



University Transportation Research Center - Region 2

Final Report



Characterizing and Quantifying the Shrinkage Resistance of Alkali-Activated (Cement-Free) Concrete and Evaluating Potential Methods for Reducing Early-Age Cracking in Pavements and Bridges

Performing Organization: Clarkson University



December 2015



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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the most responsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally. Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council, New York State Department of Transportation, and the New York State Energy and Research Development Authority and others, all while enhancing the center's theme.

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Project No(s):

UTRC/RF Grant No: 49997-24-25

Project Date: December 2015

Project Title: Characterizing and Quantifying the Shrinkage Resistance of Alkali-Activated (Cement-Free) Concrete and Evaluating Potential Methods for Reducing Early-Age Cracking in Pavements and Bridges

Project's Website:

<http://www.utrc2.org/research/projects/reducing-cracking-pavements-and-bridges>

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1. Report No.		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Characterizing and Quantifying the Shrinkage Resistance of Alkali-Activated (Cement-Free) Concrete and Evaluating Potential Methods for Reducing Early-Age Cracking in Pavements and Bridges				5. Report Date December 2015	
				6. Performing Organization Code	
7. Author(s) Sulapha Peethamparan, Ph.D. Robert J. Thomas				8. Performing Organization Report No.	
9. Performing Organization Name and Address Clarkson University 8 Clarkson Avenue Potsdam, New York 13699				10. Work Unit No.	
				11. Contract or Grant No. 49997-24-25	
12. Sponsoring Agency Name and Address UTRC The City College of New York, Marshak 910 160 Convent Avenue New York, NY 10031				13. Type of Report and Period Covered final, March 15, 2014 to December 31, 2015	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract This report summarizes the findings of an experimental investigation into shrinkage, and the mitigation thereof, in alkali-activated fly ash and slag binders and concrete. The early-age (chemical and autogenous) and later-age (drying and carbonation) shrinkage of sodium silicate-activated fly ash and slag binders was evaluated in accordance with relevant specifications. The influence of activator concentration and water content on the resulting shrinkage was investigated. The shrinkage behavior of alkali-activated binders and concrete was compared to that of ordinary portland cement. Finally, the effectiveness of several common shrinkage-mitigation techniques on the early-age and later-age shrinkage of alkali-activated binders was evaluated. Overall, this study demonstrates that, while shrinkage and associated cracking are problematic in many alkali-activated concrete mixtures, there are several promising methods which can reduce the magnitude of autogenous and drying shrinkage.					
17. Key Words Shrinkage Resistance, Cement-free concrete, cracking			18. Distribution Statement		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No of Pages 54	22. Price

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Executive Summary

This report summarizes the findings of an experimental investigation into shrinkage, and the mitigation thereof, in alkali-activated fly ash and slag binders and concrete. The early-age (chemical and autogenous) and later-age (drying and carbonation) shrinkage of sodium silicate-activated fly ash and slag binders was evaluated in accordance with relevant specifications. The influence of activator concentration and water content on the resulting shrinkage was investigated. The shrinkage behavior of alkali-activated binders and concrete was compared to that of ordinary portland cement. Finally, the effectiveness of several common shrinkage-mitigation techniques on the early-age and later-age shrinkage of alkali-activated binders was evaluated.

Chemical shrinkage is shown to increase with sodium oxide concentration and curing temperature, and decrease with silica modulus. Autogenous shrinkage followed approximately the same trend. Internal curing with saturated lightweight aggregate was effective at reducing autogenous shrinkage in both alkali-activated fly ash and slag binders. Drying and carbonation shrinkage tended to decrease with sodium oxide concentration and increase with silica modulus and solution-to-binder ratio. This is likely a result of the reduced early-age strength. Internal curing was effective at mitigating both drying and carbonation shrinkage. Elevated-temperature curing was also effective at mitigating these types of shrinkage due to the removal of most of the free water during the early curing process.

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1. Introduction

1.1 Motivation

Portland cement concrete is by far the most widely used construction material. The production of portland cement involves, among other processes, firing raw materials at temperatures in excess of 1450°C. Commercial production of portland cement is therefore extremely energy-intensive. Production of one ton of portland cement requires as much as 4 GJ of energy—predominately from fossil fuel combustion—and results in the emission of 0.95 tons of carbon dioxide. CO₂ produced by commercial cement manufacture accounts for as much as 7% of anthropogenic carbon emissions [1—3].

Alternative binders like fly ash and slag have long been used to supplement portland cement in concrete, thereby reducing the embodied energy and carbon footprint of concrete production. In addition, these supplementary binders are known to improve various fresh and hardened properties of the resulting concrete. Benefits include improvements in rheology, strength, permeability, porosity, and durability [4—9]. In addition to these performance benefits, the use of fly ash and concrete represents the beneficiation of plentiful industrial byproducts which would ordinarily be landfilled.

More recently, alkali-activated fly ash and slag concrete, which contain no portland cement, have emerged as promising sustainable alternatives to portland cement concrete. First demonstrated by Kuhl [10] in 1908 and again by Purdon [11] in 1940, the activation of aluminosilicates with metal alkalis results in the formation of strong and durable binders similar in form and function to portland cement.

The mechanical properties and durability of alkali-activated concrete has been discussed at length by myriad studies [12—16]. In general, the strength and durability of alkali-activated binders is reported to be comparable to that of portland cement. A noteworthy exception is with regard to the shrinkage properties; several studies have suggested that alkali-activated binders exhibit an increased susceptibility to shrinkage and associated cracking [17—20].

1.2 Shrinkage in concrete

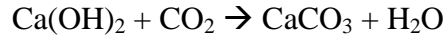
Shrinkage in concrete refers to the reduction in absolute volume of the fresh or hardened binder. This can manifest in several ways at both early and later ages. Early-age shrinkage can manifest before the binder has fully set. First demonstrated by LeChatelier [21], chemical shrinkage is a reduction in absolute volume of the hydrating binder due to the hydration reaction. The hydration products occupy less volume than the starting materials. Prior to setting, this results in bulk contraction of the binder. Following setting, this results in the formation of empty pores within the binder matrix. Chemical shrinkage continues to manifest as long as the binder continues to hydrate. Chemical shrinkage is often used as an indicator of the progression of the hydration reaction and the formation of the internal pore structure [22, 23].

Autogenous shrinkage also occurs at early ages and is due to the consumption of internal water by the hydration reaction [24, 25]. This may occur at the same time as chemical shrinkage; the difference is that chemical shrinkage occurs due to a difference in the volume of the reactants and the reaction products, while autogenous shrinkage occurs due to tensile stresses imparted by the migration of internal water. This is generally a concern when the water-to-cementitious material ratio (w/cm) is less than 0.42, that which results in complete hydration of portland cement [26].

Autogenous shrinkage occurs during three phases of cement hydration. When the binder is in the liquid phase, chemical and autogenous shrinkage occur simultaneously. When the binder reaches the skeleton phase, the matrix begins to form and weakly resist the tensile stresses imparted by the consumption of internal water. Finally, the consumption of capillary water forms menisci and causes the development of capillary tensile stresses, resulting in further autogenous shrinkage. This is of particular concern in binder with low w/cm due to the associated pore refinement. Since the capillary pores are smaller and more refined in these binders, the resulting capillary stresses increase. With increased capillary stresses comes increased shrinkage [22—25].

At later ages, shrinkage in concrete may be due either to the evaporation of internal water or due to reactions with environmental chemicals. Drying shrinkage is the volumetric reduction of concrete caused by the removal of capillary water through evaporation [27—29]. Initially, free water settles to the surface of fresh concrete in a phenomenon known as bleeding. As the heavier solids settle, the free water naturally rises to the surface of the fresh concrete, where it can evaporate. Once this bleed water has evaporated, the drying process continues as water migrates from the within the internal pore structure of the binder. This water migration causes the formation of menisci and internal capillary stresses, resulting in volumetric shrinkage. As the solid structure of the hardened binder resists the shrinkage strains caused by internal capillary stresses, cracking and warping may occur [27—29].

Carbonation shrinkage is a reduction in absolute volume as a result of chemical reactions between the hydration products and atmospheric carbon dioxide. Carbonation is chemically complex and involves the transformation of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the hydrated binder matrix into calcium carbonate (CaCO_3) in the presence of carbon dioxide (CO_2). The reaction follows the general form [31]:



The carbonation process occurs in several steps: First CO_2 from the atmosphere diffuses into the binder matrix. Then, that diffused CO_2 is dissolved into the pore fluid; this dissolution is affected by the chemistry of the pore solution, the water-to-cementitious materials ratio (w/cm), the microstructure, and the specific surface area. Finally, the precipitation of CaCO_3 occurs, which is accompanied by the production of H_2O as the calcium carbonate is desorbed [30—33]. The carbonation reaction penetrates the surface of the concrete very slowly. This rate of penetration is mainly controlled by the rate of diffusion of CO_2 into the concrete, which is in turn controlled by the water content, the relative humidity, and the concentration of carbon dioxide. In addition to volumetric shrinkage, carbonation causes several chemical and physical changes to the concrete or binder. Carbonation leads to densification, pore refinement, and rearrangement of the microstructure [30—33]. This may in turn result in crazing or cracking.

The shrinkage properties of portland cement binders and concrete are well-understood. Furthermore, the effective mitigation of shrinkage in portland cement concrete using several techniques has been previously demonstrated. In addition to the inclusion of commercial shrinkage-reducing admixtures, internal curing with saturated light-weight aggregate has been proven effective at reducing shrinkage in portland cement concrete.

1.3 Shrinkage in alkali-activated binders

The shrinkage properties and the mitigation of shrinkage within portland cement binders is generally well-understood. However, comparatively little is known about shrinkage in alkali-activated fly ash and slag binders. A few studies have discussed chemical shrinkage in alkali-activated binders; those studies have discussed the difficulties of quantifying this type of

shrinkage in alkali-activated binders (primarily alkali-activated slag). These difficulties are mainly associated with the early formation of a low-permeable shell on the surface of the hydrating binder that prevents the migration of water [34,35]. Chemical shrinkage in alkali-activated fly ash has been discussed by a few studies, most of which report that the chemical shrinkage in alkali-activated fly ash is markedly lower than in portland cement binders [18,36—38]. Several additional studies have investigated the effect of fly ash and slag as mineral admixtures on the autogenous shrinkage of portland cement binder systems. Those studies have concluded that slag as a mineral admixture increases the autogenous shrinkage, while fly ash as a mineral admixture decreases autogenous shrinkage [39].

Several studies have investigated drying shrinkage in alkali-activated binders. The magnitude of drying shrinkage in alkali-activated binder systems is known to be much higher than in portland cement binders [17, 19, 40]. The main factors influencing the magnitude of drying shrinkage in alkali-activated binders are the environmental humidity, activator concentration, and pore structure of the binder [17,19,40]. Sodium silicate-activated binders have shown greater drying shrinkage than sodium hydroxide-activated binders [17]. This may be due to the increased early strength and stiffness of the latter.

Carbonation in alkali-activated systems has been discussed by several authors, although solid conclusions have not been reached. Carbonation is known to be much more complex in alkali-activated binders than in portland cement binders [41—44]. However, few measurements of actual carbonation shrinkage are available in the literature. The rate of carbonation has been shown to be faster in alkali-activated binders than in portland cement [41—44], and it therefore stands to reason that carbonation shrinkage should occur more rapidly in those binders.

1.4 Research significance

Despite the myriad studies characterizing the shrinkage properties of portland cement binders, comparatively few investigations of the shrinkage properties of alkali-activated fly ash and slag binders have been performed. This study seeks to add to the understanding of how shrinkage occurs in alkali-activated binders, and how that shrinkage can be best mitigated.

1.5 Objectives

Specifically, the objectives of this study are to

1. Quantify chemical, autogenous, drying, and carbonation shrinkage in alkali-activated concrete in order to identify the major contributors to shrinkage;
2. Derive the fundamental mechanisms driving the aforementioned contributors to shrinkage in alkali-activated concrete;
3. Evaluate the effectiveness of internal curing and shrinkage-reducing admixtures (SRA) in mitigating or reducing the major types of shrinkage in alkali-activated concrete; and
4. Characterize workability and setting time of alkali-activated concrete and evaluate the effectiveness of water-reducing admixtures, super-plasticizers, air-entraining agents, and set-retarding admixtures in modifying the workability and setting time of alkali-activated concrete.

2. Material and methods

2.1 Materials

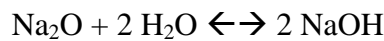
Three binder materials were used in this study. Type-I ordinary portland cement meeting the specifications of ASTM C150 was used for control mixtures. Grade-100 ground granulated blast furnace slag meeting the specifications of ASTM C989 and class-C fly ash meeting the

specifications of ASTM C618 were used for alkali-activated binders and concrete. Slag was sourced from Holcim US in Chicago, IL, and fly ash was sourced from Detroit-Edison's Belle River Power Plant. The chemical oxide compositions of these three binders are presented in Table 1.

Table 1. Oxide composition of raw binders

Oxide	Composition (% by mass)		
	Portland cement	Slag	Fly Ash
CaO	63.9	39.1	21.1
SiO ₂	20.5	37.8	40.7
Al ₂ O ₃	5.4	7.9	21.2
MgO	2.0	10.3	4.0
Na ₂ O	0.61	0.3	1.5
Fe ₂ O ₃	2.6	0.4	5.4

The alkaline activator used throughout the study was an aqueous solution of sodium silicate (Na₂O + *m* SiO₂, where *m* is the silica modulus) and sodium hydroxide (NaOH). The sodium oxide equivalent was determined according to the stoichiometry of the dissociation of sodium hydroxide into sodium oxide and water, i.e.:



Three solution parameters were varied. The sodium oxide equivalent dosage was varied between 2% and 7% (by mass of binder). The silica modulus (mass ratio of silica to sodium oxide equivalent) was varied between 0.75 and 2.5. The solution-to-binder ratio, which is correlated to the water content, was varied between 0.40 and 0.50. These solution parameters were informed by the results of a previous study funded by UTRC, and are presented in [45].

