Safety and Operations of Large-Area Rural/Urban Intermodal Systems

SOLARIS

A Tier 1 university transportation center led by the University of Nevada, Reno.

Final Report

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Use of Nevada's Natural Pozzolans to Mitigate Alkali-Silica Reactivity

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DISCLAIMER:

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Executive Summary

Alkali-silica reactivity is one of the most recognized deleterious phenomena in Portland cement concrete resulting in cracks, spalling, and other deleterious mechanisms.

The aim of this study was (i) to assess the extent of reactivity of the aggregates, quarried from seven different sources, suspected of being conducive to ASR, and (ii) to compare the effectiveness of industrial (Class F fly ash) and natural pozzolans in mitigation of alkali-silica reactivity of the studied aggregates. To this end, seven aggregate sources, four natural pozzolan sources, and one source of Class F fly ash were used. ASTM Type V Portland cement was replaced at four levels of 15, 20, 25, and 30% by different pozzolan types and sources. A uniform water-to-cementitious materials ratio of 0.47 was used. Beam shaped mortars were tested for ASR-induced expansion for eight weeks. In addition, companion mortar cubes cured for 90 days in a salt-water environment and in a controlled moisture room were tested in compression.

The findings of this investigation revealed that the ASR mitigation of the studied aggregates depended on the aggregate source, natural pozzolan source and content, and immersion age. For nearly all natural and industrial pozzolans used in this study, 15% by weight of Portland cement was sufficient to mitigate alkali-silica reactivity of the studied reactive aggregates. The loss in strength of the studied mortars also depended on aggregate and natural pozzolan types and sources, and reduced with increases in Portland cement substitution level. Overall, the four natural pozzolan sources used in this study exhibited similar to better performance, in comparison to that of the Class F Fly ash, in suppressing the alkali-silica reactivity of the reactive aggregates.

Chapter 1

Introduction

According to American Concrete Institute (ACI), "Alkali-aggregate reaction (AAR) is a reaction in concrete between the alkali hydroxides, which originate mainly from the Portland cement, and certain types of aggregate" (ACI 221.1R, 1998). AAR is classified into two types, namely, Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR). ASR involves reactions with siliceous material, whereas ACR involves with carbonate in the aggregates. ACI defines ACR as a chemical reaction between particular carbonate rocks (usually calcitic dolostone and dolomitic limestones) sourced from aggregates and hydroxyl ions (OH-) of alkalis (both, Sodium and Potassium) present in hydraulic cement. The process is generally associated with dedolomitization and volumetric dilation of the afflicted particles of aggregates which eventually results in abnormal dilation and distressing of concrete. On the other hand, ASR is defined as the chemical reaction takes place either in mortar or concrete between certain siliceous rocks and minerals (chert, opal, microcrystalline quartz, and acidic volcanic glass) of aggregates and hydroxyl ions (OH-) of the alkalis mostly from hydraulic cement. Under certain circumstances, the above mentioned reactions and alkali-silica gel can develop abnormal expansion and distress of the concrete.

The first recorded document on ASR was published in 1919 where laboratory assessment of ASR was conducted using microscopic technique (Sims 1919). In 1940, Stanton (Shanton 1940) discovered that use of reactive aggregates in concrete can cause deleterious expansion. In this paper, it was stated that inclusion of pozzolanic cementing materials can reduce formation of the distress. However, Barona (1951) and Buck (1953) showed that supplementary cementing materials like slag and fly ash also can reduce expansion of affected concrete.

In last twenty years, more than 1900 technical papers published (data from google scholar) on alkali-aggregate reactivity (see Figure 1.2). It has been found from the available studies that alkali-silica reaction is a worldwide phenomenon.

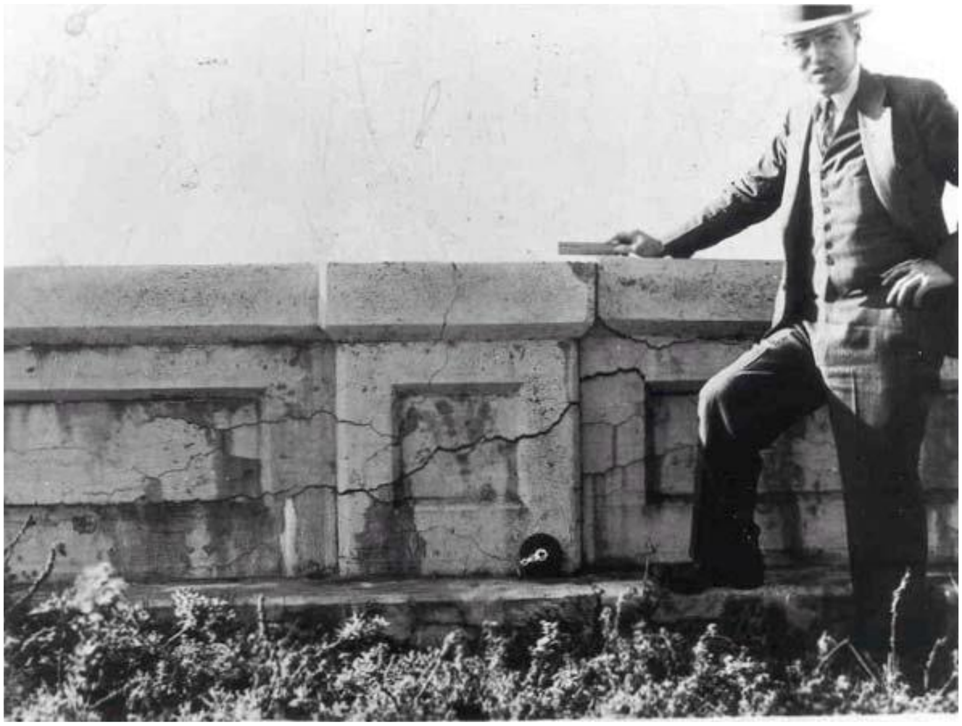


Figure 1.1: Thomas Stanton showing signs of damage due to Alkali-Silica Reaction (from Thomas et al., 2013)

