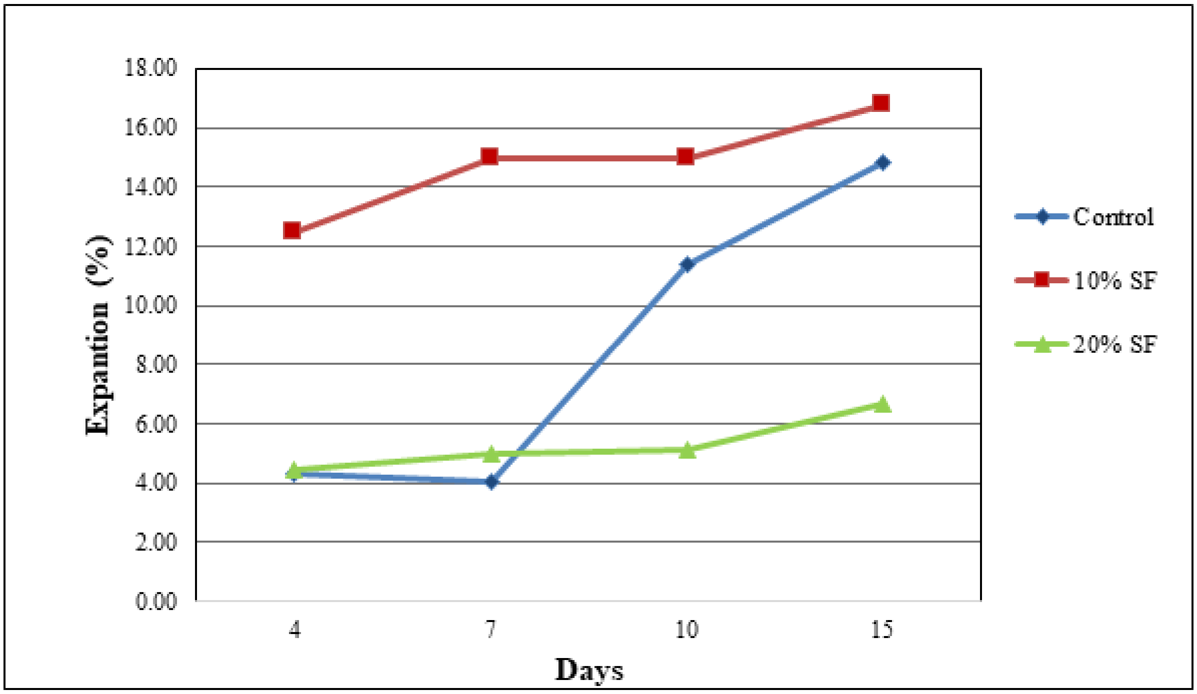

Figure 26. Effect of SF on ASR.

5.10. Scaling Resistance Test

The scaling resistance test was continued for 10 cycles of freezing and thawing. The surface damage conditions of mortar bars before and after undergoing the freeze-thaw cycles were considered to evaluate the durability of modified mortar bars in adverse condition. The mortar bars were removed from the calcium chloride solution and visually inspected. From Figure 27, it is seen that the Control mortar bar displayed slight damages (rating = 1.0) during this test.

The effect of deicing chemicals on the 10% RHA-1-modified mortar bar is shown in Figure 28. It was observed that the 10% RHA-1-modified mortar bar had severe surface damage and scaling was rated as 5.0. Figure 29 displays the surface condition of the 10% RHA-2-modified mortar bar after 10 F-T cycles. The 10% RHA-2-modified mortar bar showed moderate surface damage (rating = 2.0) in this test.

(a) (b)

Figure 27. Control mortar bar (a) before freezing and thawing cycle, and (b) after 10th freezing and thawing cycle.

(a) (b)

Figure 28. RHA-1-modified bar (a) before freezing and thawing cycle, and (b) after 10th freezing and thawing cycle.

(a) (b)

Figure 29. RHA-2-modified bar (a) before freezing and thawing cycle, and (b) after 10th freezing and thawing cycle.

The surface conditions of the 10% RHA-3 and the 10% CFA-modified mortar bars of this test are shown in Figures 30 and 31. Neither of the mortar bars showed any surface scaling after the completion of the 10th freezing and thawing cycle and their surface scaling was rated as 0 (zero).

The 10% SF- modified mortar bar showed a surface damage of rating 1. Figure 32 shows the surface condition of the SF-mortar bar after 10 cycles.

(a) (b)

Figure 30. RHA-3-modified bar (a) before freezing and thawing cycle, and (b) After 10th freezing and thawing cycle.

(a) (b)

Figure 31. CFA-modified bar (a) before freezing and thawing cycle, (b) after 10th freezing and thawing cycle.

(a) (b)

Figure 32. SF-modified bar (a) before freezing and thawing cycle, (b) after 10th freezing and thawing cycle.

From the test results, it was evident that RHA-3 and CFA-modified mortar bars had the lowest rating among all mortar bars. Results of the scaling tests are summarized in Figure 33.

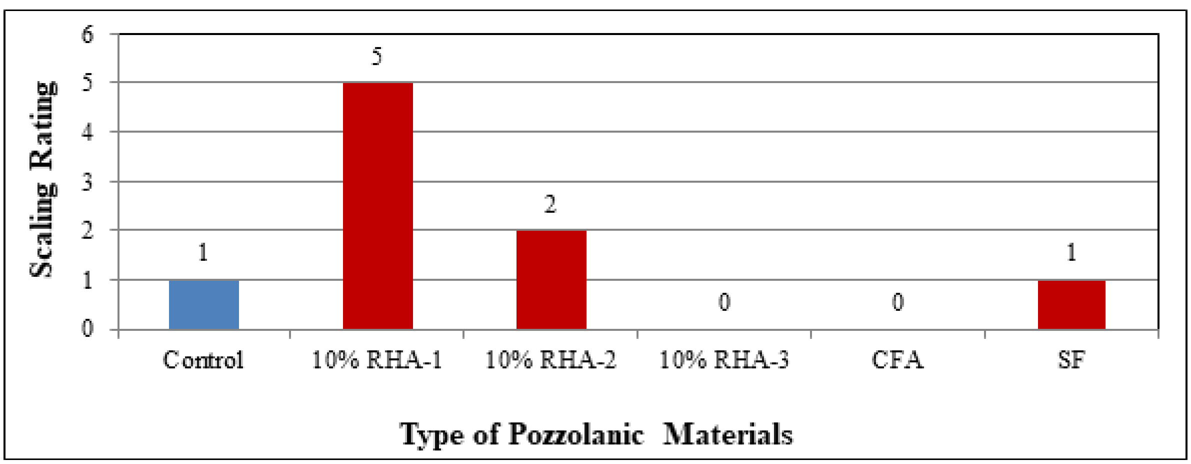

Figure 33. Scaling rating of all mortar bars.

5.11. Rotational Viscosity Test

The viscosity of the asphalt binders was tested using a rotational viscometer (RV) following the AASHTO T316 method. Viscosity was measured from 135°C to 180°C in 15°C increments. Figure 34 represents the Viscosity (mPa.s) versus temperature graph where it is seen that modified asphalt binders showed higher viscosity compared to the virgin binder PG 64-22 (source: Ergon at Memphis). At 135°C, RHA-3 modified asphalt binder showed 105%, 119% and 116% increments in viscosity compared to the virgin binder for the addition of 1%, 2% and 3% RHA-3, respectively.