Activator solutions were prepared in advance to allow time for adequate dissolution and heat dissipation. Mortar and concrete mixtures were prepared according to the mixture proportions

given in Tables 3 and 4. Mixture proportions were specified in such a way as to keep the paste volume consistent between mixtures. Mixing was performed by first batching the aggregate(s) and raw binder, and mixing the materials until homogeneous. The activator solution was then added and allowed to permeate the dry mixture for several seconds. This was followed by mixing for several minutes. Some mixtures required additional energy imparted by hand-mixing, kneading, or tamping, to provide a consistent and homogeneous mixture. Cast specimens were consolidated on a vibrating table and carefully sealed in plastic to prevent moisture loss to the environment during curing.

Table 2. Mortar mixture proportions

	s/b	Binder (g)	Sand (g)	Solution (g)
Fly ash C	0.4	684	720	274
	0.45	684	720	308
	0.5	684	720	342
Slag	0.4	342	427	137
	0.45	342	427	154
	0.5	342	427	171
Portland cement	0.4	684	908	274

Table 3. Concrete mixture proportions

	s/b	Binder (g)	Sand (g)	Gravel (g)	Solution (g)
Fly ash C	0.4	570	720	780	228
Slag	0.4	570	720	780	228
Portland cement	0.4	570	908	780	228

2.2 Experimental methods

Chemical shrinkage was measured by the capillary tube method in accordance with the specifications of ASTM C1608. This method has been previously described in detail by [46, 47]. Results from this method were further validated by the gravimetric method, which makes use of Archimedes' Principle, viz. the buoyant force on a submerged object is equal to the weight of the water displaced by that object. This process has been described in detail by [46, 48].

Autogenous shrinkage was measured by the linear (dilatometer) method in accordance with the specifications of ASTM C1698. Since autogenous and chemical shrinkage are indistinguishable prior to setting of the binder, the Vicat test was used to identify the setting time of the binder in accordance with the specifications of ASTM C191. After final set was reached, shrinkage measurements began.

Drying shrinkage of standard mortar bars and concrete prisms was measured by the length comparator method in accordance with the specifications of ASTM C157, C490, and C596. Limewater-saturated specimens were exposed to conditions of 22 ± 2 °C and 50 ± 5 %RH until the length equilibrated.

Carbonation shrinkage was also measured in accordance with the specifications of ASTM C157. In a similar manner as for drying shrinkage, mortar bars were stored at 22 ± 2 °C and 50 ± 5 %RH in a sealed chamber. The chamber was flooded with a controlled concentration of 2% food grade CO₂. Carbonated samples were also characterized by X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) to determine the effect of carbonation on the chemistry and microstructure of the binders. This has been well described by [52].

Setting time of mortars was evaluated by the modified Vicat penetration test, which measured setting time in terms of the penetration depth of a 2 mm needle in accordance with the specifications of ASTM C807. Workability was evaluated by the flow table method in accordance with the specifications of ASTM C230 and C1437.

3. Results and discussion

3.1 Chemical shrinkage

The chemical shrinkage of alkali-activated fly ash and slag binder pastes was evaluated by the capillary method. The effect of sodium oxide concentration, silica modulus, and solution-to-binder ratio are discussed here. Since chemical shrinkage can be taken as an indicator of reaction progression, correlations are drawn to the reaction kinetics of alkali-activated binders, which are well known [34,35].

3.1.1 Effect of curing temperature

Increased curing temperatures are known to greatly increase the rate of reaction in alkali-activated binders. As such, the chemical shrinkage would be expected to increase much more rapidly. The chemical shrinkage of alkali-activated fly ash and slag binders at ambient

temperature (25 °C) and elevated temperature (50 °C) is shown in Figure 1. In addition to class C fly ash and slag, Figure 1 also shows some results for class F fly ash. As expected, increased reaction temperature increases the magnitude of chemical shrinkage in fly ash binders. The same effect was not observed for slag binders. The problem with the measurement of chemical shrinkage in alkali-activated slag results from the high density and low permeability of the products which form on the surface of hydrating slag grains. As the reaction is catalyzed by either increased activator concentration or increased temperature, this effect is magnified. Since the measurement of chemical shrinkage relies on the measurement of water permeated into the binder, the measurement is affected by the formation of this dense and impermeable product. This is the reasoning for the apparent reduction in chemical shrinkage observed in alkali-activated slag at elevated curing temperature.

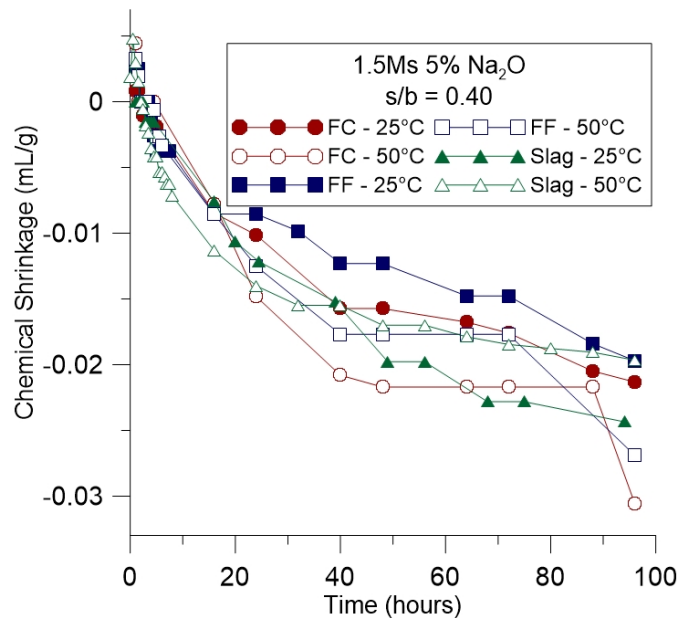


Figure 1. Chemical shrinkage of sodium silicate-activated fly ash and slag binders at ambient (25 °C) and elevated temperature (50 °C)

3.1.2 Effect of sodium oxide concentration

The chemical shrinkage of sodium silicate-activated fly ash and slag binders cured at 25 °C with varying sodium oxide concentration is shown in Figure 2. The silica modulus and solution-to-binder ratio remained constant ($m=1.5$, $s/b=0.50$) to isolate the effect of sodium oxide concentration. The chemical shrinkage tended to increase with increased sodium oxide in alkali-activated fly ash binders. This is due to the rapid hydration that occurs in alkali-activated binders with high sodium oxide dosages [34,35]. In slag binders, the chemical shrinkage increased when sodium oxide dosage increased from 2.5% to 5%, but did not increase any further as the sodium oxide dosage rose to 7%. Here, the reaction progression becomes more rapid as sodium oxide increases to a point, after which increased sodium oxide has no effect on chemical shrinkage or the rate of reaction.

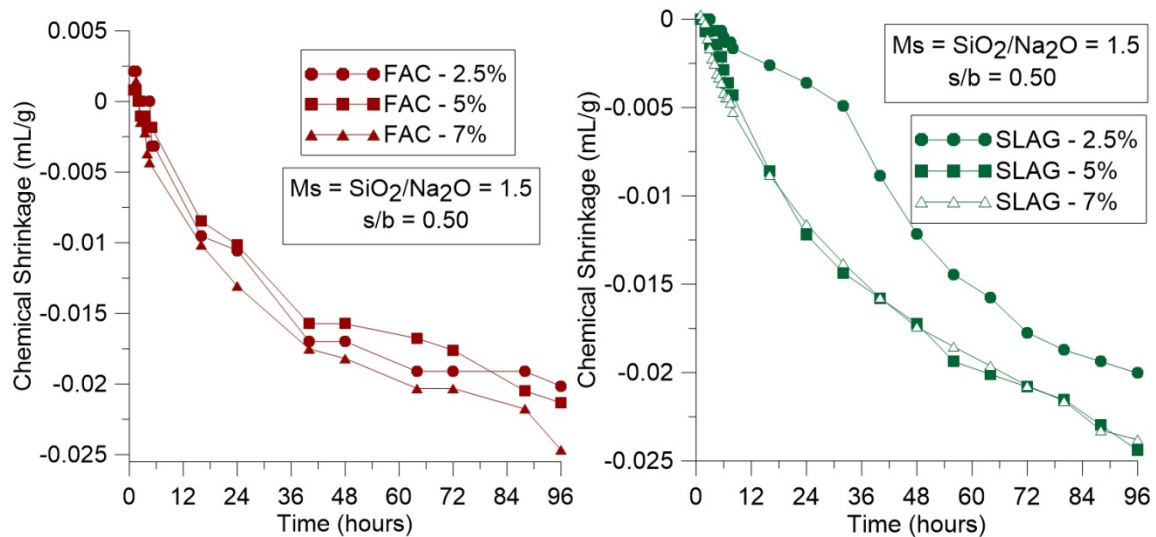


Figure 2. Chemical shrinkage of sodium silicate-activated fly ash (left) and slag (right) binders with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5$, $s/b=0.50$)

3.1.2 Effect of silica modulus

The chemical shrinkage of sodium silicate-activated fly ash and slag binders cured at 25 °C with varying silica modulus is shown in Figure 3. To isolate the effect of silica modulus, the sodium oxide concentration and solution-to-binder ratio were kept constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$). Increased silica is known to retard the reaction but lead to a higher degree of hydration at later ages [34,35]. It should therefore be expected that binders with higher silica modulus should show lower chemical shrinkage at early ages, but higher chemical shrinkage at later ages. Despite several experimental anomalies, the results presented in Figure 3 generally agree with this supposition. This effect is particularly obscured in alkali-activated slag binders due to the aforementioned effect of the formation of dense products on the surface of hydrating slag grains.

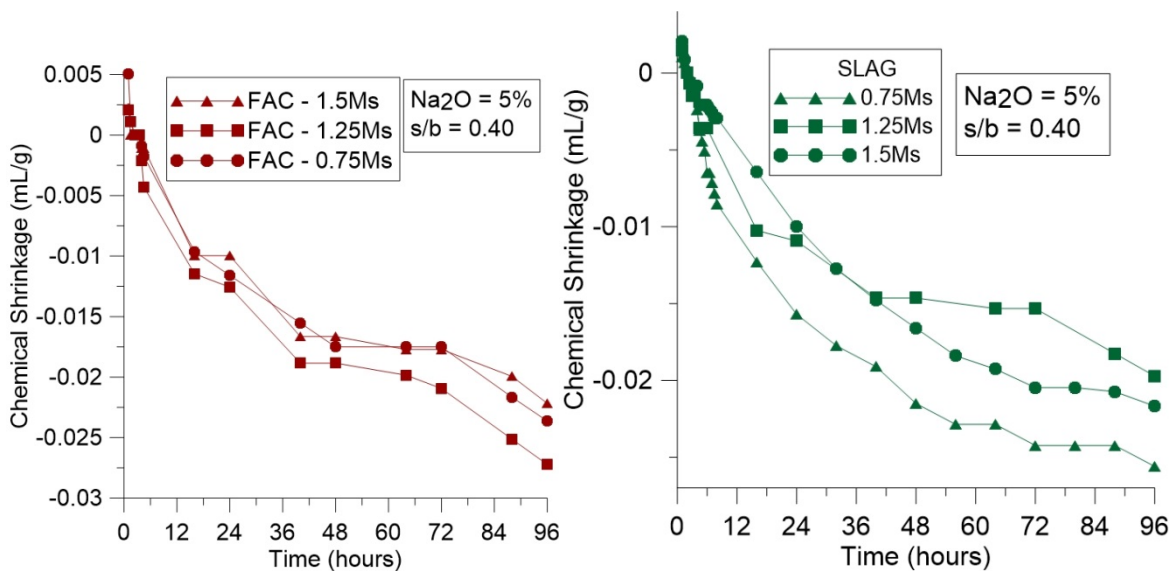


Figure 3. Chemical shrinkage of sodium silicate-activated fly ash (left) and slag (right) binders with varying silica modulus. Sodium oxide concentration and solution-to-binder ratio are constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$)

3.1.3 Effect of solution-to-binder ratio

The chemical shrinkage of sodium silicate-activated fly ash and slag binders cured at 25 °C with varying solution-to-binder ratio is shown in Figure 4. To isolate the effect of solution-to-binder ratio, the sodium oxide concentration and silica modulus were kept constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$). Solution-to-binder ratio is essentially a measure of the free water in the system. The effect of increased water content on alkali-activated fly ash binders is not known for sure. However, at least one study has shown that changes in the solution-to-binder ratio in alkali-activated slag may alter the composition of silicate anions within the binder system [53]. This generally results in reduced heat evolution during hydration, and should therefore reduce the chemical shrinkage. The results presented in Figure 4 show that the water content has a fairly minimal effect on chemical shrinkage in both alkali-activated fly ash and slag binder systems. In slag binders, this is at least partly due to the same effect of dense product formation on the hydrating slag grains. Overall, it is very difficult to measure the effect of solution-to-binder ratio on chemical shrinkage because of the nature of the test method (i.e., the use of permeated water to measure the change in volume).