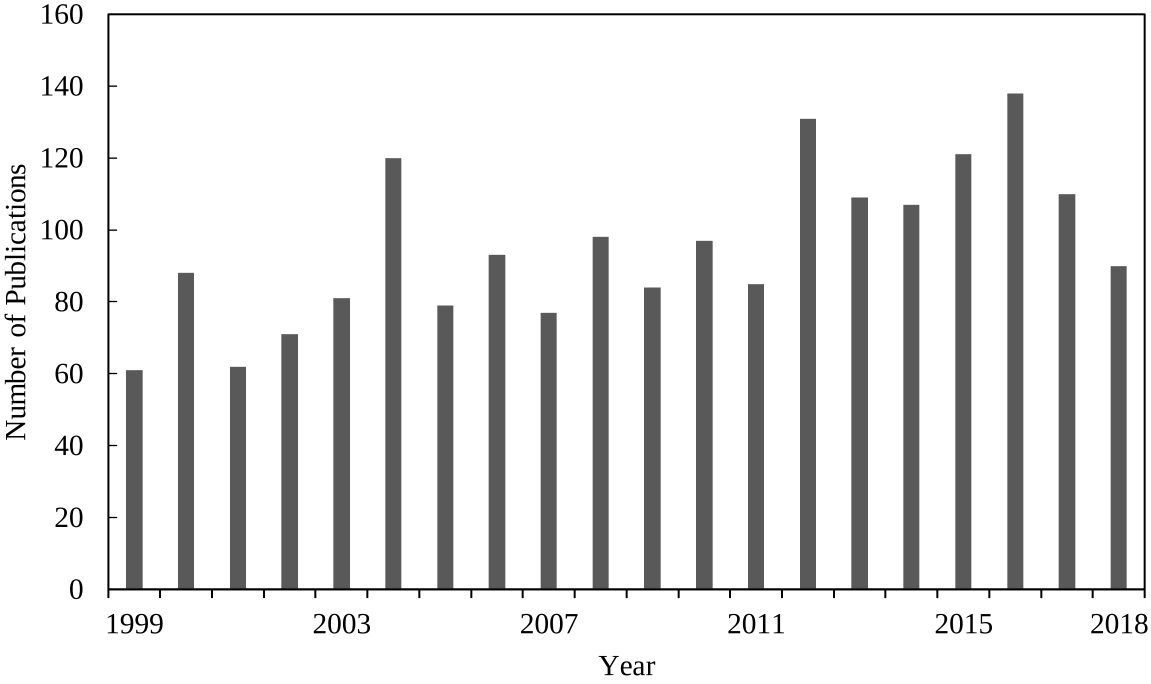
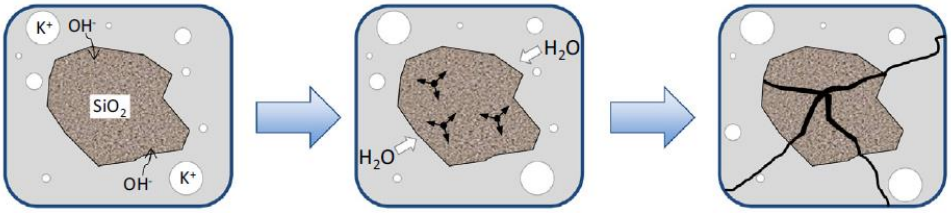


Figure 1.2: Number of researches related to ASR in last twenty years (1999-2018)

Mechanism of Alkali-Silica Reactivity

A schematic diagram as shown in Figure 1.3 is showing the reaction between the alkali hydroxides of concrete pore with certain types of minerals present in aggregates of concrete. The reaction produces alkali-silica gel with varying amounts of calcium. The gel is hygroscopic possess an inclination to absorb water and expand. Eventually, this expansion leads to cracking in hardened concrete.



Alkali cement + reactive aggregate

Fine cracking of the aggregate

Expansion gel and cracking of the paste

Figure1.3: Alkali-Silica reaction sequence (from Deschenes et al., 2009)

Despite the term, alkali-silica reaction is initiated by a reaction between the hydroxyl ions in the pore solution and certain types of silica in the aggregate. Silica (SiO_2) is composed primarily of siloxane groups (≡Si-O-Si≡) but even crystalline silica is disordered at the surface and the surface oxygens are hydroxylated (even in pure water) forming silanol groups (≡Si-OH) (Figure1.4). In the presence of a high concentration of hydroxyl ions (OH^-) silica tends towards dissolution first by neutralization of the silanol groups and then by attack on the siloxane groups; the reactions may be represented as follows (Bulteel et al., 2002):

$$\equiv Si - OH + OH^- \rightarrow Si - O^- + H_2O \qquad \text{Equation 1.1}$$

$$\equiv Si - O - Si \equiv +2OH^- \rightarrow 2Si - O^- + H_2O \qquad \text{Equation 1.2}$$

The structure breaks down progressively as the siloxane bridges are broken (Figure 1.5). The negatively charged Si-O- ions attracts positively charged species such as sodium (Na^+) and potassium (K^+), which are abundant in concrete pore solution. The initial result is an alkali-silicate solution or gel depending on the moisture content. However, in the presence of calcium, the silica precipitates from solution as an alkali-silicate gel (CaO-Na_2O/K_2O-SiO_2-H_2O), primarily composed of sodium, potassium, and silica, with small amounts of calcium. The hydroxyl ion concentration (and the pH) decreases as silica dissolves. In a system composed solely of alkali hydroxide and silica, the silica will continue to dissolve until the concentration in solution reaches the silica-pH equilibrium curve (Figure 1.6). The data show that final silica concentration depends on the initial SiO_2/Na_2O ratio as will be discussed later in the section on "pessimum behavior." The situation is more complex in concrete, probably due to the presence of abundant calcium, which reduces silica concentrations in solution and provides an additional source of hydroxyl ions. Consequently, equilibrium conditions are reached slowly in concrete (and mortar).

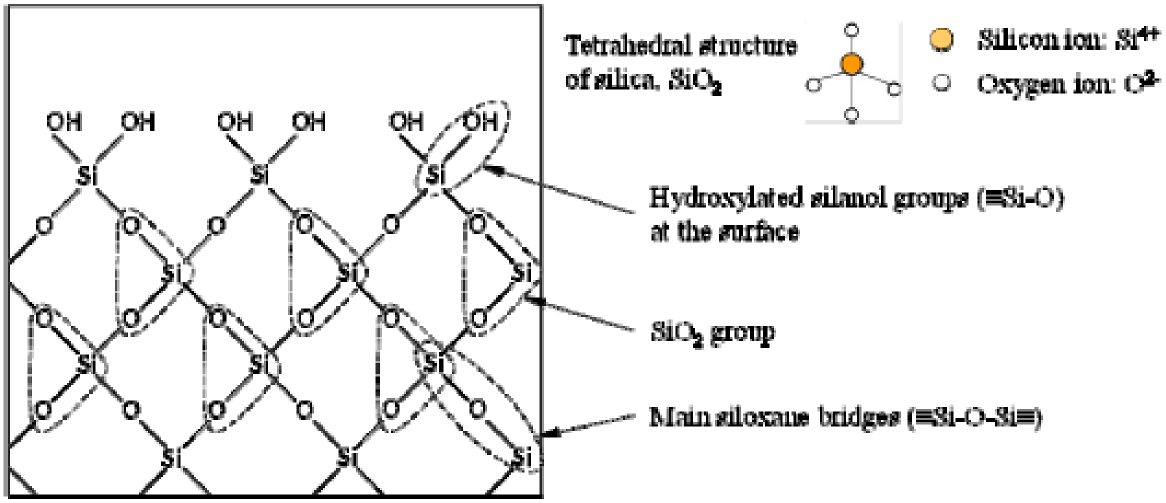


Figure 1.4: The structure of Silica (from Thomas et al., 2013)