From RV test data, the mixing and compaction temperatures for all modified asphalt binder samples were estimated as recommended by the Asphalt Institute (AI). As per the AI, these temperatures should be determined where the viscosity-temperature line crosses the viscosity ranges of 170 ± 20 mPa.s (mixing temperature range) and 280 ± 30 mPa.s (compaction temperature range) (Figure 35). The viscosity-temperature line was determined using the procedure described in ASTM D2493, "Standard Viscosity-Temperature Charts for Asphalts."

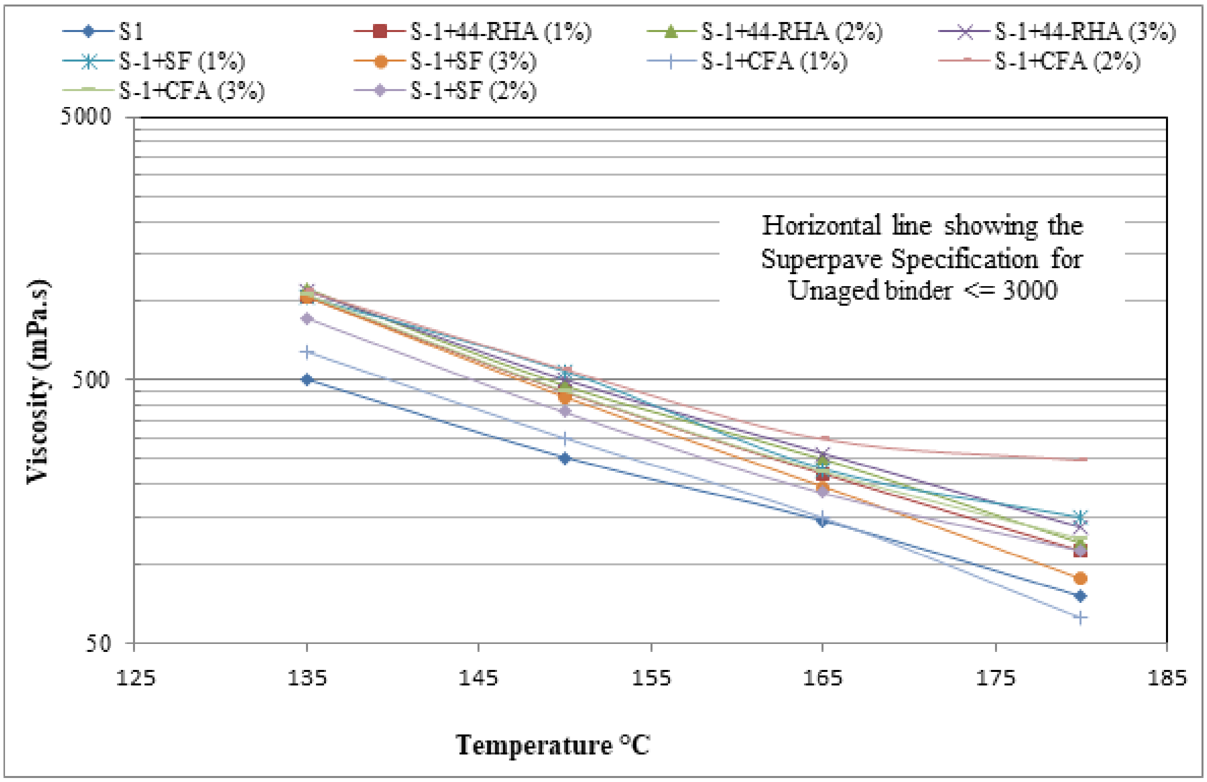

Figure 34. Viscosity vs. temperature curve for S1 modified binders.

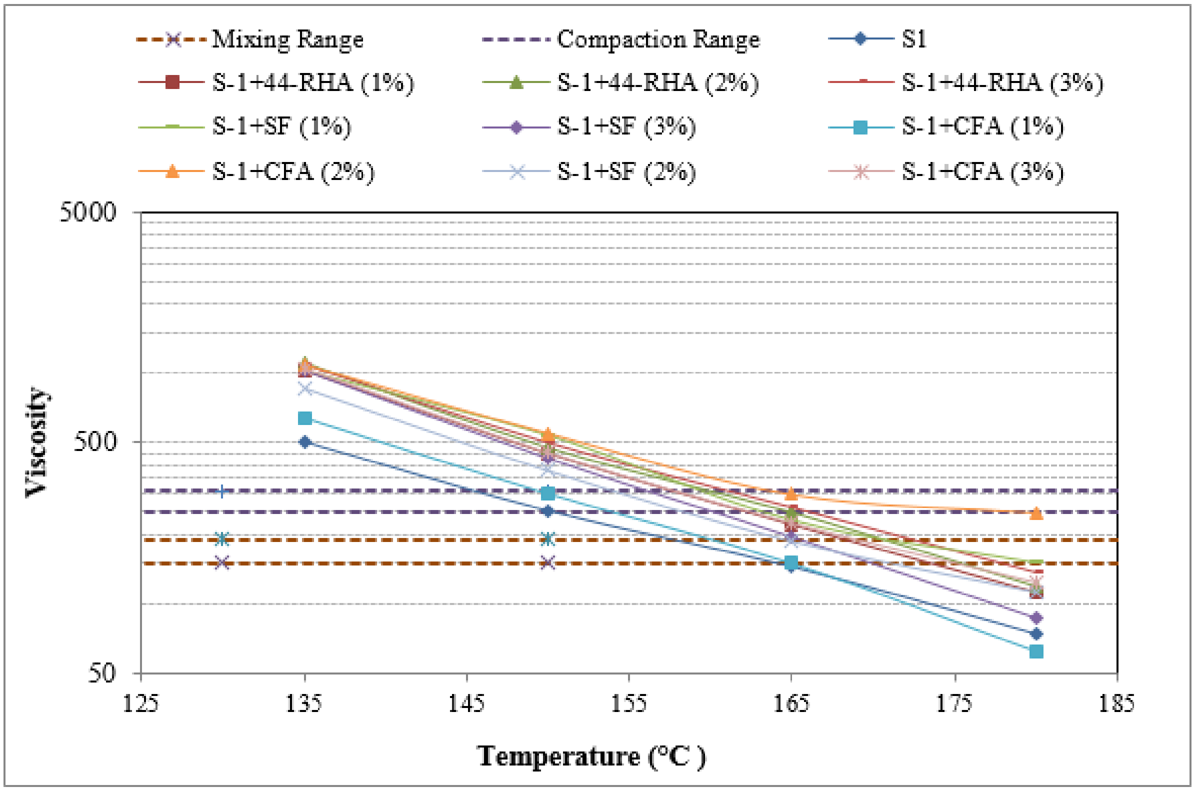

Figure 35. Viscosity versus Temperature of modified binders.