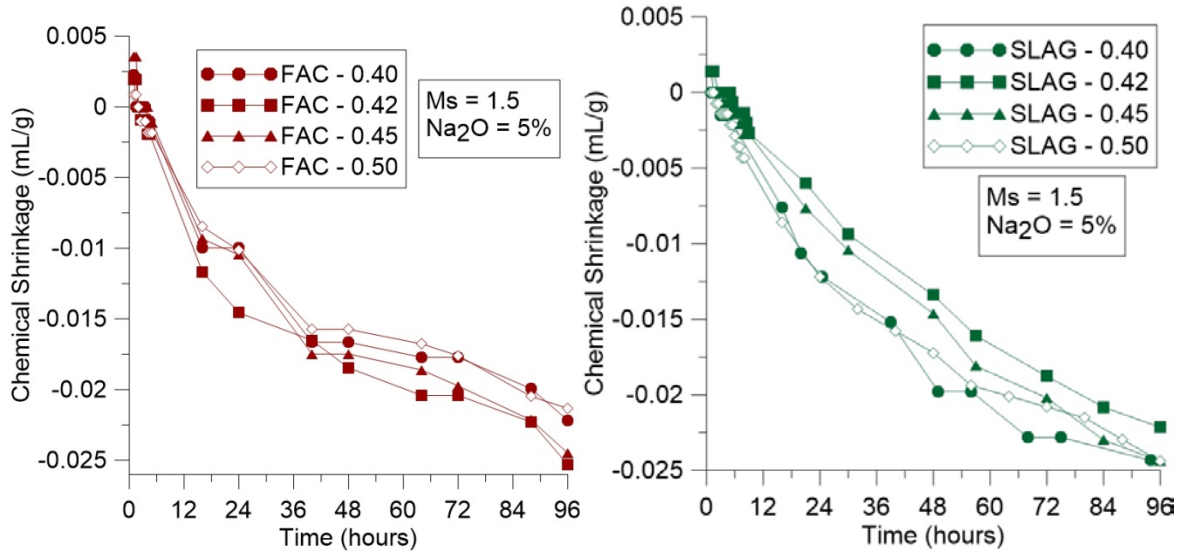


Figure 4. Chemical shrinkage of sodium silicate-activated fly ash (left) and slag (right) binders with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($Na_2O=5\%$, $m=1.5$)

3.1.4 Summary

Overall, it was determined that the evaluation of chemical shrinkage in alkali-activated binders and the use of chemical shrinkage to infer the progress and rate of the alkali-activation reaction is problematic using normal accepted methods. In slag, this is mainly due to the formation of dense impermeable reaction products which limit the flow of water into the pores of the hydrating binder. Since the evaluation of chemical shrinkage relies on the measurement of the water absorbed by the pores, this makes measuring chemical shrinkage difficult, if not impossible. It was possible, however, to observe general trends. For example, the chemical shrinkage generally increased with lower silica modulus; increased silica is known to retard the activation reaction. Additionally, chemical shrinkage generally increased with temperature and sodium oxide dosage. Both are known to accelerate the product formation in alkali-activated binders. Comparison of

chemical shrinkage results for alkali-activated binders with those for portland cement is not necessarily appropriate due to the well-established differences in hydration mechanisms.

3.2 Autogenous shrinkage

The autogenous shrinkage of alkali-activated fly ash and slag binders was measured by the linear (dilatometer) method. Specimens were cast within soft corrugated plastic tubing which could be sealed without restricting deformation. The effect of sodium oxide concentration, silica modulus, solution-to-binder ratio, and mitigation methods are discussed here.

3.2.1 Effect of sodium oxide concentration

Autogenous shrinkage in sodium silicate-activated fly ash and slag binders cured at 25 °C with varying sodium oxide concentration is shown in Figure 5. To isolate the effect of sodium oxide concentration, the silica modulus and solution-to-binder ratio remained constant ($m=1.5$, $s/b=0.50$). In fly ash binders, increased sodium oxide resulted in a pronounced increase in autogenous shrinkage. In contrast, the autogenous shrinkage in alkali-activated slag binders decreased as sodium oxide concentration increased.

Increased sodium oxide dosage naturally results in increased abundance of soluble salts in the hydrating binder system. This leads to a reduction in the internal relative humidity, which is the main mechanism behind most autogenous shrinkage. This is likely the reason for increased autogenous shrinkage in alkali-activated fly ash systems with increased sodium oxide dosage. In addition, reduced porosity generally increases autogenous shrinkage. Increased sodium oxide concentration has been shown to result in pore structure refinement in alkali-activated fly ash, further increasing the autogenous shrinkage. The same effect on porosity has been observed for alkali-activated slag binders [54], but the opposite trend was observed for autogenous shrinkage of these systems. The mechanism here is unclear. It is unknown if this is again a result of the

dense product formed on the surface of hydrating slag grains, or if this is a result of some other phenomenon. More focused investigations may later reveal the mechanism at play.

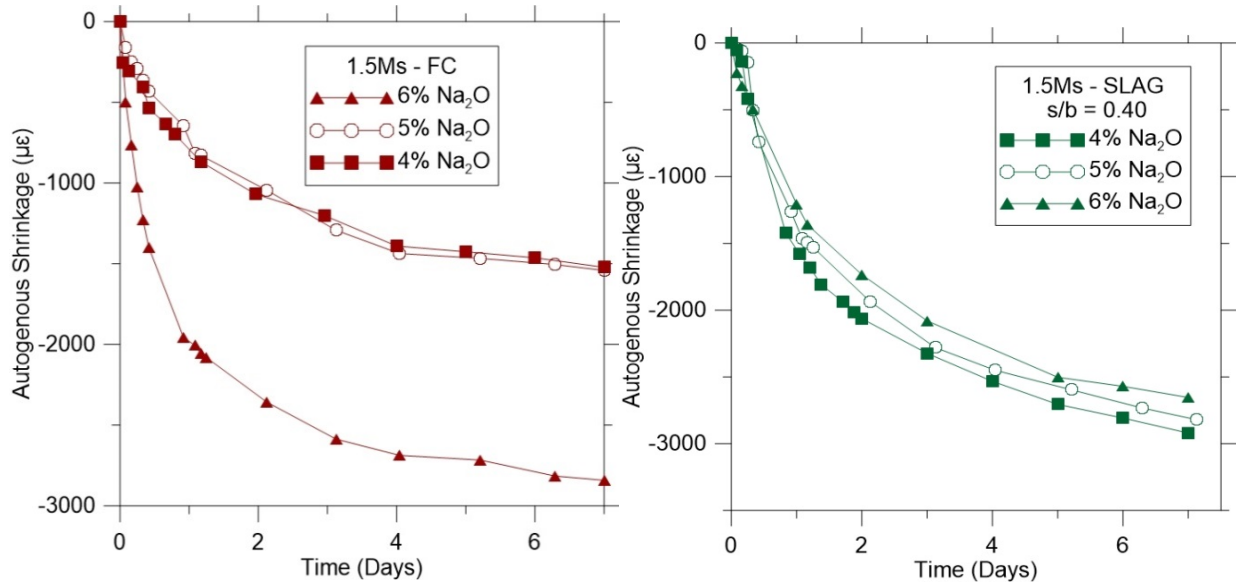


Figure 5. Autogenous shrinkage of sodium silicate-activated fly ash (left) and slag (right)

binders with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5$, $s/b=0.40$)

3.2.2 Effect of silica modulus

Autogenous shrinkage in sodium silicate-activated fly ash and slag binders cured at 25 °C with varying silica modulus is shown in Figure 6. To isolate the effect of silica modulus, the sodium oxide concentration and solution-to-binder ratio were kept constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$). Here, the autogenous shrinkage increased with decreased silica modulus in both fly ash and slag binders. This is likely due to the retarding effect of silica on the alkali-activation reaction. With longer induction period and slower hydration comes coarser porosity and reduced tensile stress within the pore system. This manifests as reduced autogenous shrinkage as observed in Figure 6. This increase in porosity with increased silica modulus has been observed in the literature [54].

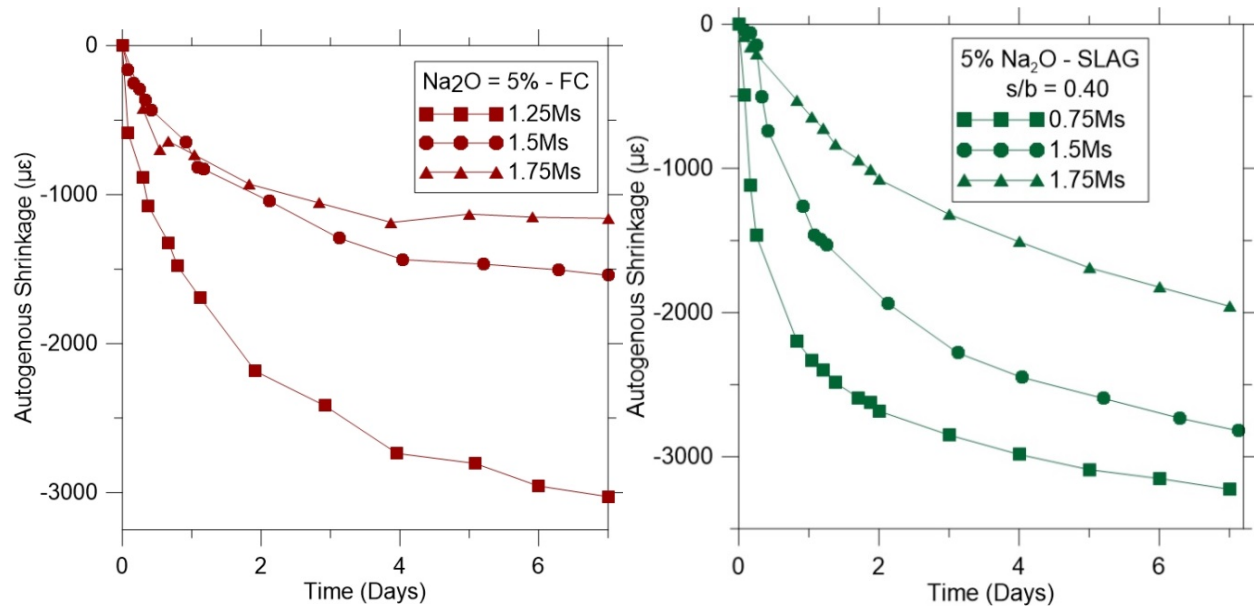


Figure 6. Autogenous shrinkage of sodium silicate-activated fly ash (left) and slag (right)

binders with varying silica modulus. Sodium oxide concentration and solution-to-binder ratio are constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$)

3.2.3 Effect of solution-to-binder ratio

Autogenous shrinkage in sodium silicate-activated fly ash and slag binders cured at 25 °C with varying solution-to-binder ratio is shown in Figure 7. To isolate the effect of solution-to-binder ratio, the sodium oxide concentration and silica modulus were kept constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$). In sodium silicate-activated fly ash binders, higher s/b resulted in increased autogenous shrinkage. This could be a result of the increased free water content of the activator solution; more water available for consumption results in more shrinkage. However, the porosity of the binder should increase with higher solution-to-binder ratio, thereby resulting in less autogenous shrinkage. It is possible that the increased water content of the activating solution results in faster dissolution, increased product formation, and the more rapid development of capillary stresses leading to volume reduction. In alkali-activated slag binders, the effect of solution-to-binder ratio

on autogenous shrinkage is minimal. Again, this is not surprising since water absorption is hindered in these binder systems. Despite the minimal effect, the expected trend of increasing autogenous shrinkage with lower solution-to-binder ratio is weakly observed.

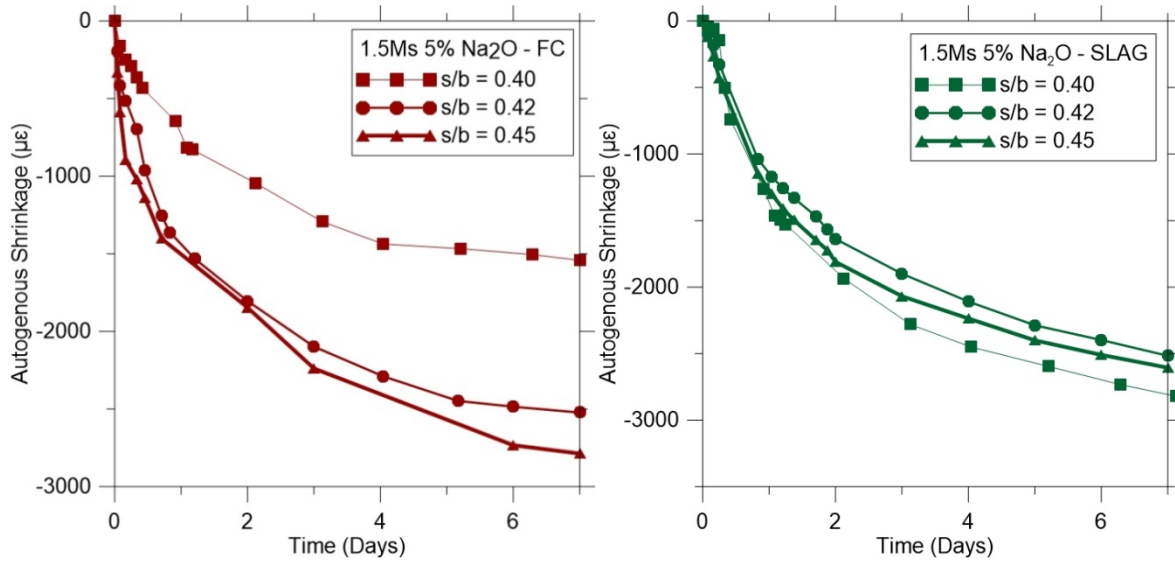


Figure 7. Autogenous shrinkage of sodium silicate-activated fly ash (left) and slag (right)

binders with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$)

3.2.4 Effect of shrinkage mitigation techniques

Internal curing with saturated lightweight aggregate has been shown to reduce autogenous shrinkage by providing easily accessible water which can be preferentially consumed by hydrating binders without the development of unwanted internal stresses and shrinkage strains [49, 50]. Shrinkage-reducing admixtures have also proven effective at mitigating shrinkage in cementitious binders. The effect of these mitigation techniques on autogenous shrinkage in alkali-activated binders is unknown.