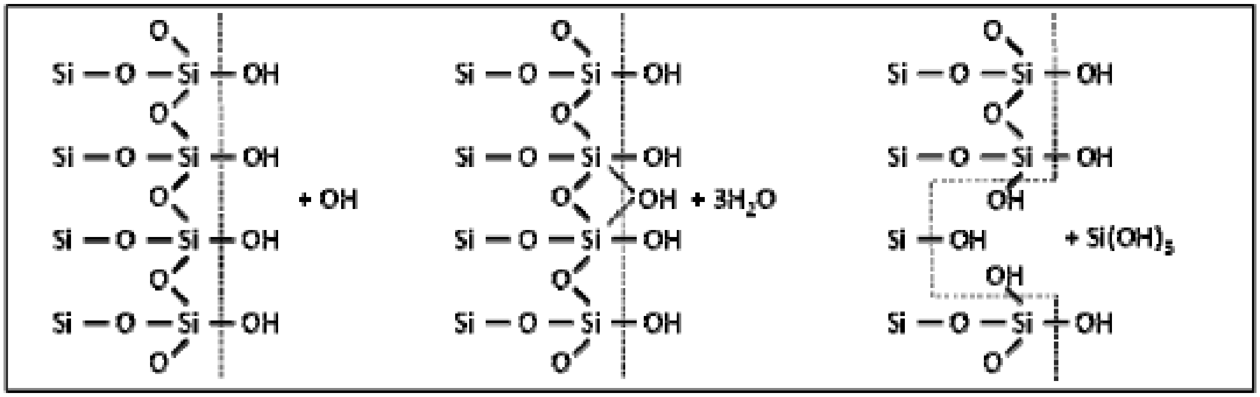


Figure 1.5: Mechanism of dissolution of silica due to attack by hydroxyl ions. Dotted line represents the interface between silica and water (from Urhan, 1987)

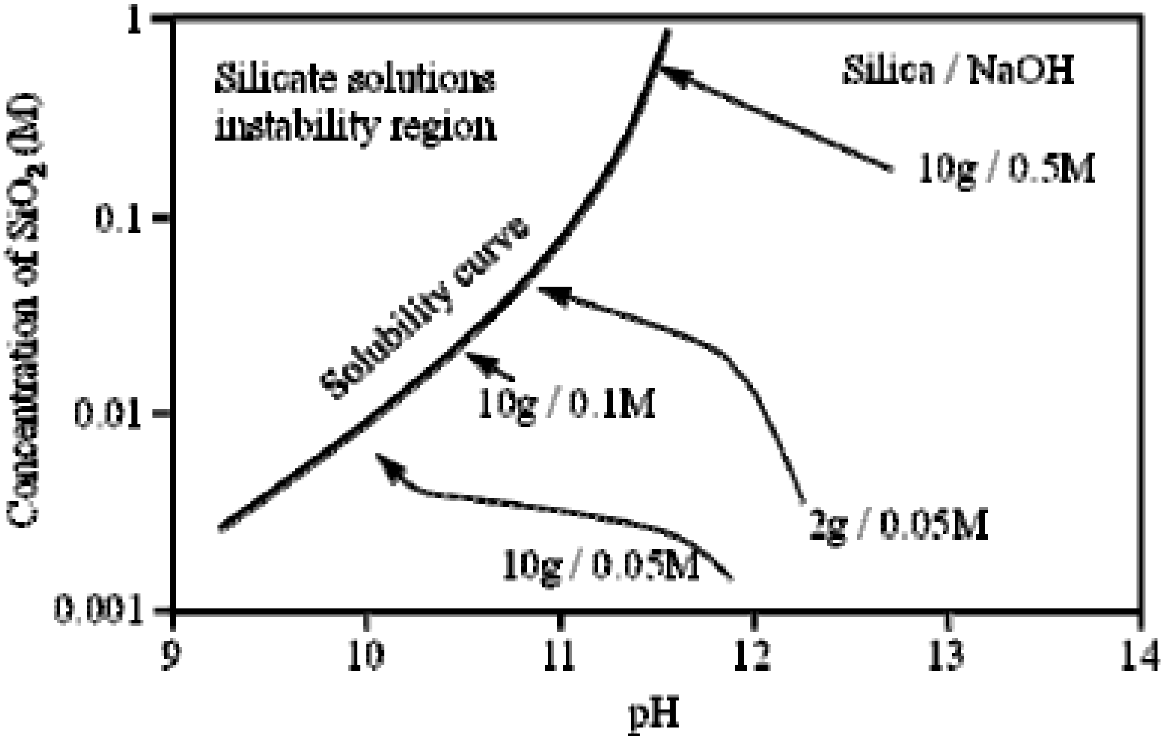


Figure 1.6: Equilibrium solubility curve (SiO_2-pH) and change in composition for different solutions of SiO_2-NaOH (from Glasser and Kataoka, 1981)

Cracking of concrete due to ASR

Numerous factors influence pattern of crack in concrete, namely, the size and shape of concrete member, conditions of environment, presence and orientation of rebar, and stress fields applied to the concrete. Pattern crack or map crack is usually identified as the symptom of ASR, as shown in Figure 1.7.

Distress between or within member may be often varied such an extent due to ASR:

- structural units may have a relative movement (Figure 1.8a);
- spalling of concrete at joints due to deflection, closure of joints associated with squeezing/extrusion of sealing materials. (Figure 1.8b).

Alkali-reactive aggregates experiencing expansion on the surface of concrete may cause the disengagement of a conical portion of the mortar overlying the aggregate. Thus, it left the ASR affected aggregate exposed in the bottom of the resulting conical recess (Figure 1.9).