Figure 36 shows the mixing and compaction temperatures of virgin binder (PG 64-22), RHA-3, CFA, and SF modified asphalt binder. As seen from Figure 36, the mixing and compaction temperatures of virgin binder were found to be 158-165°C and 145-150°C, respectively. On the contrary, RHA (1%) showed 168-174°C for mixing and 157-162°C for compaction, RHA (2%) showed 171-176°C for mixing and 160-165°C for compaction, and RHA (3%)-modified binder showed 172-178°C for mixing and 161-166°C for compaction, each of which was significantly higher than the corresponding temperatures of the neat binder (PG 64-22).

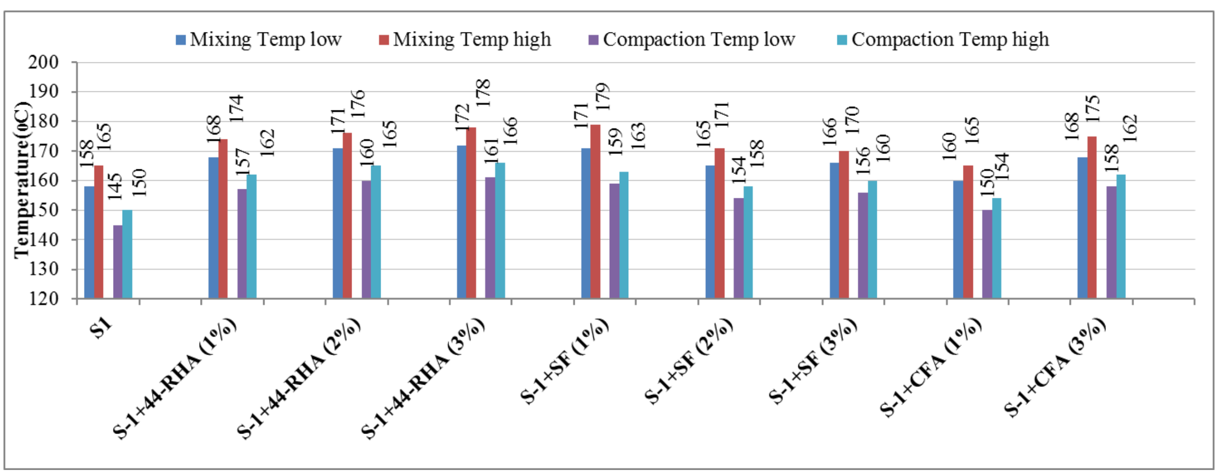

Figure 36. Mixing and compaction temperatures for modified binders.

5.12. Dynamic Shear Rheometer (DSR) Test

The DSR tests were performed on unaged unmodified PG 64-22, RHA-, CFA-, and on SF-modified asphalt binder. Tests were performed for different temperatures, from 64°C to 82°C. The complex shear modulus (G*), phase angle (δ), and rutting factor (G*/sin δ) were found from the DSR test.

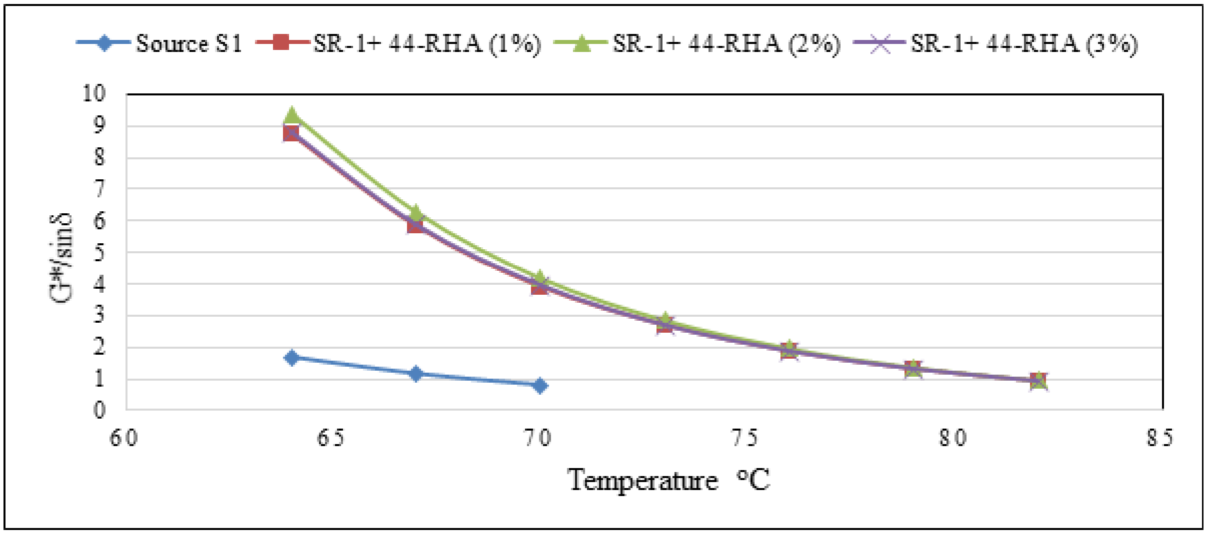

Figure 37. G*/sinδ vs. test temperatures of RHA-modified binders.

Figure 37 shows that the higher value of G*/sinδ was obtained at the lower temperature, and G*/sinδ was decreased with the increase of temperature. As asphalt binders are viscoelastic materials, binders become stiffer with the reduction of temperature. Figure 37 also shows that with the addition of RHA in the PG 64-22 neat binder the G*/sinδ values were increased significantly. At 64°C the PG 64-22 neat binder showed 1.68 kPa of G*/sinδ value where the RHA-modified binder showed 8.74 kPa, 9.38 kPa, and 8.81 kPa for the addition of 1%, 2% and 3% RHA, respectively.

A similar trend was also found for CFA- and SF- modified binders (Figure 38 and Figure 39). The increased G*/sinδ values indicate the higher rutting resistance of that binder. Therefore, the addition of RHA, CFA, and SF to the asphalt binder improves the rutting resistance.

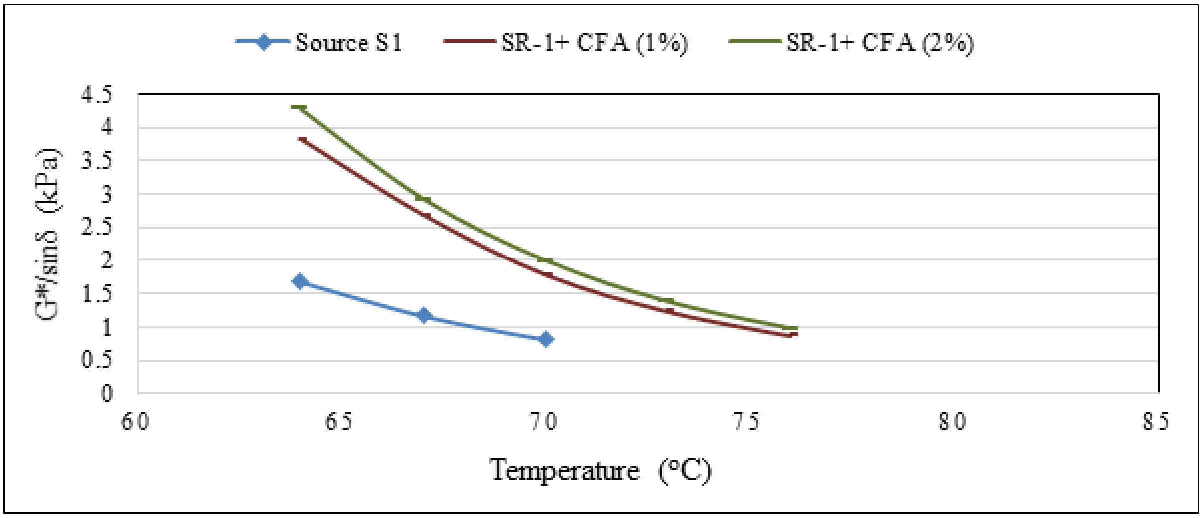

Figure 38. G*/sinδ vs. test temperatures of CFA-modified binders.