Autogenous shrinkage in sodium silicate-activated fly ash binders with and without internal curing and shrinkage reducing admixture is shown in Figure 8. Similarly, autogenous shrinkage

in sodium silicate-activated slag binders with and without internal curing and shrinkage reducing admixture is shown in Figure 9. Internal curing was performed with 20%, 25%, and 30% replacement of normal fine aggregate with saturated lightweight aggregate, and the dosage of the shrinkage-reducing admixture used was 1%, 2%, and 3% by mass of binder. Internal curing was effective at greatly reducing autogenous shrinkage in both fly ash and slag binders, regardless of replacement percentage. The effect was far more significant in slag binders, reducing autogenous shrinkage by a full order of magnitude. The autogenous shrinkage was cut in half by the use of internal curing in fly ash binders.

Shrinkage-reducing admixture proved entirely ineffective at mitigating autogenous shrinkage in fly ash binders. In slag binders, a slight reduction in autogenous shrinkage was observed with shrinkage-reducing admixture at the weakest dosage; increasing the admixture dosage negated that reduction. It has been suggested that shrinkage-reducing admixtures can retard hydration in alkali-activated slag [55], which provides some context for this behavior.

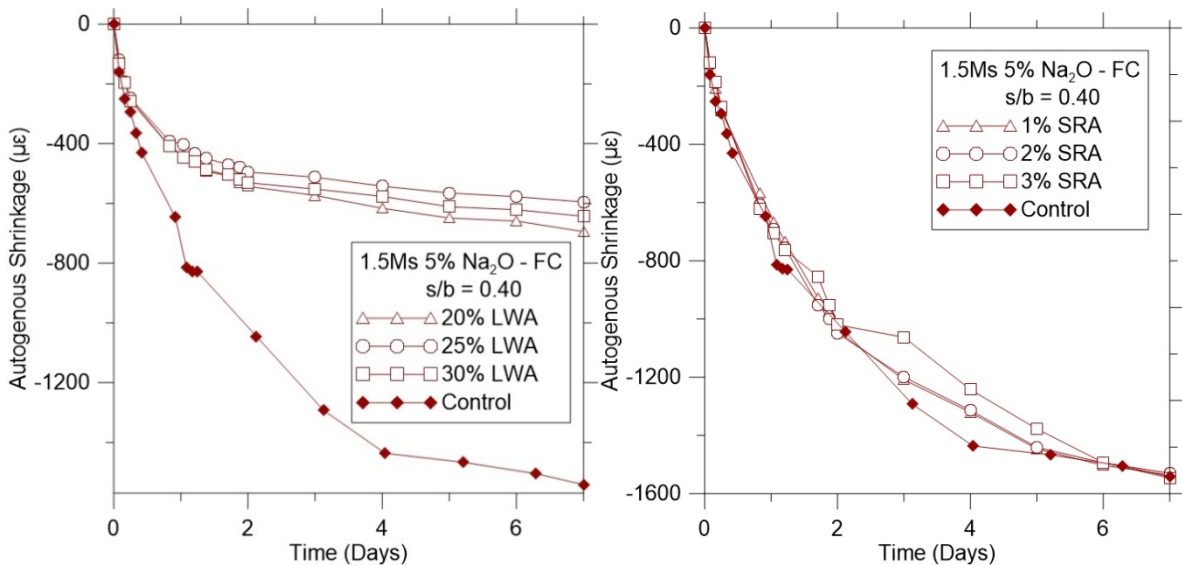


Figure 8. Autogenous shrinkage of sodium silicate-activated fly ash binders with and without internal curing with saturated lightweight aggregate (left) and shrinkage-reducing admixture (right)

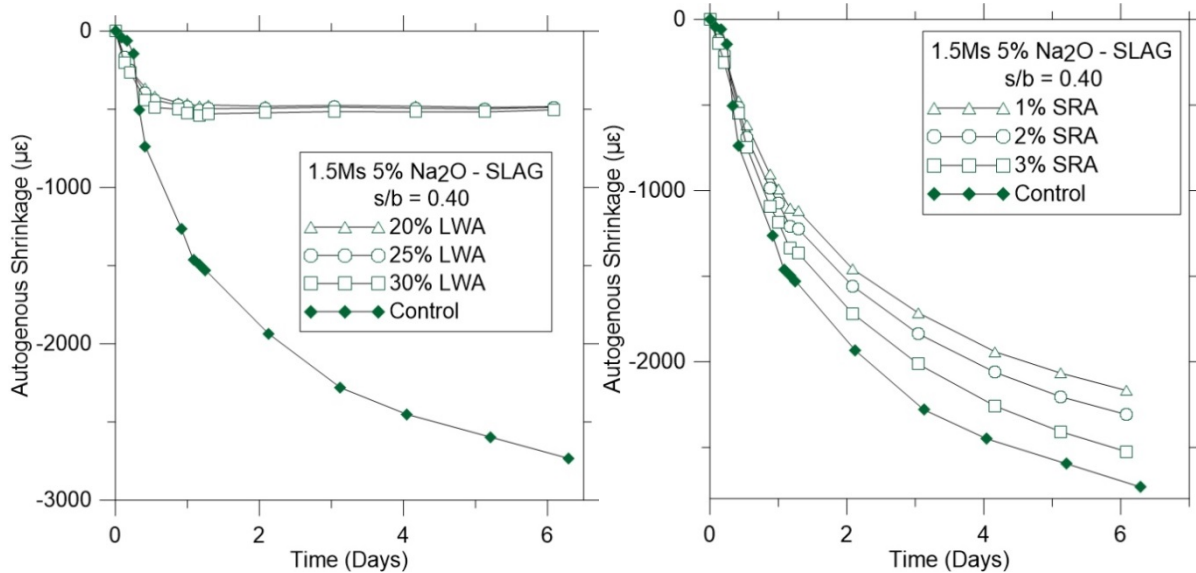


Figure 9. Autogenous shrinkage of sodium silicate-activated slag binders with and without internal curing with saturated lightweight aggregate (left) and shrinkage-reducing admixture (right)

3.2.5 Summary and comparison with portland cement

A comparison of the autogenous shrinkage in portland cement and alkali-activated fly ash and slag binders is presented in Figure 10. Autogenous shrinkage in sodium silicate-activated slag is about twice the magnitude of that in sodium silicate-activated fly ash. Further, autogenous shrinkage in sodium silicate-activated fly ash is about an order of magnitude higher than that in portland cement. This is probably due to the more refined pore structure in alkali-activated binder systems, which normally results in the development of higher internal stresses and, therefore, more reduction in volume.

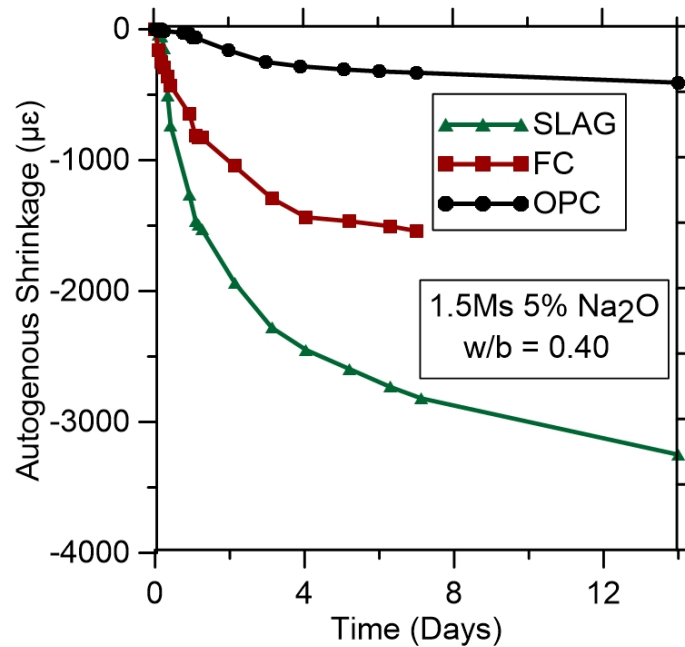


Figure 10. Autogenous shrinkage in alkali-activated fly ash and slag binder compared to portland cement binder

Overall, it was observed that autogenous shrinkage in alkali-activated fly ash systems increased with solution-to-binder ratio and sodium oxide concentration, and decreased with silica modulus. Autogenous shrinkage in alkali-activated slag binders tended to decrease with silica modulus and was only mildly affected by sodium oxide concentration and solution-to-binder ratio. Internal curing was extremely effective at mitigating autogenous shrinkage in fly ash and slag binders, while shrinkage reducing admixtures had very limited effect in slag binders and no effect in fly ash.

3.3 Drying shrinkage

3.3.1 Drying shrinkage of alkali-activated fly ash and slag mortar

Drying shrinkage in alkali-activated fly ash and slag mortar with varying sodium oxide concentration is shown in Figures 11 and 12, respectively. To isolate the effect of sodium oxide, the silica modulus and solution-to-binder ratio were kept constant ($m=1.5$, $s/b=0.40$). In the fly

ash mortar, shrinkage decreased with sodium oxide concentration. This is likely due to the weak early strength of the activated fly ash system when sodium oxide dosage is low, which provides little resistance to internal tensile stresses. In the activated slag mortar, the opposite trend was observed. In the slag system, the decreased porosity in binders with higher sodium oxide likely resulted in increased shrinkage. It must be noted here that the specimens represented in Figure 11 were demolded only after 72 hours; the magnitude of the drying shrinkage observed in those specimens was therefore reduced compared to the rest of the data presented in this study.

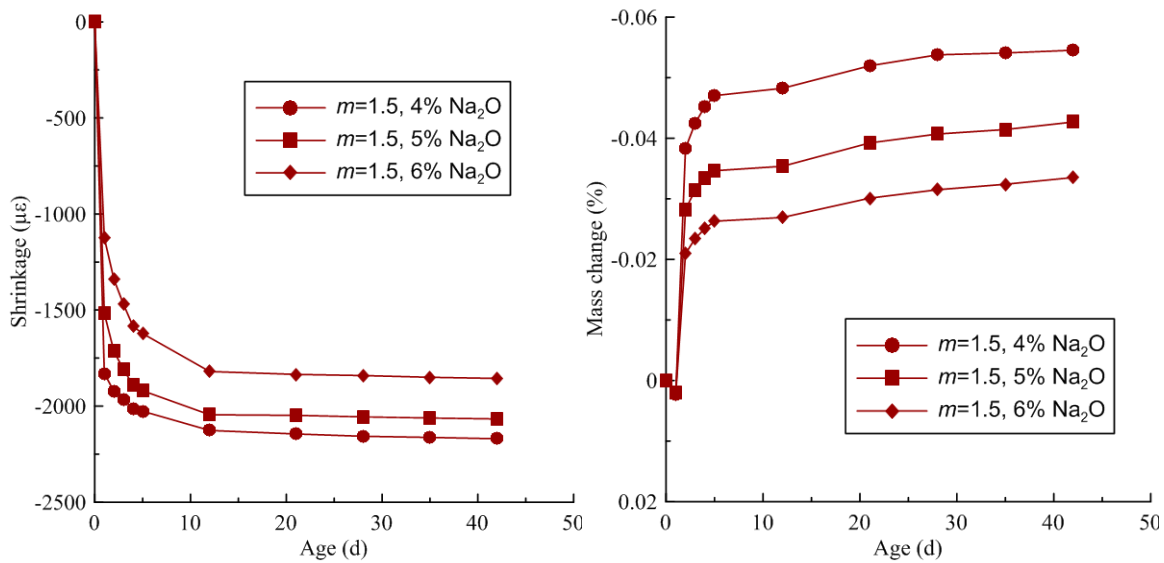


Figure 11. Drying shrinkage of sodium silicate-activated fly ash mortar with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5, s/b=0.40$)

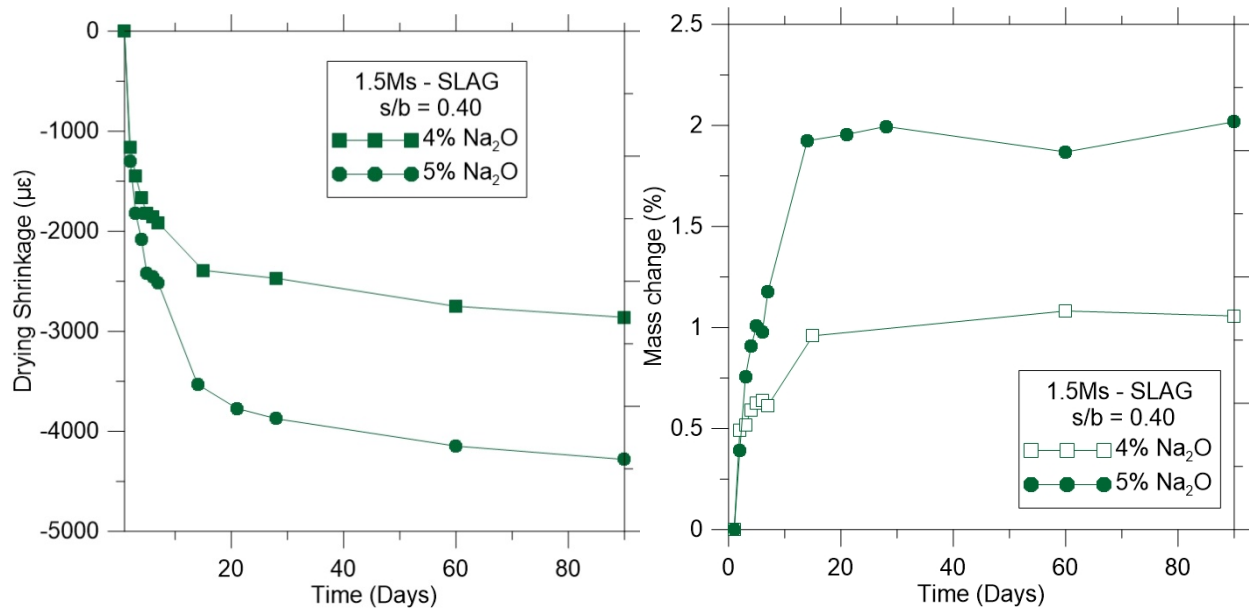


Figure 12. Drying shrinkage of sodium silicate-activated slag mortar with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5$, $s/b=0.40$)

Drying shrinkage in alkali-activated slag mortar with varying silica modulus is shown in Figure 13. To isolate the effect of silica modulus, sodium oxide concentration and solution-to-binder ratio were kept constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$). Here, a reduction in silica modulus resulted in a drastic reduction in the overall magnitude of drying shrinkage. This can also be explained by the porosity, as the porosity in alkali-activated slag is known to be reduced with lower silica modulus.