Cracks due to ASR are often surrounded by a wide “brownish” zone, often it appears like a permanent dampness (Figure 1.10). Another common feature of ASR is exudations of surface gel. It can be both alkali-silica gel or lime (either of them) leaching from the cracked concrete.

(a) (b)

Figure1.7: Map cracking due to ASR, (a) Map cracking of a wing wall affected by ASR (from CSA, 2000), (b) Serious map-cracking in a median highway barrier affected by ASR (from Thomas et al., 2013)

(a) (b)

Figure 1.8: Structral distress due to ASR, (a) Relative movement of abutting sections of parapet wall in a bridge structure affected by ASR (from Stark, 1991), (b) Expansion of concrete pavement due to ASR (overlaid with asphalt), which pushes against the adjacent building foundation causing shearing of concrete columns (from Thomas et al., 2013).

Figure 1.9: Map-cracking along with several pop-outs caused by particles of shale limestone (from Thomas et al., 2013)

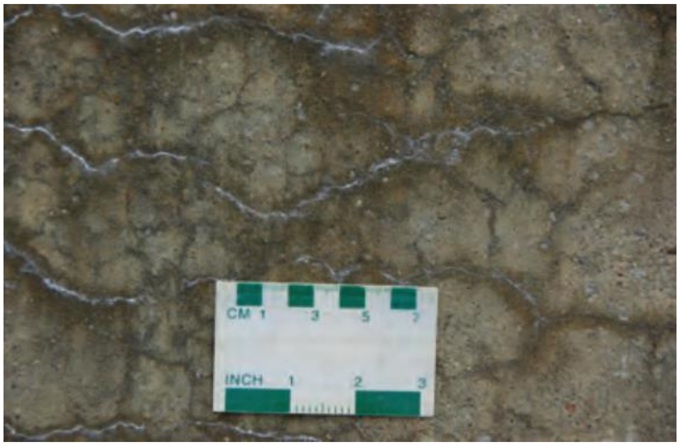


Figure 1.10: Surface discoloration and exudation associated with cracks (from Thomas et al., 2013).

Factors Affecting ASR

Reactive Silica

1.1.1.1 Petrography of Reactive Silica

The reactivity of an aggregate for ASR depends on the composition geologic origin and textural characteristics of the rock from which the aggregate derived. The Table 1.1 (ACI committee 201, 1991) provides a list of harmful reactive rock, synthetic substances and minerals.

The presence of reactive mineral can be determined by petrographic analysis but a more appropriate method of test is still recommended to confirm ASR reactivity. Little amount as 1% of poorly crystalline or amorphous silica minerals can induce rapid reaction and may cause deterioration of concrete structure in a few years. Besides, cryptocrystalline, microcrystalline, or strain quartz, which derived from quartz, react more slowly. A great amount of such components is required to provoke damage of the structure.

It is worth to mention that the classification of the silica-reactivity based only on mineralogy is quite limited. Other factor such as particle size and pessimum effect may have to be taken into account.

Table 1.1: Deleteriously reactive rocks, minerals and synthetic substances (adapted from ACI committee 201, 1991)

Reactive Substance (Mineral)	Chemical Composition	Physical Character
Opal	$SiO_2.nH_2O$	Amorphous
Chalesdony	SiO_2	Microcrystalline to cryptocrystalline; commonly fibrous
Certain forms of quartz	SiO_2	Microcrystalline to cryptocrystalline; crystalline but intensely fractured strained, and/or inclusion-filled
Cristobalite	SiO_2	crystalline
Tridymite	SiO_2	crystalline
Rhyolitic, dacitic, laticic, or andesite glass or cryptocrystalline devitrification products	Silicious with lesser proportions of Al2O3, Fe_2O_3, alkaline earths and alkalis	Glass or cryptocrystalline material as the matrix of volcanic rocks or fragments in tuffs
Synthetic siliceous glass	Siliceous, with lesser proportions of alkalis, Al_2O_3, and/or other substances	Glass
The most important deleteriously alkali-reactive rocks (that is, rock containing excessive amounts of one or more of the substances listed above) are as follows:		
Opaline cherts	Rhyolites and tuffs	Opaline concretions
Chalcedonic cherts	Dacites and tuffs	Fractured, strained, and limestone-filled quartz and quartzites
Quartzose cherts	Andesites and tuffs	
Siliceous limestones	Silicius dolomites	Phylites

1.1.1.2 Particle Size

In his studies, Staton (1940) indicated that the expansion of mortar bars can be affected by the particle size of the reactive aggregate. Figure 1.11 shows the expansion of reactive siliceous magnesium limestone containing mortar bar with various size ranges. Hence, mortar containing finer aggregates present greater expansion than bigger size.

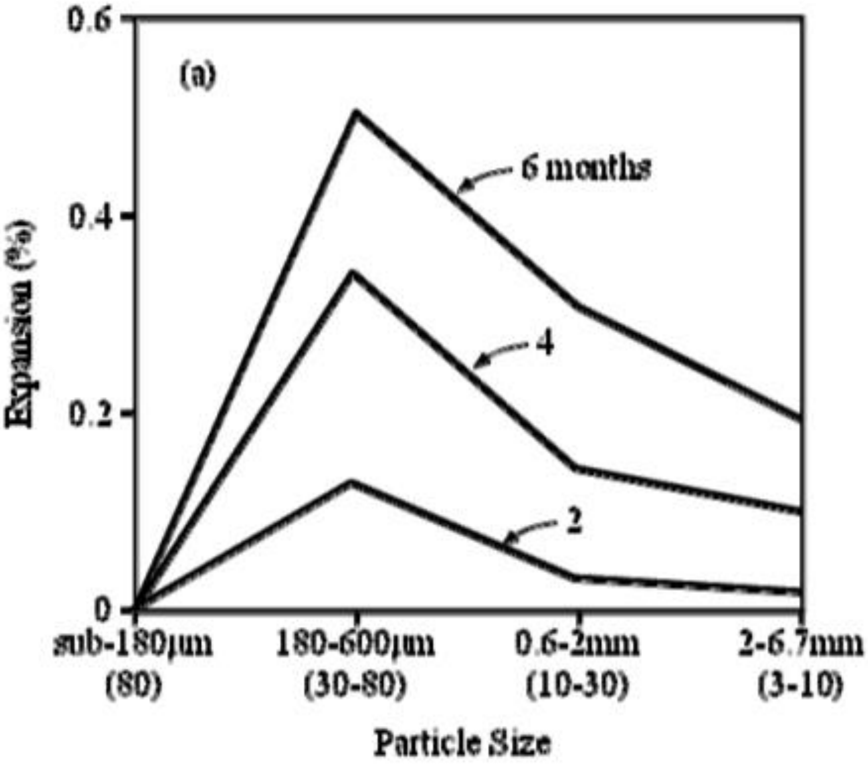


Figure 1.11: Effect of aggregate size (from Stanton, 1940)

1.1.1.3 Pessimum Effect

Staton (1940) also highlighted the pessimum effect phenomenon. The expansion of mortar bars did not always increase as the reaction aggregate amount increased. Figure 1.12 shows the expansion of mortar bars stored over water as a function of the proportion of reactive aggregate, in this case the siliceous magnesian limestone in the mix 20% is the pessimum percentage since the maximum expansion occurs at 20% of reactive aggregate content in mortar bars and decreases for greater amount of reactive aggregate. Form of the reactive silica, the degree of alkalinity, and the w/c ratio often has an influence on pessimum percentage (Shehata and Thomas , 2002). The pessimum percentage is due to the fact that quantity of silica dissolved depends on the ratio silica to alkali.