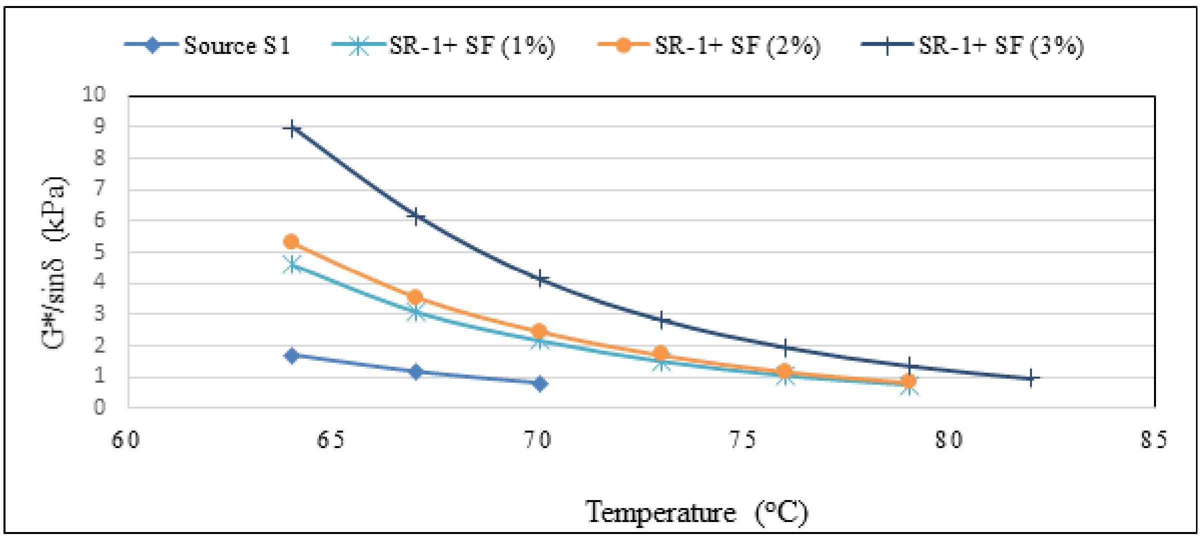

Figure 39. G*/sinδ vs. test temperatures of SF-modified binders.

Figure 40 represents the characterization of the rheological properties of asphalt binder through the black curve, which is the relation of the complex modulus as a function of the phase angle. The small phase angle indicates the prevalence of the elastic properties of the material. Figure 40 shows the phase angles of the modified asphalt binder were increased with the increase of temperature. For RHA-modified asphalt binder, the maximum G* values were found when 2% RHA was mixed with the neat binder. For the 1% RHA-3 and 3% RHA-3, G* values were found to be 12.4 kPa and 12.7 kPa, respectively.

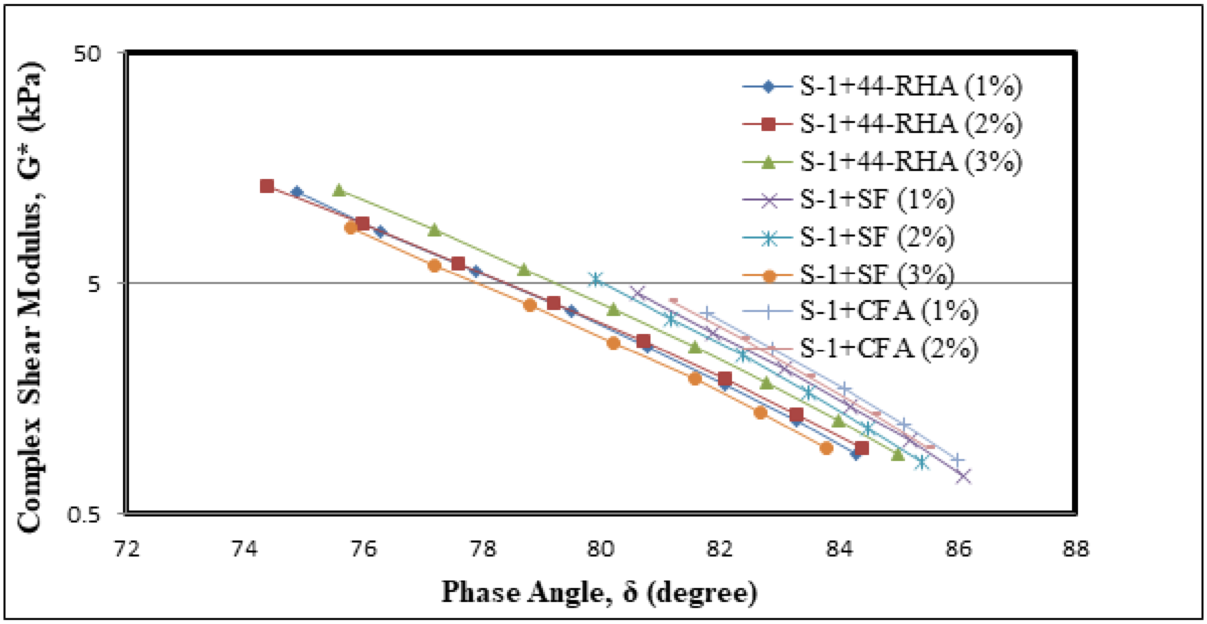

Figure 40. Complex shear modulus (G*) vs. phase angle (δ) curve for modified asphalt binders.

5.13. Cost Analysis

5.13.1. Life-Cycle Cost Analysis

The overall long-term economic efficiency between RHA modified rigid pavement and flexible pavement compared to the regular structure have been evaluated through a life-cycle cost analysis (LCCA). Usually, in LCCA, a net present worth (NPW) represents all activity costs considering a discount rate over time. In this study, "LCCA Express" software was used to represent the LCCA analysis. The following four example scenarios have considered for LCCA in this study:

1. Using conventional unmodified asphalt binder in asphalt pavement construction;
2. Using RHA modified asphalt binder in asphalt pavement construction;
3. Using regular unmodified concrete in rigid pavement construction; and
4. Using RHA modified concrete in rigid pavement construction.

In the process of comparing different types of pavement, LCCA Express does not directly quantify the longevity of the pavement. To evaluate the expected improvement in pavement a mechanistic-empirical prediction model was used for rutting and load-related fatigue cracking. For the construction of pavement, assumptions were made based on previous research *(26)*. Figures 41 and 42 show the pavement design conditions and other traffic properties which were considered for performing life cycle analysis.