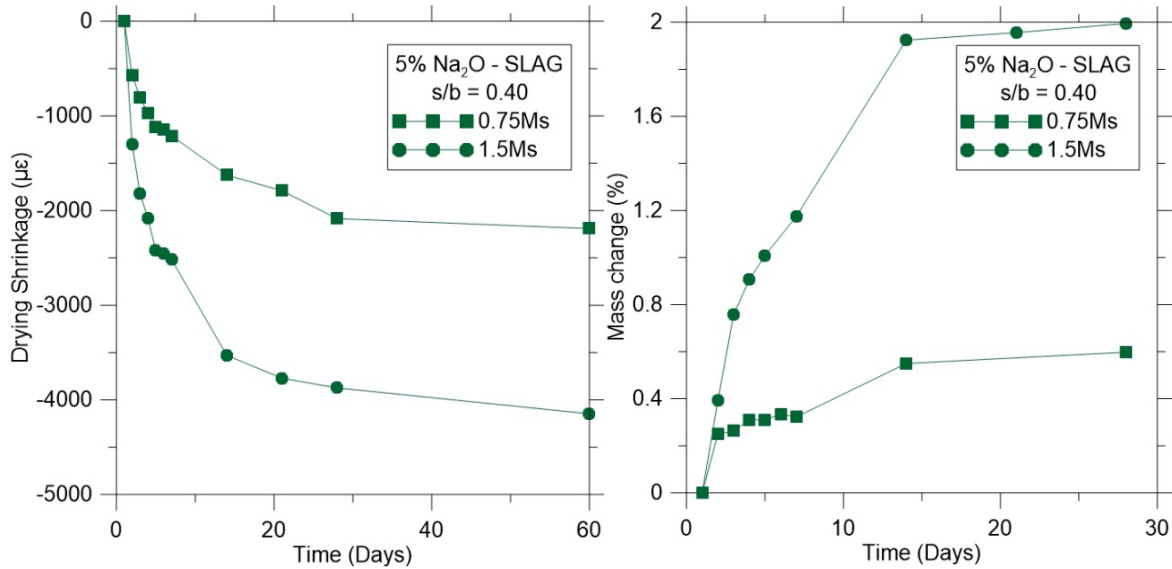


Figure 13. Drying shrinkage of sodium silicate-activated slag mortar with varying silica modulus. Sodium oxide concentration and solution-to-binder ratio are constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$)

Drying shrinkage in alkali-activated fly ash and slag mortar with varying solution-to-binder ratio is shown in Figures 14 and 15, respectively. To isolate the effect of solution-to-binder ratio, sodium oxide concentration and silica modulus were kept constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$). In both binders, increased solution-to-binder ratio, and therefore increased free water content, resulted in increased shrinkage. This was the expected trend, as the same is known to occur in portland cement binders.

It is important to note that the majority of the drying shrinkage in alkali-activated fly ash and slag binders seems to occur within the first few days of drying. In contrast, the drying shrinkage process in portland cement is known to be more gradual. This is discussed in further detail in the next sub-section.

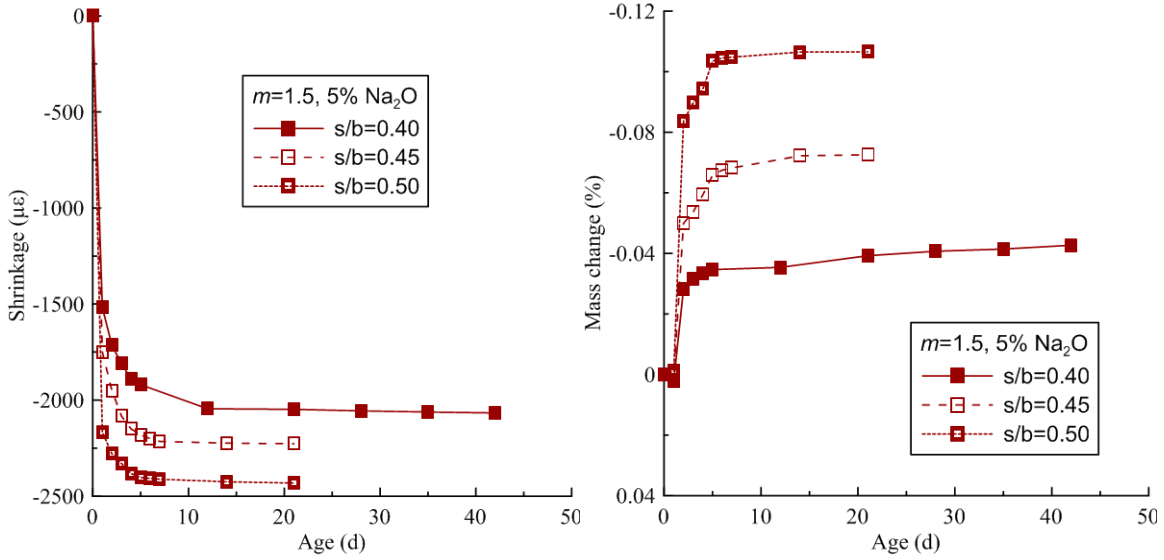


Figure 14. Drying shrinkage of sodium silicate-activated fly ash mortar with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$)

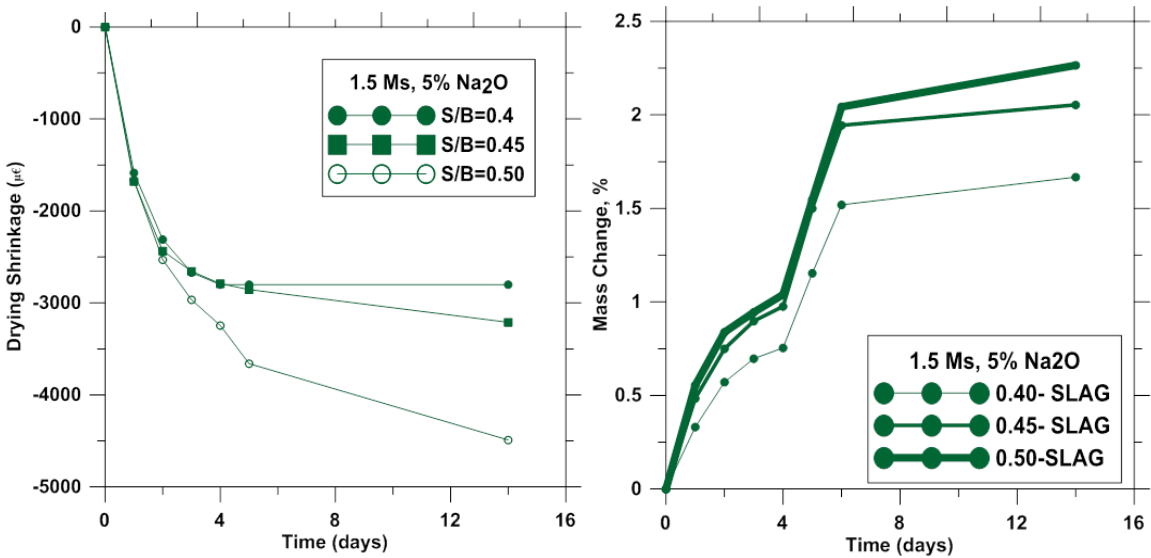


Figure 15. Drying shrinkage of sodium silicate-activated slag cement mortar with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$)

3.3.2 Drying shrinkage of alkali-activated concrete

The drying shrinkage and weight change of prismatic alkali-activated concrete specimens measuring 2 x 2 x 10 inches exposed to 50 %RH was evaluated by the length comparator method. The resulting shrinkage in sodium silicate-activated fly ash and slag concrete was compared to that of a control portland cement concrete. The drying shrinkage and water loss of alkali-activated fly ash and alkali-activated slag concrete are presented in Figures 16 and 17, respectively. These specimens were demolded only after 72 hours due to the slow strength gain in these concretes, and so the magnitude of shrinkage reported here may be lower than that observed in specimens demolded after 24 hours.

In alkali-activated fly ash concrete, the drying shrinkage tended to be indirectly related to sodium oxide concentration. At low dosages of sodium oxide, the drying shrinkage was very high—in excess of 1200 microstrain. At higher dosages, the drying shrinkage was reduced to values much more comparable with portland cement concrete. As expected, the magnitude of drying shrinkage was directly related to the water loss from the specimen.

The opposite trend was observed in alkali-activated slag concrete; the magnitude of drying shrinkage tended to increase as sodium oxide dosage increased. In addition, the magnitude of drying shrinkage increased with increased dosage of silica in the activator. In contradiction with expectations, the water loss was indirectly related to the magnitude of drying shrinkage. In ordinary cementitious binders, the drying shrinkage is caused by tensile strains that develop as a result of the migration of water from internal pores; as a result, the shrinkage increases when the water loss increases. This trend was not observed for alkali-activated slag concrete, suggesting that an alternative mechanism may be in play.

Overall, the magnitude of drying shrinkage in alkali-activated binders was arguably similar in magnitude to that in portland cement binders. In the most extreme cases, the drying shrinkage of alkali-activated concrete was twice that of portland cement concrete, but the maximum shrinkage recorded was around 1200 macrostrains; this is well within the expected range for portland cement concrete. However, in both alkali-activated fly ash and slag, the rate of shrinkage was much faster. About half of the total overall shrinkage occurred during the first day, and over 90% occurred during the first week in alkali-activated concrete. In comparison, about half of the total magnitude of drying shrinkage in portland cement concrete occurs during the first 7 days. Since alkali-activated concrete is known to develop strength more slowly than portland cement concrete, the excessive early-age shrinkage could be a result of the lower early strength. Further investigation is necessary to evaluate this theory.

It was observed that, despite the similarities in the magnitude of drying shrinkage between alkali-activated and portland cement concrete, there were easily observable differences in the response to that same shrinkage. In alkali-activated concrete, surface cracking was abundant and prolific, with the formation of pronounced surface cracks after as little as a few days. Few, if any, cracks were observed in portland cement concrete even at later age. In all, most of the trends observed in the drying shrinkage of alkali-activated fly ash and slag mortars were replicated in alkali-activated fly ash and slag concrete.

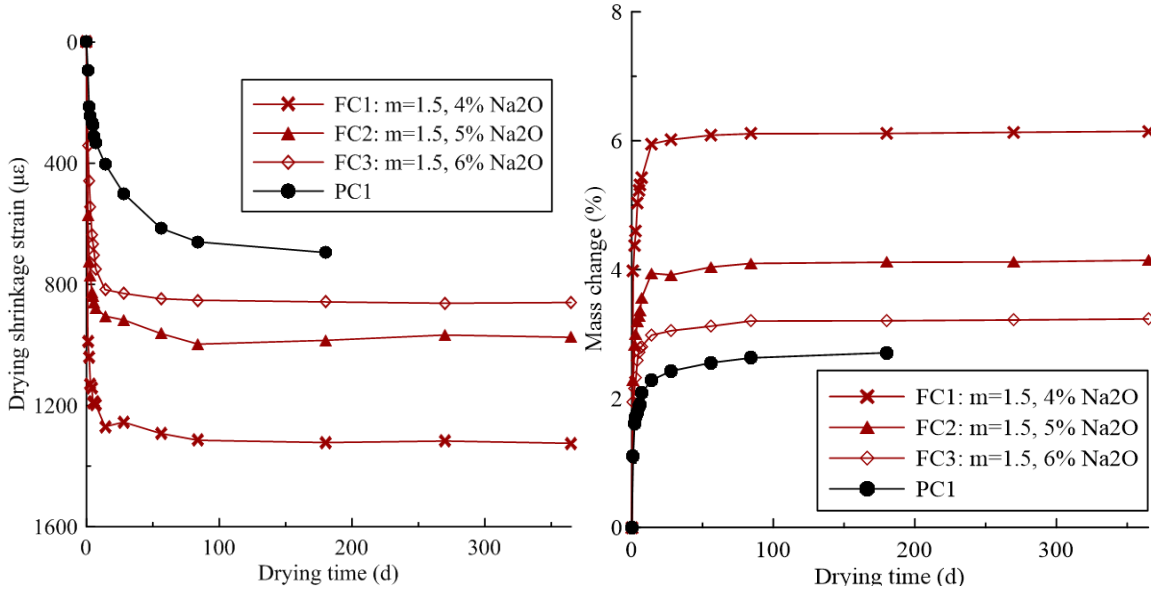


Figure 16. Drying shrinkage and water loss of alkali-activated fly ash and portland cement concrete prisms exposed to 50 %RH.