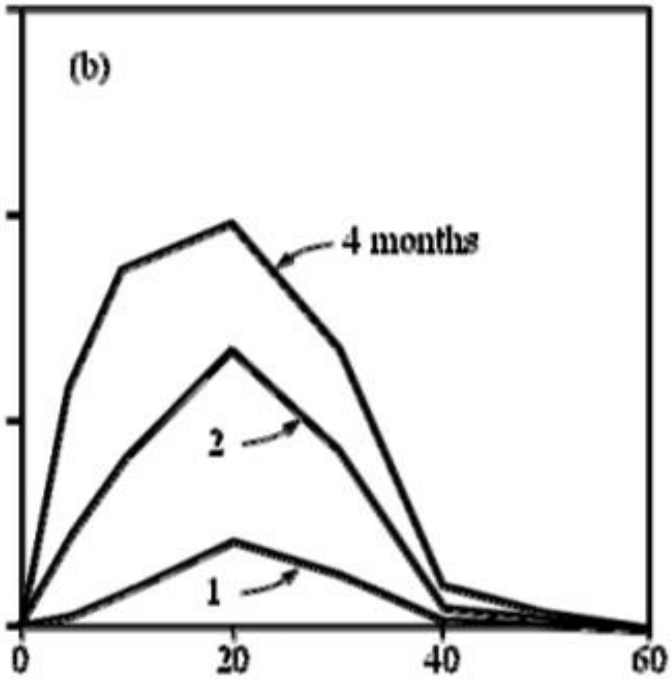


Figure 1.12: Effect of aggregate proportion due to ASR (Stanton, 1940)

Source of Alkali

The main source of alkalis in Portland cement concrete that may participate in the ASR are as follow:

- Portland Cement

Equivalent sodium (Na_2O_e) is generally used to express the quantity of alkalis in Portland cement. Following formula can be used for calculation:

$Na_2O_e = Na_2O + 0.658 \times K_2O$ Equation 1.3

Where, Na_2O and K_2O are the mass percentages of sodium oxide and potassium oxide of Portland cement. The percentage of alkalis in Portland cement varies between 0.2 to 1.3% Na_2O_e for most North American sources, but it is possible to be as high of 1.65% Na_2O_e.

Stanton 1940 showed that the alkali content of Portland cement had a direct influence on potential expansion. Diamond (1989) showed that the cement-alkali content influences the concentration of hydroxyl ions and hence the pH of the pore solution. A limit of 0.60 percent on the Na_2O_e in Portland cement (low-cement alkali) was specified by Stanton (1940) to minimize the deterioration of concrete structure due to ASR. Nonetheless, if moisture movement gathers the alkalis in one location as stated by Perenchio et al. (1991), or if the reactivity of aggregates is high and if alkalis are provided by other sources such as supplementary cementitious materials, and chemical admixtures, concrete made with low-cement alkali can be deteriorated by ASR.

- Supplementary cementitious materials

Pozzolanic materials, composed of siliceous or siliceous and aluminous material reacting with lime, produced from the hydration of cement, are used as partial replacement of cement or a part of cementitious material to enhance concrete properties.

Using natural pozzolans to replace a portion of Portland cement enables lowering the overall ability of alkalis to react with reactive aggregates. Indeed, the amorphous silica of pozzolans react with the calcium hydroxide (CH) formed from the hydration of the calcium silicates in Portland cement to produce calcium silicate (C-S-H). The C-S-H of this pozzolanic reaction can absorb more alkali ions than C-S-H formed by the hydration of calcium silicates. This reaction makes alkalis in Portland cement less available to react with reactive aggregates. As a result, the chance that alkali-silica reactions occur decreases but not entirely (Ramlochan et al., 2000)

- Aggregates

Aggregates can also be a source of alkalis. Goguel and Milestone (1997) showed that an alkali-rich basalt in Auckland in New Zealand can provide alkalis to initiate the AAR, when low-alkali cement is used.

- Chemical admixture

Sodium and potassium compounds can be present in chemical admixtures such as water reducers and air-entraining agents and hence, can contribute to the alkalis content in concrete.

- External sources

Alkalis contained in deicing salts or sea water can penetrate the structure through cracks in concrete or due to the high permeability of concrete, and thus contribute to the ASR.

Moisture

Sufficient moisture is necessary to initiate and sustain the expansion process of ASR. According to Thomas et al. (2013), when the internal relative humidity inside the concrete falls below 80%, The ASR stops. Moreover, the difference in moisture content within a structure is responsible for a variable deterioration throughout the concrete member. Indeed, portions steadily exposed to a source of moisture will present significant damage due to ASR, while the other dry parts will present less damage (Thomas et al., 2013).

Temperature

The rate of ASR increases with increases in temperature. The chemical reaction occurs rapidly under warmer condition with given concrete materials and proportion (ACI 221, 1998).

Test methods to assess ASR

Petrographical Examination

Any assessment of an aggregate combination for AAR potential should ideally commence with petrographical examinations of the component aggregates, which establishes their individual and combined compositions and identifies the types and concentrations of any potentially reactive constituents. This usually allows an aggregate combination to be assigned to one of three categories, as follows:

Class I—very unlikely to be alkali-reactive
Class II—potentially alkali-reactive or alkali-reactivity uncertain
Class III—very likely to be alkali-reactive

Accelerated Mortar-Bar Testing (ASTM C1260/ C1597)

ASTM C1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method) is often used as a screening test to determine the potential reactivity of aggregates. ASTM C1260 defines an aggregate sample reactive if test specimen of 25mm X 25mm X 285mm expands by more than 0.10% after 14 days of soaking. Bars that expand between 0.10% and 0.20% are considered as slowly to moderately reactive. Bars with expansion of greater than 0.20% are considered highly reactive. In all of these cases, supplemental information should be developed.