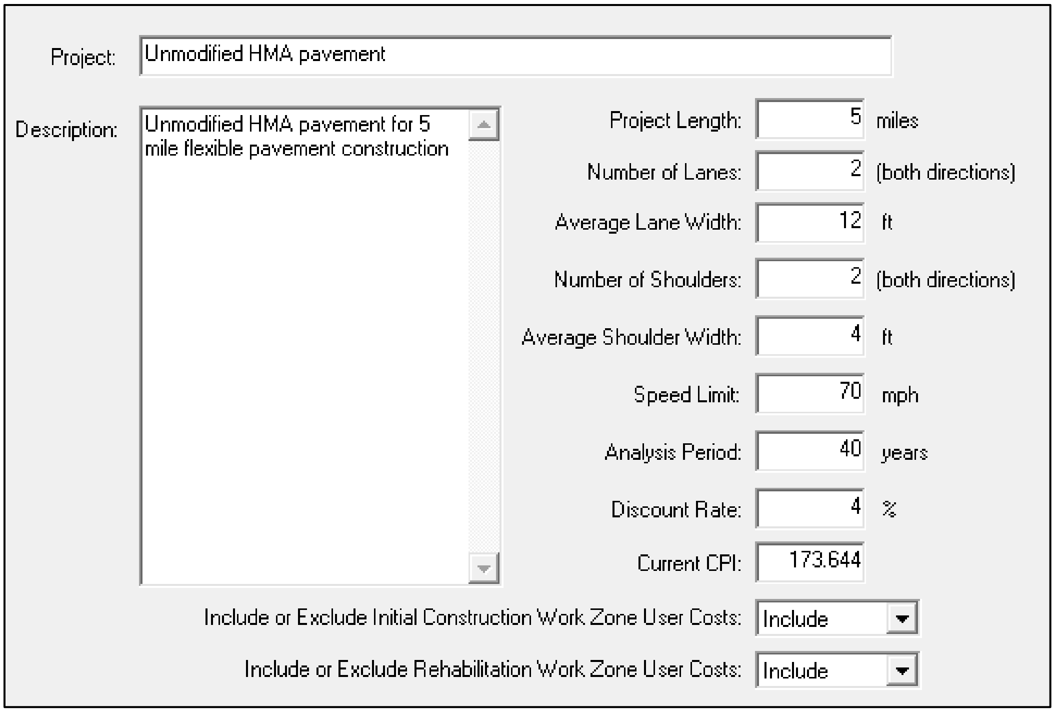

Figure 41. Assumed pavement criteria for performing LCCA.

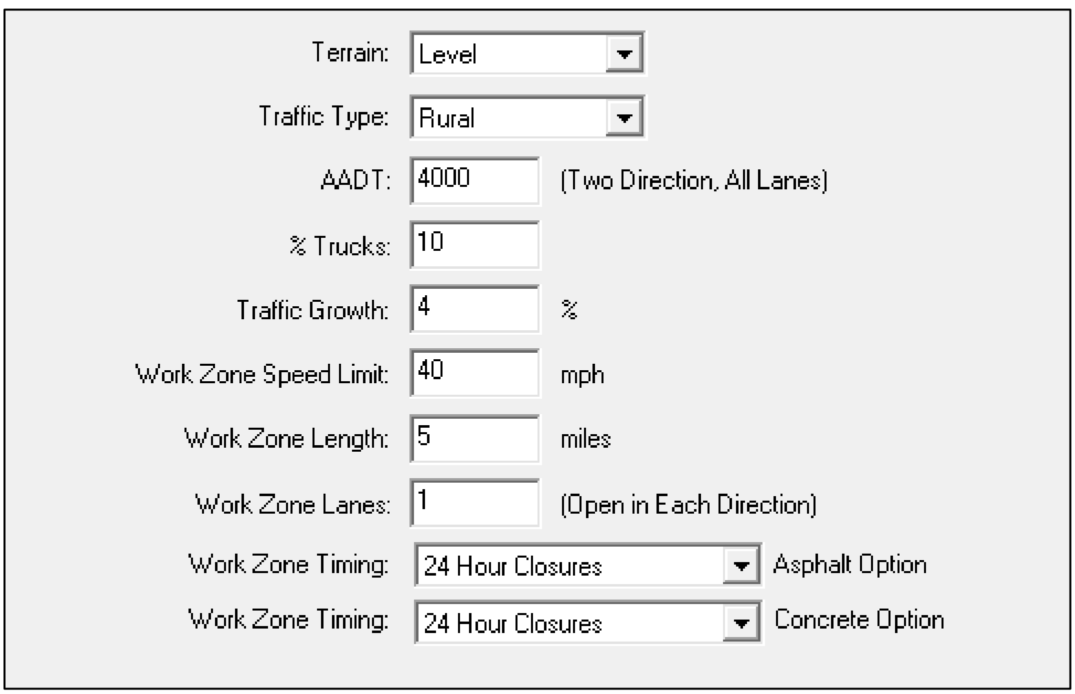

Figure 42. Assumed work zone data for performing LCCA.

Figure 41 shows that a 5-mile road with 24-foot width was considered in this study. An analysis period of 40 years with a discount rate of 4% was also considered. Figure 42 represents that with a 4% traffic growth 4000 AADT were assumed for work zone data. This pavement and traffic criteria remained the same for all four LCCA analyses. A traffic type of "Rural" was considered because RHA is expected to be placed on rural roadways (e.g., County Roads) before approved on urban roads or interstate systems.

Table 9 shows the net present worth value of example scenario 1. For scenario 1, resurfacing was scheduled for years 10 and 28 and structural overlays for years 18 and 34. For the unmodified asphalt binder pavement, the net present cost value was found to be USD $5.35 million for per-mile quantities. On the other hand, for RHA modified asphalt binder pavement (example Scenario 2) the resurfacings at years 10 and 28 were eliminated. Therefore, the net present value for per-mile quantities was found to be USD $4.68 million (Table 9) which is 12.5% less compared to the unmodified asphalt binder pavement.

With the reduction of initial construction, the cost of RHA-modified rigid pavement exhibited less net present value compared to the rigid pavement made of regular concrete. From Table 9 it is evident that RHA modified rigid pavement showed 22% lower NPV value compared to the regular rigid pavement.

Different analysis data along with material prices are given in Appendix E. It is also important to emphasize different example scenarios (1 to 4) by illustrating different pavement structures where they are quantitatively analyzed for identifying the long-term cost benefits of different pavements. For further analysis, design strategies, prices, periods and discount rates can also be varied in acquiring new LCCA results.

Table 9. Net present value ($/mile) for different pavements.