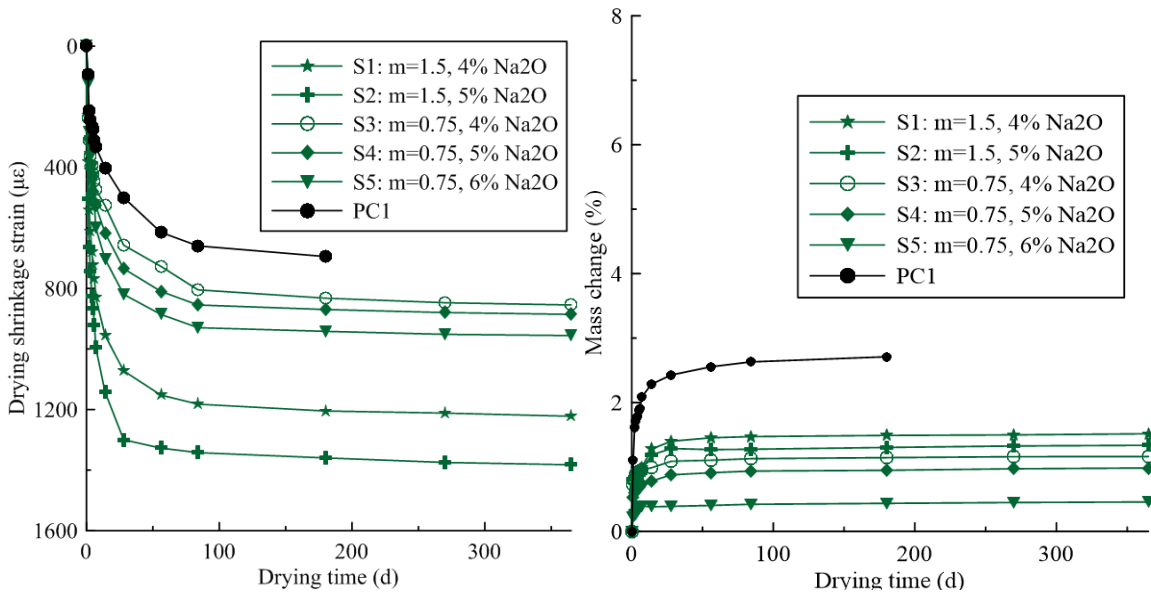


Figure 17. Drying shrinkage and water loss of alkali-activated slag and portland cement concrete prisms exposed to 50 %RH.

3.3.3 Drying shrinkage mitigation

Mitigation of drying shrinkage in alkali-activated fly ash and slag mortars was attempted through internal curing with saturated lightweight aggregate (at replacement dosages of 20%, 25%, and 30% of the total aggregate weight), shrinkage-reducing admixture, and curing at elevated temperature (50 °C). Drying shrinkage in alkali-activated fly ash mortar with and without internal curing is shown in Figure 18. Internal curing was effective at reducing the total magnitude of drying shrinkage by about half, but the remaining magnitude of drying shrinkage is still very high. Similarly, drying shrinkage in alkali-activated slag mortars with and without internal curing, shrinkage-reducing admixture, and elevated-temperature-curing is shown in Figure 19. Both shrinkage-reducing admixture and internal curing were mostly ineffective at reducing drying shrinkage in the alkali-activated slag system. However, curing at elevated temperature reduced the total magnitude of drying shrinkage by a factor of five. This is likely due to the early evaporation of free water prior to the setting of the mortar in the elevated-temperature environment.

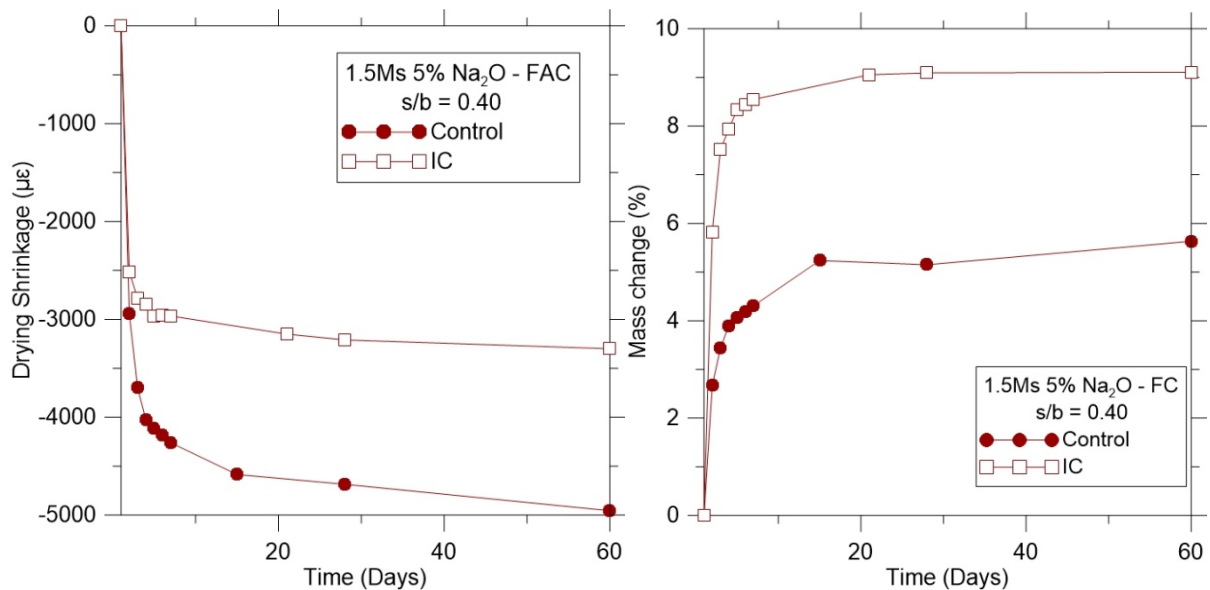


Figure 18. Effect of internal curing on drying shrinkage in alkali-activated fly ash mortar

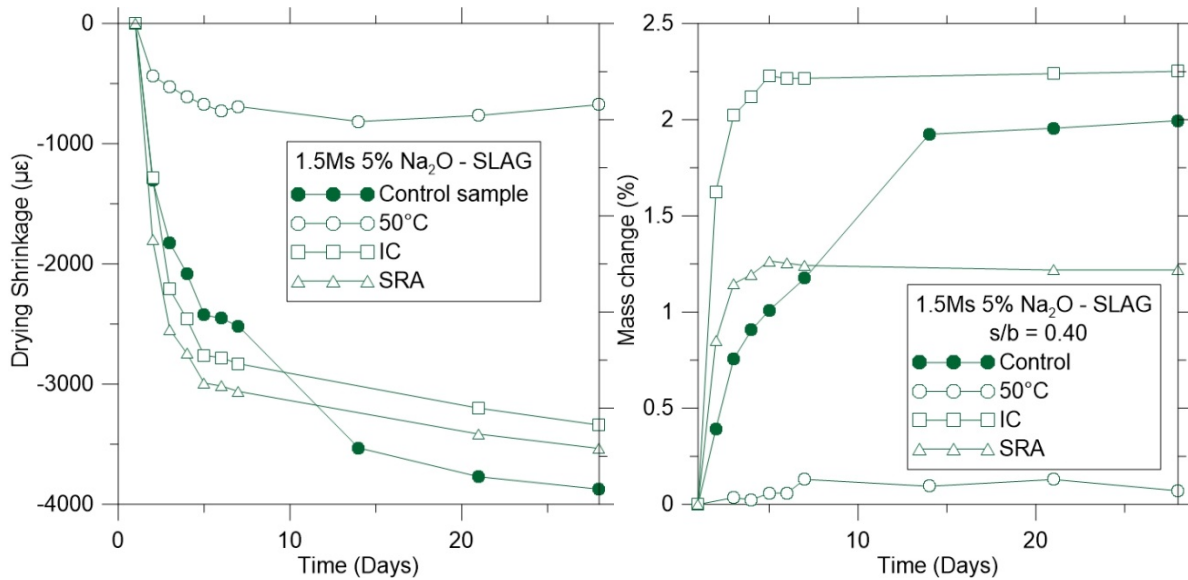


Figure 19. Effect of internal curing, shrinkage-reducing admixture, and elevated-temperature-curing on drying shrinkage in alkali-activated slag mortar

3.4 Carbonation shrinkage

The shrinkage of standard alkali-activated fly ash and slag mortar bars measuring 1 x 1 x 10 inches and exposed to 2% CO₂ and 50 %RH was measured by the length comparator method. The results of these evaluations, and the effect of sodium oxide concentration, silica modulus, and solution-to-binder ratio are discussed in this section.

3.4.1 Effect of sodium oxide concentration

Carbonation shrinkage and weight change in sodium silicate-activated fly ash binders with varying sodium oxide concentration is shown in Figure 20. To isolate the effect of sodium oxide concentration, silica modulus and solution-to-binder ratio were kept constant ($m=1.5$, $s/b=0.40$). As with drying shrinkage, the magnitude of shrinkage and weight loss tended to decrease with increased sodium oxide dosage. This is likely due to the reduced early strength and increased porosity of the lower-Na₂O systems. The magnitude of carbonation shrinkage observed in fly ash binders was alarming, and pronounced cracking was observed. Furthermore, the very high

change in mass observed in carbonated fly ash binders is indicative of some additional mechanism. Further investigation is necessary to explain this unexpectedly large mass deviation.

Similarly, carbonation shrinkage in sodium silicate-activated slag binders with varying sodium oxide concentration is shown in Figure 21. The magnitude of carbonation shrinkage in alkali-activated slag binders was less than that observed in alkali-activated fly ash binders, but was still very high. As with the fly ash binders, carbonation shrinkage in slag binders decreased with silica modulus, although the effect was less pronounced. The major changes in mass observed in alkali-activated fly ash binders were not found in alkali-activated slag. This suggests that whatever mechanism is responsible for the deviation in mass in fly ash binders is not present in slag.

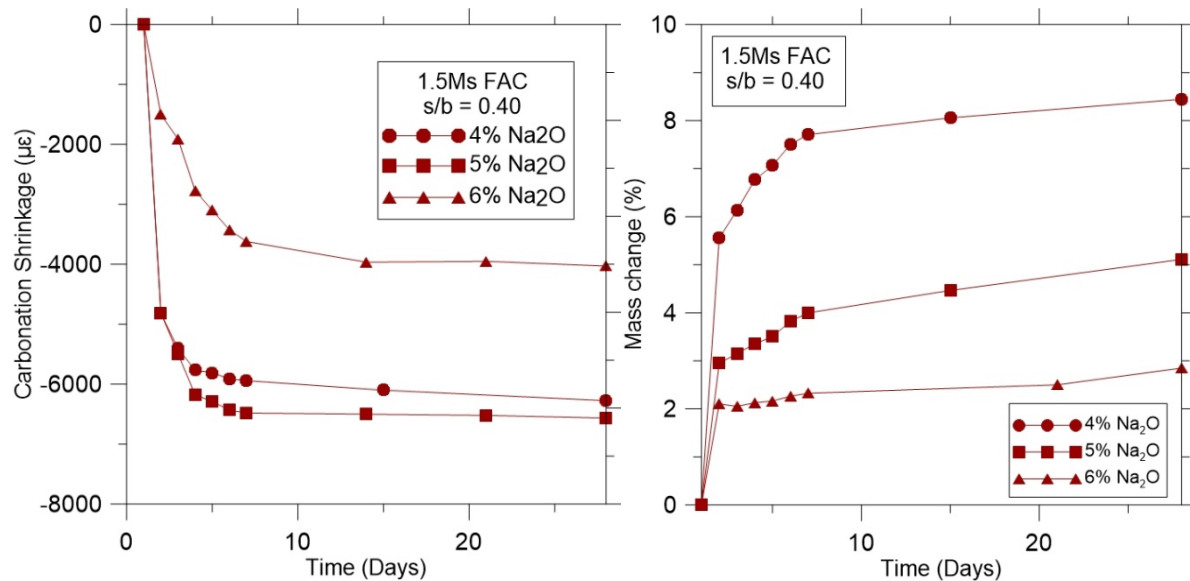


Figure 20. Carbonation shrinkage and mass change of sodium silicate-activated fly ash mortar with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5$, $s/b=0.40$)

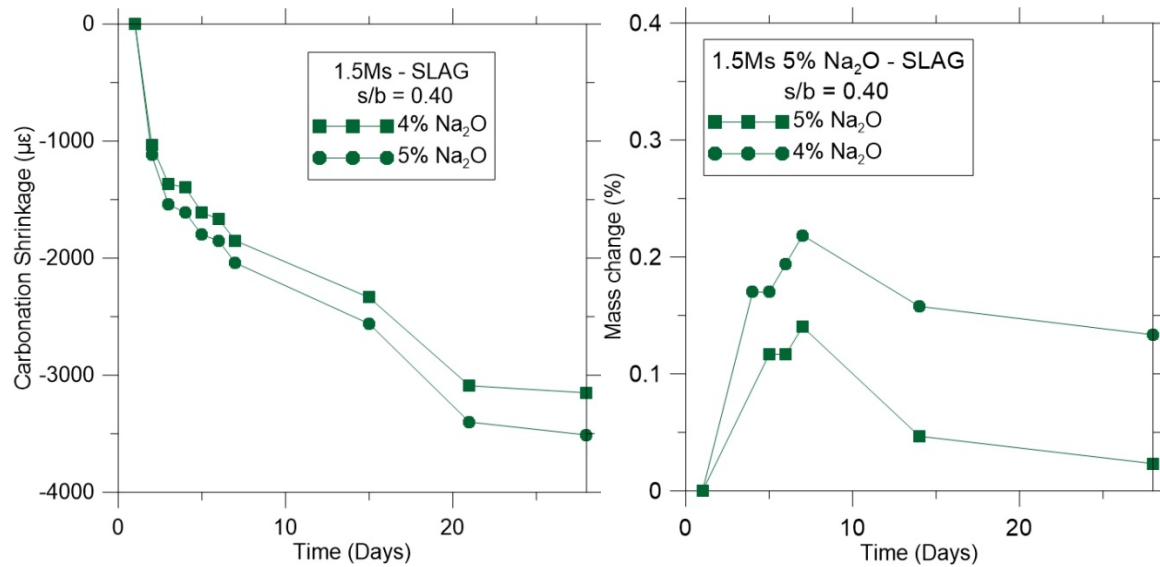


Figure 21. Carbonation shrinkage and mass change of sodium silicate-activated slag mortar with varying sodium oxide concentration. Silica modulus and solution-to-binder ratio are constant ($m=1.5$, $s/b=0.40$)

3.4.2 Effect of solution-to-binder ratio

Carbonation shrinkage in sodium silicate-activated fly ash binders with varying solution-to-binder ratio is shown in Figure 22. To isolate the effect of solution-to-binder ratio, sodium oxide concentration and silica modulus remained constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$). Increased solution-to-binder ratio resulted in increased mass change but reduced carbonation shrinkage. Generally, mass change and shrinkage magnitude are well-correlated. It is unclear what mechanism results in this behavior, but it is likely due to the reduction in pore volume associated with the formation of calcium carbonate, and the effect of solution-to-binder ratio on the porosity of the binder system.