Concrete Prism Testing (ASTM C 1293)

It is often considered that ASTM C1293 or also known as concrete prism test as the correct method to determine reactivity of aggregate. However, it requires very long time; it takes 1 year to reactivity of the aggregate, or 2 years to evaluate the efficacy of SCMs to mitigate deleterious expansion.

Carbonate Aggregate Testing (RILEM AAR 5)

Concrete aggregate testing method, also known as AAR 5 was developed by RILEM (Sommer et al., 2005). The suspicious aggregate material is subjected to testing using both the mortar-bar test and concrete-bar. Aggregate grading of 4/8 mm is used in this mortar bar test.

Quick Chemical Method (ASTM C 289)

ASTM C289 (Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (chemical method)) aims at determining the potential silica-reactivity of an aggregate. For this method, a representative sample of the aggregate in question is crushed to pass a 300 μm sieve and be retained on a 150 μm sieve. The crushed material is immersed in a hot (80±1 °C) 1N NaOH solution and is selected for 24 hours. After 24 hours, the solution is filtered and measure for dissolved silica (S_c) and reduction of the original hydroxide ion concentration (R_c) due to the reaction. The quantity of dissolved silica and reduction in alkalinity are plotted on a graph presented in ASTM C 289. Three categories are presented on the graph namely innocuous aggregates, potentially reactive aggregates, and deleterious aggregates.

Preventive Measures

ACI (ACI 201.2R, 2008) recommends the following methods for minimizing the risk of damaging ASR include one or more of the following:

- Use of nonreactive aggregate;
- Use of low-alkali cement;
- Limits on the alkali content of the concrete;
- Use of pozzolan or slag; and
- Use of suitable chemical admixtures.

Use of Non-Reactive Aggregate

It is suggested to avoid use of non-reactive aggregate to prevent ASR induced damage (Thomas et al., 2013). To ensure this a competent and through investigation is required. To obtain this a combined investigation different test, such as, petrographic examination, expansion testing of mortar (as per ASTM C 1260) or concrete (as per ASTM C 1293), and field performance should be performed. Investigation in a regular basis should be performed to ensure this. If an aggregate is found innocuous, such aggregate can be used to produce concrete. However, in most of the cases, it is not possible to utilize non-reactive aggregates in the project because of:

- Innocuous aggregates may not be locally available and it becomes costly to ship this from outside.
- Readily and abundant supply of reactive aggregate can help to decrease environmental impact to non-reactive aggregate.
- Variability and insufficient confidence in laboratory test result makes it difficult.
- Failure of locally found aggregates in very aggressive accelerated test disregarding of true reactivity.

Table 1.2 summarizes the geological composition of the aggregates in order of reducing profusion.

Table 1.2: Geological composition of the reactive aggregates (Fertig et al. 2017)

Aggregate	Major	Other
BR	Rhyolite	Andesite, quartzite, limestone
DF	Andesite	Ryholite, ash, quartzite
GP	Rhyolite	Granite, quartzite, andesite, chert
HP	Andesite	Ryholite, feldspar, ash
KR	Granitic	Rhyolite
LBG	Granitic	Quartzite
LX	Rhyolite	Andesite, quartzite, limestone, dioritic
WOR	Rhyolite	Quartzite, andesite, granite, limestone

Use of Low-Alkali Cement

Stanton (1940) reported that expansive reaction is not likely to happen when the alkali content of the cement is less than 0.60% Na_2O_e. However, it was later found that distress due to ASR could happen both in the laboratory and in the field, even when low-alkali cements are used (e.g., Woolf 1952; Stark 1980). In spite of this, the alkali cement content of 0.60% has been assumed as the maximum threshold for cement to be used with reactive aggregates in the USA, and finds in ASTM C 150 Standard Specification for Portland cement as a not compulsory threshold when concrete made of deleteriously reactive aggregate.

It can be found that the limiting amount of alkali need to start damaging expansion in the concrete prism test differs noticeably among different aggregates, with values varying from approximately 3.0 kg/m^3 (5 lb/yd^3) Na_2O_e to more than 5.0 kg/m^3 (8.3 lb/yd^3) Na_2O_e for the aggregates shown in Figure 1.13.

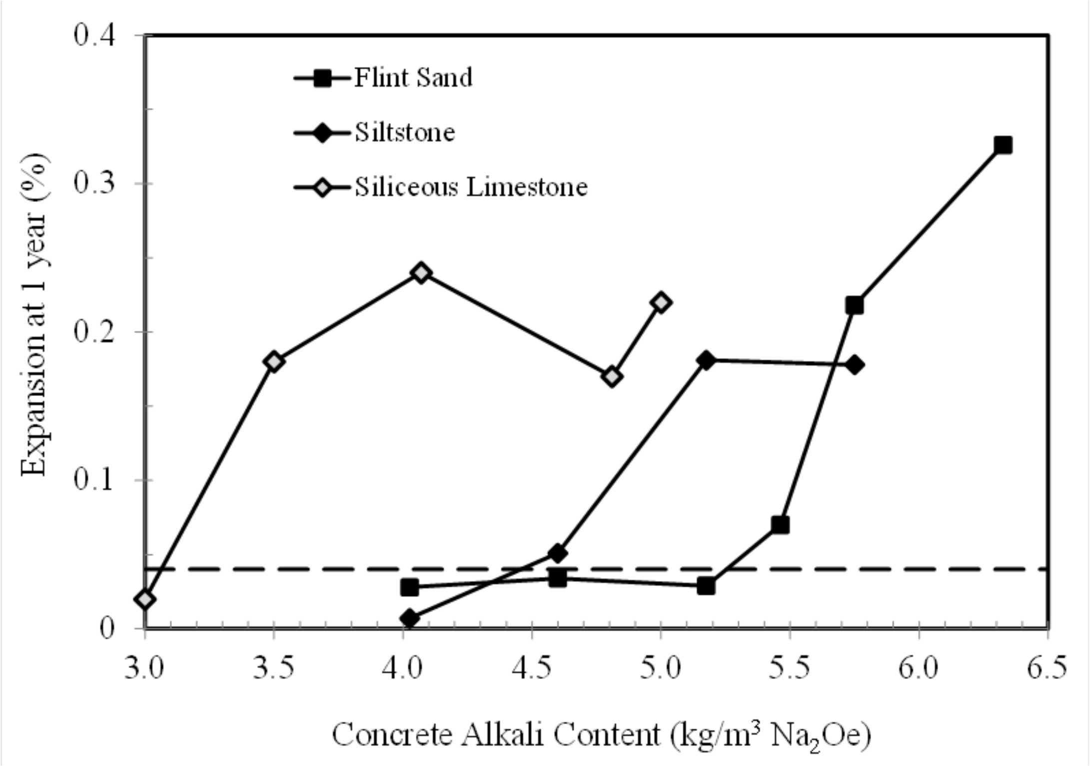


Figure 1.13: Influence of alkali content on expansion of concrete prisms (Stored over Water at 38ºC, 100ºF) with varies aggregates (from Thomas et al. 1996)