	Unmodified Asphalt		**RHA-Modified Asphalt**		**Unmodified Rigid Pavement**		**RHA-Modified Rigid Pavement**	
	Agency	**User**	**Agency**	**User**	**Agency**	**User**	**Agency**	**User**
Initial Construction	3,285,103	45,742	3,285,103	45,742	3,234,595	91,484	3,058,595	91,484
1st Overlay	352,386	7,620	578,856	0	810,397	22,872	625,926	22,875
2nd Overlay	578,856	15,245	309,056	15,246	547,475	22,875	347,554	22,872
3rd Overlay	173,948	7,625	0	0	369,855	22,872	0	22,871
4th Overlay	309,056	15,246	0	15,247	0	762	0	762
Recurring Maintenance	566,264	566,264	436,605	436,605	730,857	730,857	365,428	365,428
Total cost, Net present value ($)	5,357,091	5,357,091	4,685,855	46,85,855	5,854,044	5,854,044	4,558,367	4,558,367

5.13.2. Materials Cost Analysis

In this part of the study, the initial material costs of different pavements were considered for the comparative cost analysis. A 5-mile road was considered for calculating the corresponding required cementitious materials. For the rigid pavement analysis, a 6-inch thick slab with a mix ratio of 1:2:4 was considered for both regular and RHA modified rigid pavement. Based on the findings of this study, a 10% replacement of OPC with RHA-3 was considered for analyzing RHA modified rigid pavement. Table 10 shows that in the case of regular concrete rigid pavement about 4,921 tons of cement would be required for the constructions of a 5-mile road segment which would cost around USD $556,073. On the contrary, for the RHA modified rigid pavement the cost of cement would be USD $500,364. This is 10% less than the regular concrete rigid pavement. Because RHA has been considered as a waste material, the costs of RHA were neglected in this calculation.

Table 10. Cost of cementitious material for 5-mile road construction.

Types of Rigid Pavement	Required Cement (Ton)	Unit Price ($/Ton)	Total Cost ($)
Unmodified	4921	113	556,073
RHA-modified	4428	113	500,364

In the case of flexible pavement road, a 6-inch asphalt concrete thickness with 5% binder content was considered for determining the required binder amount for a 5-mile flexible pavement road construction. Table 11 represents the amount of required binder along with their unit prices. It is evident from Table 11 that RHA modified asphalt binder cost 46% less compared to the polymer modified asphalt binder.

Table 11. Cost of asphalt binder for 5-mile road construction.

Types of Flexible Pavement	Required Binder (Ton)	Unit Price ($/Ton)	Total Cost ($)
Polymer-modified	1148	901	1,034,348
RHA-modified	1148	485	556,780

6. CONCLUSIONS

Rice Husk Ash (RHA) is considered agricultural waste material, but it has the potential to be used as supplementary cementitious material (SCM) in preparing regular concrete. However, sufficient studies have not been performed on the application and use of RHA in construction. In this study, three different types of RHA with different particle sizes were considered to evaluate the effect of RHA in regular concrete. For the control mix design, the finer RHA (RHA-3) modified concrete mixes exhibited a lower slump value indicating a very stiff and less workable mix. It can be said that finer RHA incorporated mix required more water to have a similar consistency to the Control sample.

In the case of compressive strength, the use of RHA-1 and RHA-2 in concrete decreased the compressive strength. On the other hand, RHA-3, CFA, and SF modified concrete showed greater compressive strength than the regular concrete. A similar trend was observed for the tensile and flexural strengths as well. Regarding Alkali-Silica Reactivity (ASR), RHA-3, CFA, and SF were found to be effective in mitigating the concrete expansion in the presence of alkaline water. Similarly, based on the durability test RHA-3, CFA and SF showed the lowest surface damage among all other modified concrete. From the test results, it was observed that the 10% replacement by weight of cement with RHA-3 had the most beneficial results among all types of RHA modified concrete.

In the study of asphalt modification, an addition of RHA into a virgin binder showed higher viscosity compared to the neat binder. The complex shear modulus also increased by the incorporation of RHA in the virgin binder, which eventually increased the rutting resistance factor of the asphalt binder.

The life -cycle cost analysis suggested that the RHA-modified rigid pavement also showed less net present value compared to the regular concrete pavement. Cost analysis also demonstrated that the incorporation of RHA in asphalt modification resulted in lower construction cost for flexible pavement compared to the unmodified asphalt binder pavement.

The findings of this study are expected to encourage the concrete industry and asphalt industry to consider RHA in the construction of rigid and flexible pavements.

7. RECOMMENDATIONS

Considering the test results of CFA-, SF-, RHA-modified concrete and asphalt samples of this study, the following recommendations were made for future investigations and applications:

- The coarse RHA particles were detrimental to concrete strength development. Therefore, the use of coarse RHA should be avoided where high strength concrete is needed.
- The coarse RHA particle can be used where a large quantity of low strength concrete is needed. The use of coarse RHA in backfill and flowable fill as controlled low strength material (CLSM) could lower the construction cost.
- RHA particles could be ground and burned to improve the efficiency of concrete because the finer and lower carbon content helps regular concrete have more strength.
- An extensive study would be required on the use of locally available coarse RHA.
- XRD analysis is required to analyze the C-S-H gel formation of RHA in modified concrete.
- Unaged RHA-, SF, and CFA modified asphalt binder showed an increased value of complex shear modulus. Further studies need to be carried out for the RTFO and PAV aged specimens to evaluate the RHA modified asphalt performance in the long run.
- Performance tests such as SCB and HWT of RHA-modified mixes will have to be conducted to obtain their laboratory performance.
- A field demonstration will have to be conducted to demonstrate the developed techniques to DOT’s engineers, county engineers, and local contractors.

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APPENDIX A: GRAIN SIZE DISTRIBUTION