Similarly, carbonation shrinkage in sodium silicate-activated slag binders with varying solution-to-binder ratio is shown in Figure 23. Again, increased solution-to-binder ratio resulted in increased mass change. Despite this, the mass change was still greatly reduced from that

observed in alkali-activated fly ash binders. Although the mass change was noticeably affected by solution-to-binder ratio, the magnitude of carbonation shrinkage was not.

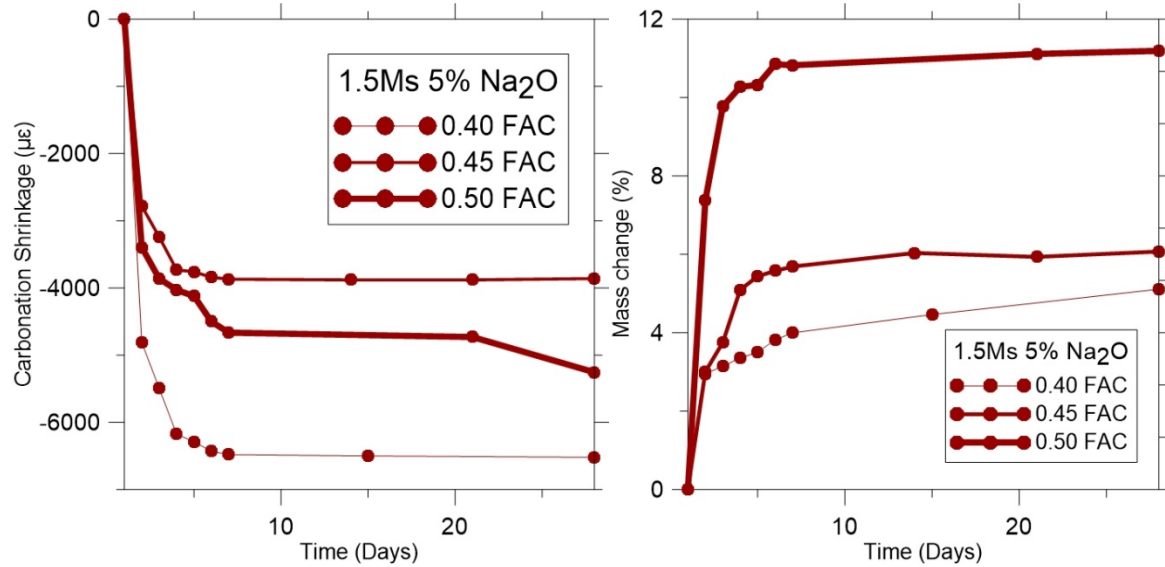


Figure 22. Carbonation shrinkage and mass change of sodium silicate-activated fly ash mortar with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$)

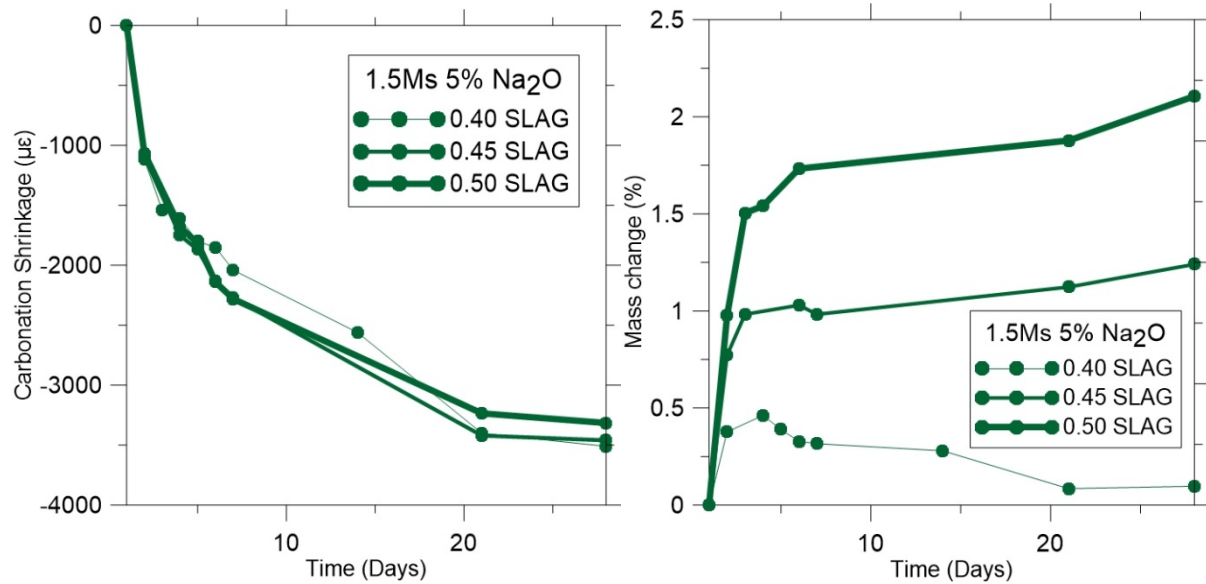


Figure 23. Carbonation shrinkage and mass change of sodium silicate-activated slag mortar with varying solution-to-binder ratio. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $m=1.5$)

3.4.3 Effect of silica modulus

Carbonation shrinkage in sodium silicate-activated slag binders with varying silica modulus is shown in Figure 24. To isolate the effect of silica modulus, the sodium oxide concentration and solution-to-binder ratio were kept constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$). Lower silica modulus resulted in a drastic reduction in both mass change and magnitude of carbonation shrinkage. The mechanism behind this is not surely known, but this shows that silica may be an effective means of mitigating carbonation shrinkage in alkali-activated binders.

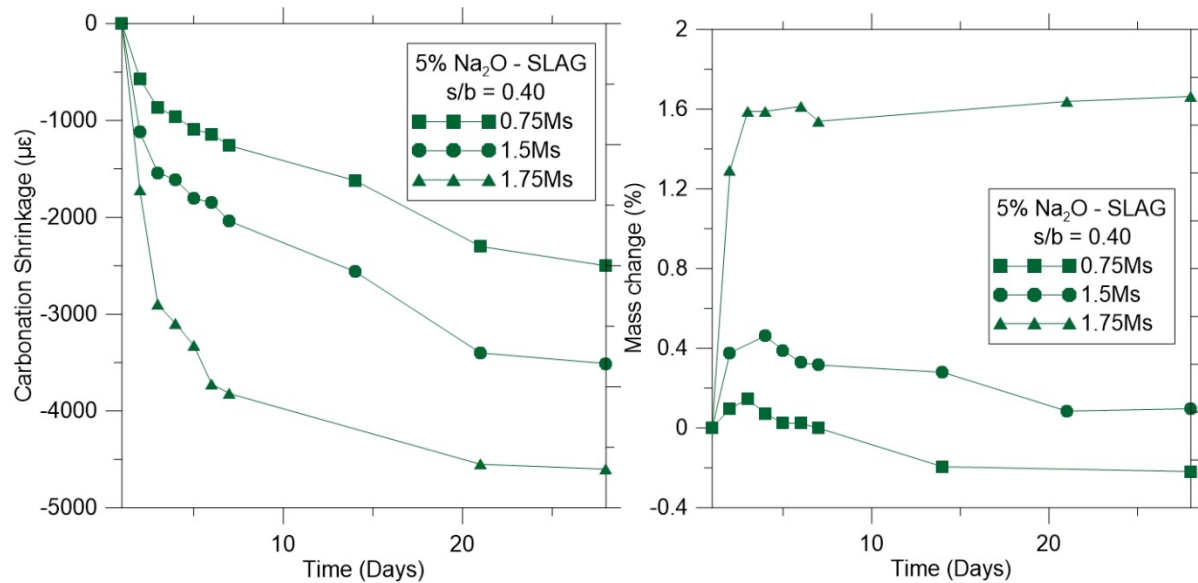


Figure 24. Carbonation shrinkage and mass change of sodium silicate-activated slag mortar with varying silica modulus. Sodium oxide concentration and silica modulus are constant ($\text{Na}_2\text{O}=5\%$, $s/b=0.40$)

3.4.4 Mitigation methods

The effect of shrinkage mitigation techniques including internal curing with saturated lightweight aggregate and shrinkage-reducing admixture on carbonation shrinkage in alkali-activated fly ash and slag binders was evaluated. Carbonation shrinkage in sodium silicate-activated fly ash with and without internal curing is shown in Figure 25. Although the weight

loss was much higher with internal curing, the magnitude of carbonation shrinkage was greatly reduced. Since a large reservoir of water was intentionally provided by the internal curing method, the large mass change was expected. The water drawn from the voids in the lightweight aggregate does not cause shrinkage as it would if the water were drawn from the mesopores of the binder, and therefore the magnitude of shrinkage is reduced.

Carbonation shrinkage in sodium silicate-activated slag binders with and without internal curing and shrinkage-reducing admixtures is shown in Figure 26. That figure also shown carbonation shrinkage in the same binder system cured at elevated temperature. Neither internal curing or shrinkage-reducing admixture was effective at reducing the magnitude of carbonation shrinkage, but curing at increased temperature greatly reduced it.

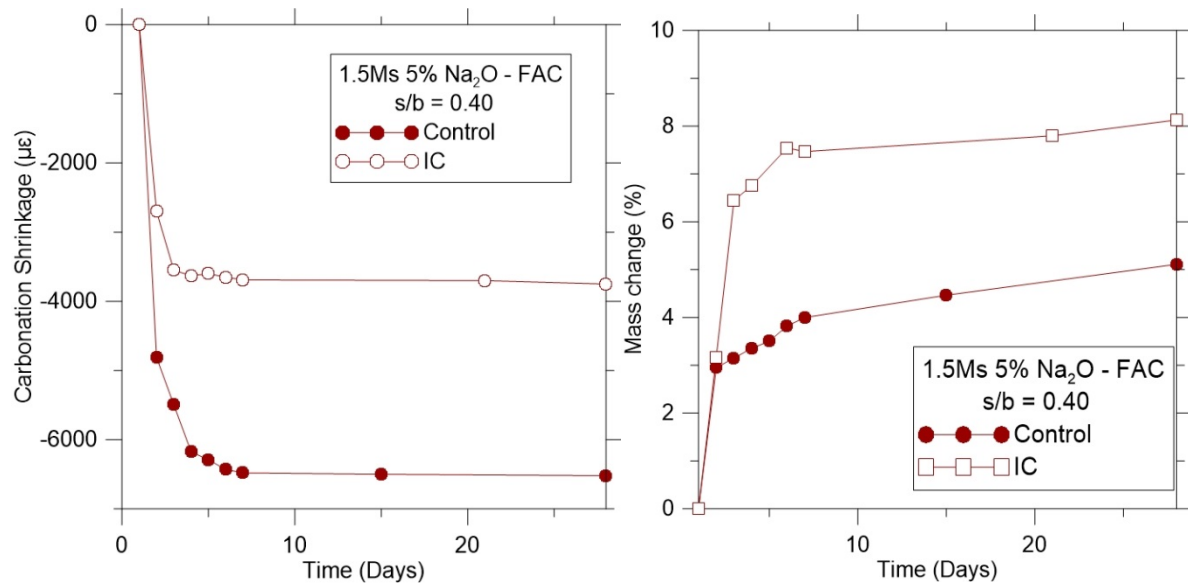


Figure 25. Carbonation shrinkage and mass change of sodium silicate-activated fly ash mortar with and without internal curing with saturated lightweight aggregate

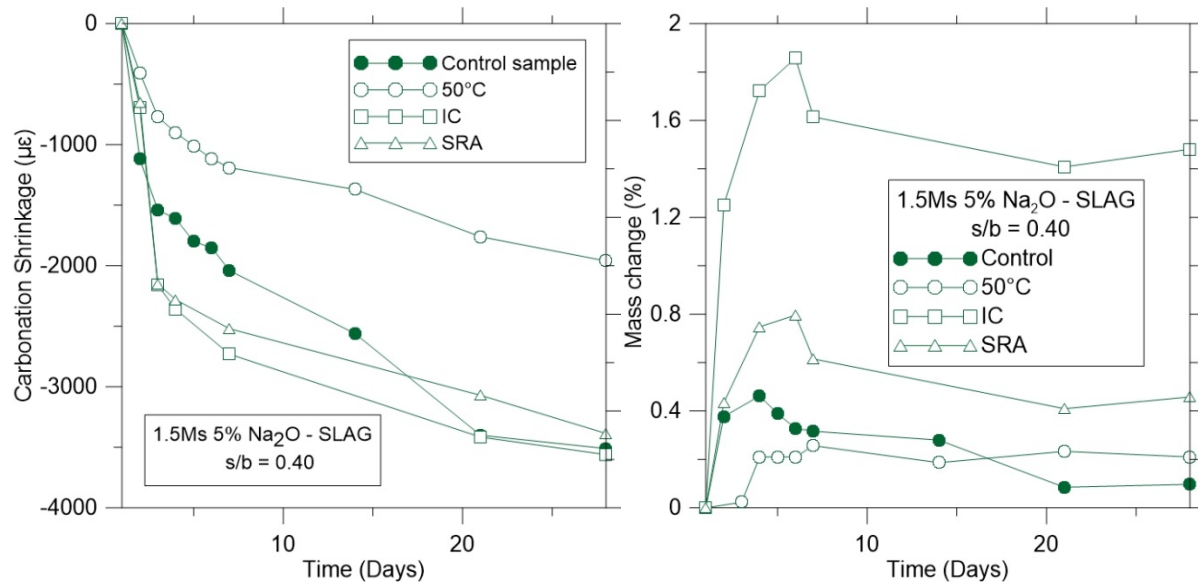


Figure 26. Carbonation shrinkage and mass change of sodium silicate-activated slag mortar with and without internal curing with saturated lightweight aggregate and shrinkage-reducing admixture

3.4.5 Summary and comparison with portland cement

Carbonation shrinkage was very high in alkali-activated fly ash. Carbonation shrinkage in alkali-activated slag was higher than in portland cement, but not nearly as high as in alkali-activated fly ash. The shrinkage in fly ash binders did appear to reach a plateau within about 10 days, however, while the shrinkage in slag and portland cement binders continued to rise with time. This is illustrated in Figure 27.