To control expansion of concrete due to presence of reactive aggregates, a number of specifications have employed a maximum alkali content in concrete. Nixon and Sims (1992) stated maximum permissible alkali contents between 2.5 and 4.5 kg/m^3 (4.2 to 7.5 lb/yd^3) Na_2Oe have been specified by different agencies and countries, depending on aggregate reactivity with the allowable alkali content often varying. It is a matter of unfortunate that concrete prism tests that have been traditionally adopted is likely to underestimate the threshold alkali content for aggregates because of alkali being leached from the concrete during exposure. This phenomenon has been discussed in literature (Thomas et al. 2006; Lindgård et al. 2012). In 2000, Canadian Standard (CSA A23.2-27A) introduced a “sliding-scale” for the alkali threshold used as a preventive measure, the value ranging from 1.8 to 3.0 kg/m^3 (3 to 5 lb/yd^3) Na_2O_e as follows:

Table 1.3: Alkali limits specified in CSA A23.2-27A

Level of prevention required	Alkali Limit (lb/yd^3)
Mild	5
Moderate	4
Strong	3
Exceptional	3+SCM

Past Studies on Use of Natural and Industrial Pozzolan to Reduce ASR

Fly ash, silica fume, slag, and natural pozzolans are considered as Supplementary cementing materials (SCM) which may also carry significant quantities of alkali. However, these alkalis usually are not important to be regarded in the calculation of the concrete alkali content since SCMs tend to decrease the alkalis that are found for reaction with the aggregate. To decrease ASR, the characteristics of the reaction need to be altered. Supplementary cementitious materials (SCMs) suppress the alkali-silica reaction by varying different characteristic mechanisms as described by Shafaatian et al. (2013). These mechanisms include

- Diluting the pore solution alkalinity;
- Binding alkalis into an insoluble form by converting them into salts;
- Reducing concrete permeability;
- Increasing tensile strength;
- Altering the aggregate dissolution rate; and
- Increasing the consumption of $Ca(OH)_2$ through pozzolanic reaction.

Use of Fly Ash to Reduce ASR

Use of fly ash has been studied thoroughly to mitigate ASR. Contradictory opinions on its effect can be observed amongst researchers. Table 1.4 summarizes the impact of different replacement level of class C and class F fly ash on ASR expansions. It was reported in different studies that class F fly ash performs better than class C fly ash pertaining to ASR mitigation. The chemical constituents of class F fly ash play an important role in this regard. Class F fly ash carries a high fraction of amorphous silica and considerably low amount of lime. Due to this, the presence of high amorphous silica absorbs the portlandite from pore solution (Shehata and Thomas, 2000). This reduces the alkalinity in the pore solution (Moser et al., 2010). In contrast, On the other hand, class C fly ash has a higher amount of calcium oxide as compared to class F fly ash that eventually contributes to the generation of portlandite (Esteves et al. 2012). Furthermore, the amorphous silica of class F fly ash decreases porosity by the product of the pozzolanic reaction. As a result, fewer voids are available in class F fly ash mixed concrete to accumulate the viscous ASR gels (Shehata and Thomas, 2000). The expansions of samples also depend on the CaO to silica ratio of fly ash. The expansion of samples increases with the increase of CaO/SiO_2 as shown in Figure 1.14. Table 1.5 provides a summary of past research studies related to the effect of fly ash on ASR.

Table 1.4: ASR expansions for different cement replacements by fly ash.

Fly ash type	Test type	Cement replacement (%)										References
		10	15	20	25	30	35	40	45	50	60	
Class F	AMBT	-	-	-	-	0.08	-	-	-	-	-	Saha & Sarker (2016)
Class C	CPT	-	-	-	-	0.14	-	-	0.06	-	0.03	Shehata & Thomas (2002)
Class F		-	0.08	0.04	-	-	-	-	-	-	-	
Class F	AMBT	0.55	-	0.18	-	0.06	-	-	-	-	-	Choi & Choi (2015)
Class C	CPT	-	-	0.123	-	0.10	-	0.068	-	0.042	-	Shehata & Thomas (2000)
Class F		-	0.083	0.043	0.03	-	-	-	-	-	-	
Class F	AMBT	-	-	-	-	0.03	-	-	-	-	-	Garcia-Lodeiro et al. (2007)
Class C	AMBT	-	-	-	0.485	-	-	-	-	-	-	Moser et al. (2010)
Class C	AMBT	-	-	0.41	-	0.38	-	-	-	-	-	Esteves et al. (2012)
Class F		-	-	0.38	-	0.33	-	-	-	-	-	
Class C	AMBT	-	-	0.23	-	-	0.11	-	-	-	-	Shon et al. (2004)
Class F		-	-	0.27	-	-	0.10	-	-	-	-	
Class F	AMBT	0.15	-	-	-	0.12	-	-	-	0.07	-	Awal & Hussain (1997)

Note: AMBT= Accelerated mortar bar test; CPT =Concrete prism test

Table 1.5: Summary and subjects of previous studies related to the effect of fly ash on ASR