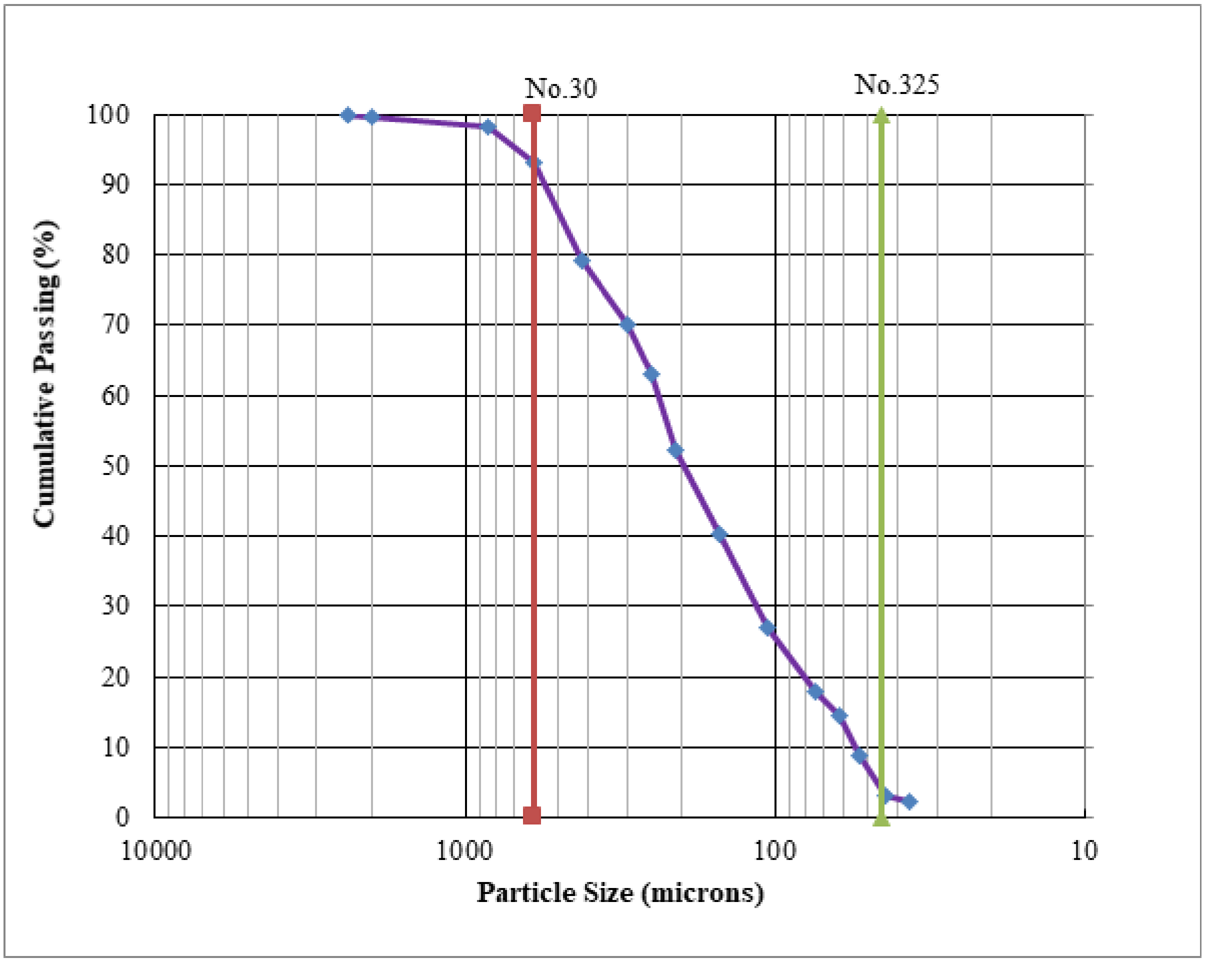

Figure A.1. Grain size distribution of RHA-1.

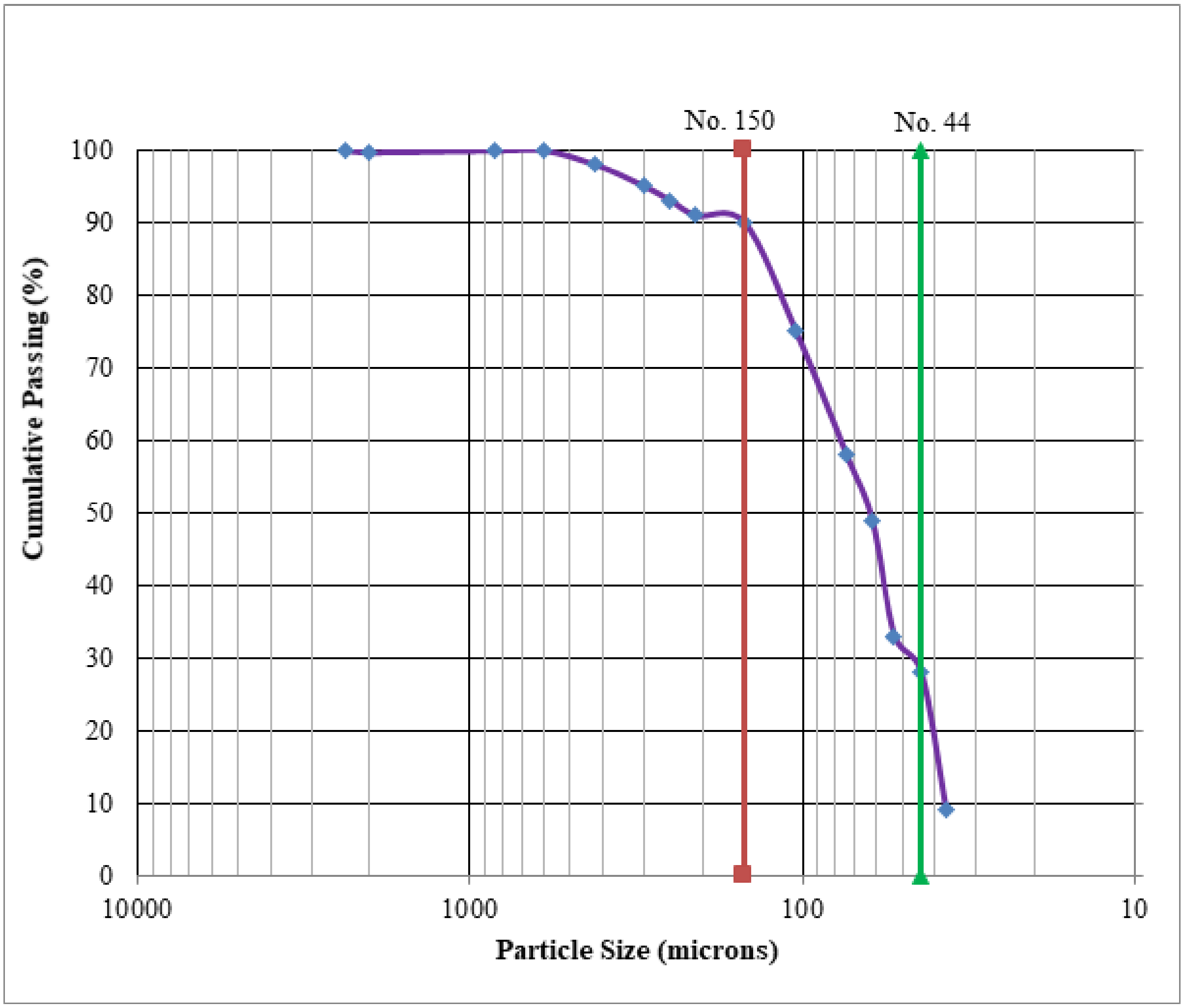

Figure A.2. Grain size distribution of RHA-2.