The carbonation shrinkage results presented in this section highlight what little information is known about the carbonation process in alkali-activated binders. The results are, at times, seemingly in disagreement. There is a total lack of understanding of the mechanisms at play, which makes it impossible to logically disseminate these results. This is an area which is in dire need of additional investigation.

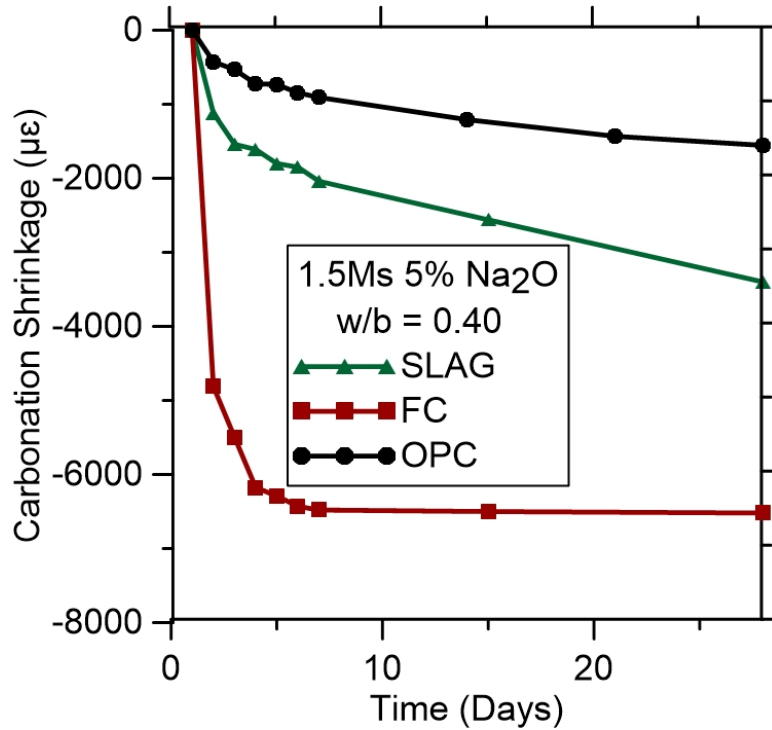


Figure 27. Carbonation shrinkage comparison between portland cement and alkali-activated fly ash and slag

3.5 Setting time and workability

The setting time and workability of alkali-activated fly ash and slag mortars were evaluated by the modified Vicat test and flow table test, respectively. The setting time and workability of several alkali-activated fly ash mortars which have been evaluated elsewhere in this study are listed in Table 4. Similarly, the setting time and workability of several alkali-activated slag mortars which have been evaluated elsewhere in this study are listed in Table 5.

In general, alkali-activated fly ash mixtures were highly fluid and had setting times in the range of 20 to 110 minutes. As silica modulus increased, the setting time decreased from 110 minutes when $m=0.75$ to 22 minutes when $m=1.75$. At the same time, the flow increased from 141% to greater than 160%. As sodium oxide concentration increased, the setting time and flow were both

reduced. Increased solution-to-binder ratio visibly increased the fluidity of the binders, but the fluidity was increased beyond the capacity of the flow table and could not be accurately measured quantitatively. As solution-to-binder ratio increased from 0.4 to 0.5, setting time increased from 17 to 35 minutes.

The alkali-activated slag binders were noticeably less workable, although all mixtures did have acceptable workability for application in normal construction. The fluidity and setting time were more greatly influenced by solution-to-binder ratio and activator concentration in slag binders than in fly ash binders. Increasing sodium oxide concentration from 4% to 6% resulted in increased flow from 11% to 98%, and setting time reduced from 15 to 7 minutes. Increased solution-to-binder ratio from 0.4 to 0.5 resulted in increased workability from 88% to 124% and delayed setting time from 1 to 24 minutes.

Table 4. Setting time and workability of alkali-activated fly ash mortars

Activator concentration	s/b	Flow (%)	Mortar setting time (minutes)
0.75MS 5% Na ₂ O	0.40	141±5	110
1.25MS 5% Na ₂ O	0.40	158±5	77
1.75MS 5% Na ₂ O	0.40	> 160	22
1.5 MS 4% Na ₂ O	0.40	> 160	30
1.5MS 6% Na ₂ O	0.40	123±5	13
1.5MS 5% Na ₂ O	0.40	151±5	17
1.5MS 5% Na ₂ O	0.42	> 160	23
1.5MS 5% Na ₂ O	0.45	> 160	30
1.5MS 5% Na ₂ O	0.50	> 160	35

Table 5. Setting time and workability of alkali-activated slag mortars

Activator concentration	s/b	Flow (%)	Mortar setting time (minutes)
0.75MS 5% Na ₂ O	0.40	86±5	22
1.25MS 5% Na ₂ O	0.40	115±5	9
1.75MS 5% Na ₂ O	0.40	43±5	6
1.5 MS 4% Na ₂ O	0.40	98±5	15
1.5MS 6% Na ₂ O	0.40	11±5	7
1.5MS 5% Na ₂ O	0.40	51±5	10
1.5MS 5% Na ₂ O	0.42	88±5	15
1.5MS 5% Na ₂ O	0.45	114±5	19
1.5MS 5% Na ₂ O	0.50	124±5	24

4. Conclusions and recommendations

4.1 Conclusions

A comprehensive experimental investigation into shrinkage—and the mitigation thereof—in alkali-activated fly ash and slag binders was performed. Several conclusions may be drawn from the results of this study. These are itemized below.

- Observation of chemical shrinkage in alkali-activated slag binders is hindered by the formation of a low permeable, dense shell of reaction product on the surface of slag grains. Since the measurement of chemical shrinkage relies partly on the quantification of water absorbed by the pores within the hydrating binder, the low permeability of the early-age reaction product limits the accuracy of the measurement.

- Autogenous shrinkage in alkali-activated binders is a full order of magnitude greater than in portland cement. This is a result of the more highly-refined pore structure in alkali-activated binders, which results in the formation of greater internal stresses and, therefore, more shrinkage.
- Drying shrinkage in alkali-activated concrete is similar in magnitude to that observed in portland cement concrete. Despite this, the cracking associated with drying is far more severe in alkali-activated binders. This may be a result of increased brittleness or reduced early-age strength.
- Alkali-activated fly ash binders are especially susceptible to rapid and high-magnitude carbonation shrinkage. Internal curing with saturated lightweight aggregate can reduce the carbonation shrinkage by as much as half. Alkali-activated slag is less susceptible to this type of shrinkage than alkali-activated fly ash, but is still more susceptible than portland cement.
- Increased silica modulus tends to retard hydration, limit shrinkage, and improve workability. Increased sodium oxide concentration tends to promote more advanced hydration, increase shrinkage, and hinder workability. Increased solution-to-binder ratio tends to increase shrinkage, improve workability, and delay setting time.
- Cracking due to early- and later-age shrinkage in alkali-activated concrete is a major concern, although some promising methods of shrinkage mitigation have been shown to be effective in this study.

4.2 Future work

The results of this investigation provide several avenues of opportunity for future work. Primarily, the investigation of the carbonation shrinkage properties of alkali-activated binders is far from conclusive. Recent literature agrees that the issue of carbonation in alkali-activated systems is highly complex, and that this phenomenon is one in need of further characterization. To add to the results presented here, a full physiochemical analysis of carbonated alkali-activated binders is necessary. This would involve X-ray diffraction (XRD), thermo-gravimetric analysis (TGA), and Fourier transform infrared spectroscopy (FTIR) of carbonated binder specimens, as well as microstructural evaluation through scanning electron microscopy (SEM). Furthermore, additional research into the drying shrinkage properties of alkali-activated concrete would be appropriate, with the intent of investigating the cause of the very-high-magnitude shrinkage at early ages; if the shrinkage in the first 24 hours of curing could be mitigated, the overall shrinkage could be drastically reduced. Finally, the effect of shrinkage mitigation methods on the mechanical properties and other durability properties of alkali-activated binders would inform the efficacy of their use in mitigating shrinkage.

5. Publication and presentation of results

A portion of the work presented here has been presented at the Thirteenth International Conference on Recent Advances in Concrete Technology and Sustainability Issues in Ottawa, ON in July, 2015. The presentation was entitled “Characterization of Early Age Shrinkage in Alkali-Activated Cement-Free Binders,” and was authored by Margueritte Ngami and Sulapha Peethampan.

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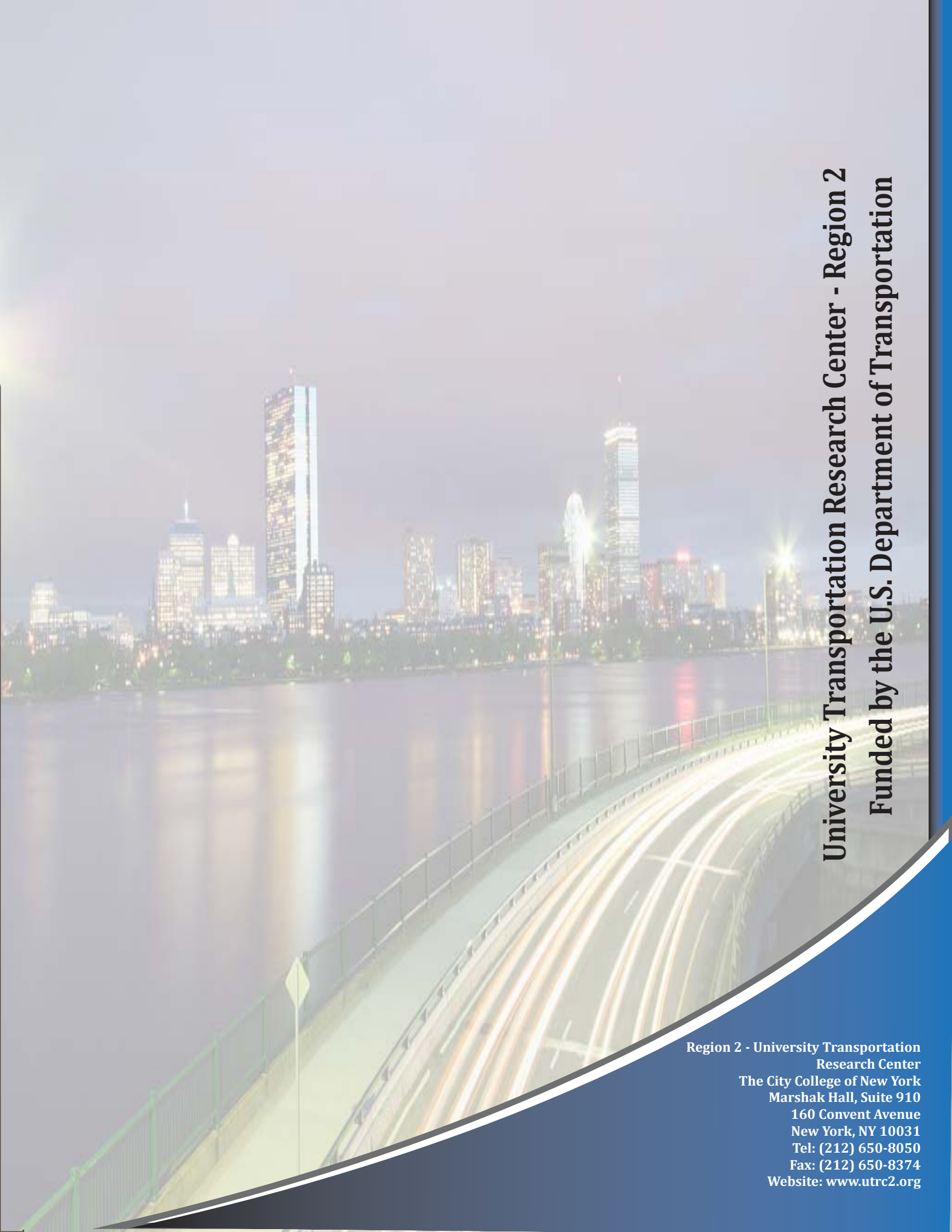
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A long-exposure photograph of a city skyline at night, viewed from across a wide river. The city lights are reflected in the water. In the foreground, a bridge with a green railing is visible, and light trails from moving vehicles create a sense of motion. The sky is a pale, hazy blue.

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