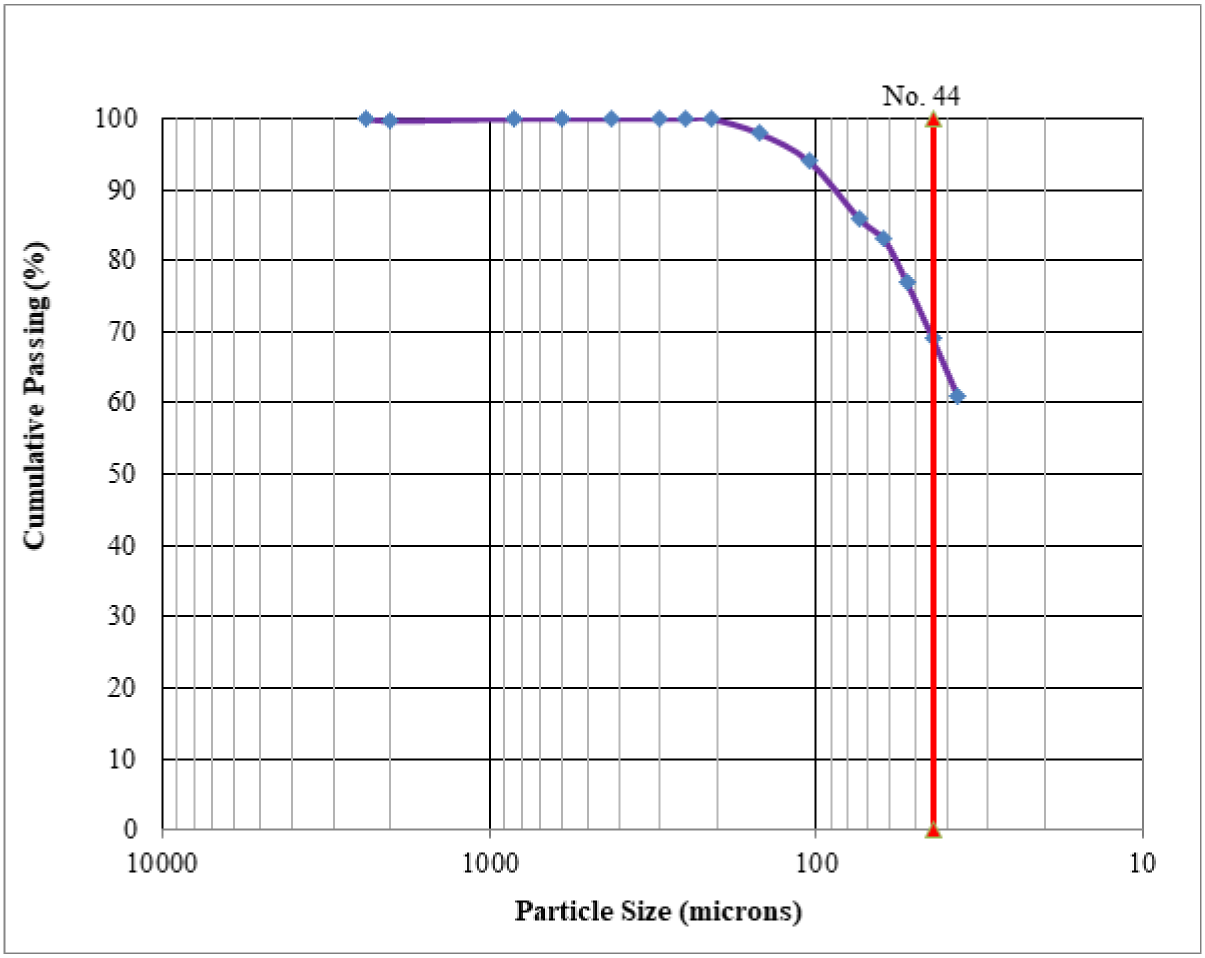

Figure A.3. Grain size distribution of RHA-3

APPENDIX B: COMPRESSIVE STRENGTH RESULTS

Table B.1. Compressive strength of RHA-1-modified concrete.

Days	Control	10% RHA-1	20%-RHA-1
7	24.3	13.5	10.8
14	29.1	15.9	12.8
21	32.6	18.1	14.5
28	36.1	20.1	16.2

Table B.2. Compressive strength of RHA-2-modified concrete.

Days	Control	10% RHA-2	20%-RHA-2
7	24.3	16.3	11.7
14	29.1	18.4	13.7
21	32.6	21.4	15.0
28	36.1	22.8	16.8

Table B.3. Compressive strength of RHA-3-modified concrete.

Days	Control	10% RHA-3	20%-RHA-3
7	24.3	26.3	25.1
14	29.1	31.6	29.4
21	32.6	33.9	32.1
28	36.1	37.7	36.6

Table B.4. Compressive strength of CFA-modified concrete.

Days	Control	CFA	CFA
7	24.3	24.1	21.6
14	29.1	31.1	26.5
21	32.6	36.1	34.1
28	36.1	39.8	38.7

Table B.5. Compressive strength of SF-modified concrete.

Days	Control	SF	SF
7	24.3	26.12	22.07
14	29.1	32.44	26.15
21	32.6	34.37	33.82
28	36.1	37.54	36.47

APPENDIX C: TENSILE STRENGTH RESULTS

Table C.1. Tensile strength of modified concrete.

Types of Pozzolan	Tensile Strength (MPa)
Control	2.79
10% RHA-1	2.69
20% RHA-1	2.10
10% RHA-2	2.72
20% RHA-2	2.45
10% RHA-3	3.52
20% RHA-3	3.41
10% CFA	4.07
20% CFA	3.14
10% SF	3.48
20% SF	3.07

APPENDIX D: FLEXURAL STRENGTH RESULTS

Table D.1. Flexural strength of modified concrete.

Types of Pozzolan	Flexural Strength (MPa)
Control	4.17
10% RHA-1	3.14
20% RHA-1	2.69
10% RHA-2	3.62
20% RHA-2	2.79
10% RHA-3	4.72
20% RHA-3	4.41
10% CFA	5.03
20% CFA	4.76
10% SF	3.45
20% SF	2.69

APPENDIX E: COST ANALYSIS DATA

	Initial Construction	1st Overlay	2nd Overlay	3rd Overlay	4th Overlay
Year:	0	10	18	28	34
HMA Wearing Course, in:	2	2	2	2	2
HMA Wearing Course, pcf:	145	145	145	145	145
HMA Binder Course, in.:	2.5	0	2.5	0	2.5
HMA Binder Course, pcf.:	145	145	145	145	145
HMA Base Course, in.:	5	0	0	0	0
HMA Base Course, pcf:	145	145	145	145	145
Aggregate Base, in.:	10	0	0	0	0
Aggregate Base, pcf:	115	115	115	115	115
Misc., miles: Misc Description...	0	0	0	0	0
Milling, sy:	0	0	0	0	0
Patching,	0	0	0	0	0
Days to Complete:	60	10	20	10	20

Figure E.1. Asphalt overlay conditions for unmodified asphalt binder pavement.

	Initial Construction	1st Rehab Activity	2nd Rehab Activity	3rd Rehab Activity	4th Rehab Activity
Year:	0	20	35	0	0
Concrete, sy:	35200	17600	17600	0	0
Number of Dowel Bars:	21120	10560	10560	0	0
Reinforcement Bars, lb:	1102311	0	0	0	0
Concrete Milling, sy:	0	35200	35200	0	0
Joint Sealing, ft:	42240	42240	42240	0	0
Concrete Patching, sy:	35200	17600	17600	0	0
Asphalt Milling, sy:	0	0	0	0	0
HMA Overlay, in.:	0	0	0	0	0
HMA Overlay, pcf:	145	145	145	145	145
Aggregate Base, in.:	20	0	0	0	0
Aggregate Base, pcf:	115	115	115	115	115
Miscellaneous 1: Misc Description...	0 miles	0 miles	0 miles	0 miles	0 miles
Miscellaneous 2: Misc Description...	0 miles	0 miles	0 miles	0 miles	0 miles
Miscellaneous 3: Misc Description...	0 miles	0 miles	0 miles	0 miles	0 miles
Days to Complete:	120	30	30	30	1

Figure E.2. Asphalt overlay conditions for RHA-modified asphalt binder pavement.