Author/Authors, Year	Subject of study	Major findings of study
Ha et al., 2018	Load Bearing Capacity of PC Girders with and Without Fly Ash Affected by ASR Deteriorations	This study conducted full-scale destructive tests of prestressed concrete girders. Specifically, two PC girders, which were constructed and placed outside the laboratory, had been exposed to weather conditions. The first girder was affected by alkali-silica reaction while the second one was kept at an inactive state with ASR acceleration due to the addition of fly ash.
Shi et al., 2018	Alkali-silica reaction in waterglass-activated slag mortars incorporating fly ash and metakaolin	In conventional Portland cement-based concrete, alumina-rich supplementary cementitious materials such as low-calcium fly ash and metakaolin have been successfully used to mitigate ASR. The results demonstrated that there was an optimum dosage of fly ash to reduce ASR expansion of the studied mortars, whereas ASR expansion decreased with increasing the amount of metakaolin.
Turk et al., 2017	Use of binary and ternary cementitious blends of F-Class fly-ash and limestone powder to mitigate alkali-silica reaction risk	Mortar prisms were prepared with potentially deleterious aggregates and tested by using Mortar-Bar Method according to ASTM C 1260. It was found that the reduction of ASR expansion rate due to increase in limestone powder (LSP) content was more prominent compared to the increase of fly ash (FA) content in the binary blends system. Also, ternary blends of 20% FA/LSP were more effective than the binary mixes.
Kandasamy and Shehata, 2014	The capacity of ternary blends containing slag and high-calcium fly ash to mitigate alkali silica reaction	The efficiency of ternary blends containing high-calcium fly ash and slag in mitigating alkali-silica reaction (ASR) was evaluated. The concrete prism expansions showed that the ternary blends did not offer significant advantage over binary blends of portland cement and either of the individual material at the same total SCM content.
Shafaatian et al., 2013	How does fly ash mitigate alkali–silica reaction (ASR) in accelerated mortar bar test (ASTM C1567)?	This study performed a quantitative evaluation of six potential ASR mitigation mechanisms and how fly ah affects these mechanisms: (1) alkali dilution, (2) alkali binding, (3) mass transport reduction, (4) increasing tensile strength, (5) altering ASR gel, and (6) reducing aggregate dissolution rate. The results suggested that (2), (3), (4), and (6) were the primary mitigation mechanisms, while (1) and (5) showed a negligible impact.
Thomas et al., 2011	Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies	45 concrete blocks (915 × 915 × 815 mm or 350 mm cubes) containing alkali-silica reactive aggregates, and various levels of high-alkali cement and fly ash were placed on an outdoor exposure site in S.E. England for a period of up to 18 years to determine the efficacy of fly ash in controlling damaging alkali-silica reaction (ASR). Fly ash used at replacement levels of 25% and 40% was effective

Author/Authors, Year	Subject of study	Major findings of study
		in significantly reducing expansion and cracking with all three flint aggregates at all levels of alkali. Of the 27 blocks containing fly ash and flint sand only two blocks showed evidence of damage after 16–18 years. The expansion of these blocks was significantly lower than similar blocks with the same Portland cement content without fly ash.
Malvar and Lenke, 2006	Efficiency of Fly Ash in Mitigating Alkali-Silica Reaction Based on Chemical composition	Data from previous research studies were used to assess the effectiveness of fly ashes in preventing ASR based on their chemical composition, the composition of the cement, and the reactivity of the aggregates. For the fly A chemical index was derived to characterize the fly ash and cement based on their chemical constituents. ashes, this index correlated well with ASTM C 618 and CSA A3001 classifications.
Shehata and Thomas, 2000	The effect of fly ash composition on the expansion of concrete due to alkali–silica reaction	Eighteen fly ashes representing those commercially available in North America were tested. The results showed that the bulk chemical composition of the fly ash provided a reasonable indication of its performance in physical expansion tests but could not be used to accurately predicted the degree of expansion or the minimum safe level of fly ash required to suppress expansion to an acceptable limit.

Use of Silica Fume to Reduce ASR

Silica fume imparts major improvement in concrete strengths and durability. A number of studies has been done on reduction of ASR-induced expansion by utilizing silica fumes as presented in Table 1.6. However, performance of silica fume in reducing ASR-induced expansion was found to be less effective than fly ash.

Table 1.6: Summary and subjects of previous studies related to the effect of silica fume on ASR

Author/Authors, Year	Subject of study	Major findings of study
Maas et al., 2007	Alkali silica reactivity of agglomerated silica fume	It appears that when silica fume was alkali silica reactive, there was a pessimum effect with expansion related to the percentage of silica fume used; smaller amounts of silica fume resulted in higher expansions than larger amounts.
Boddy et al., 2003	The effect of the silica content of silica fume on its ability to control alkali–silica reaction	The mixtures tested with these procedures included 0%, 4%, 8%, and 12% SF replacement by mass of cement. Results showed that the SF with lower than

Author/Authors, Year	Subject of study	Major findings of study
		standard silica contents could not control ASR at the levels of replacement examined in this program.
Shehata and Thomas, 2002	Use of ternary blends containing silica fume and fly ash to suppress expansion due to alkali–silica reaction in concrete	It was found that practical levels of silica fume (SF) with low-, moderate- or high-calcium fly ash (FA) were effective in maintaining the expansion below 0.04% after 2 years. Pore solution chemistry showed that while pastes containing SF yielded pore solutions of increasing alkalinity at ages beyond 28 days, pastes containing ternary blends maintained the low alkalinity of the pore solution throughout the testing period (3 years)

Use of Ground-Granulated Blast-Furnace Slag (GGBS) to Reduce ASR

Research studies on ground-granulated blast-furnace slag (GGBS) in mitigating ASR expansion are summarized in Table 1.7. Rasheeduzzafar and Hussain (1991) found that GGBS is active remover of ASR-induced expansion for cement with low alkali content. Beglarigale and Yazici (2013) recommended to use 20-40% GGBS for practical application to reduce ASR in concrete. A summary related to the effect of GGBS on ASR is given in Table 1.7.

Table 1.7: Summary and subjects of previous studies related to the effect of GGBS on ASR

Author/Authors, Year	Subject of study	Major findings of study
Beglarigale & Yazici, 2013	Mitigation of Detrimental Effects of Alkali-Silica Reaction in Cement-Based Composites by Combination of Steel Microfibers and Ground-Granulated Blast-Furnace Slag	This research indicated that using a combination of steel microfibers and GGBS was extremely effective at controlling ASR expansion and preventing the deleterious effects of ASR on mechanical properties, even at relatively low volumes of fiber (1–2%) and GGBS (20–40%), which can generally be used in practical applications.
Hester et al., 2005	A study of the influence of slag alkali level on the alkali–silica reactivity of slag concrete	No significant difference in behavior was apparent, irrespective of aggregate type or alkali load, indicating that the alkali level of the slag was not a contributory factor at the 50% replacement level. Ground granulated blast furnace slag (GGBS), reduced the alkali load in concrete, despite its relatively high alkali content.
Lumley, 1993	The ASR expansion of concrete prisms made from cements partially replaced by ground	The partial replacement of Portland cement by slag delayed both the onset and completion of expansion, the latter sometimes by a few years.

Author/Authors, Year	Subject of study	Major findings of study
	granulated blastfurnace slag	
Rasheeduzzafar and Hussain, 1991	Effect of microsilica and blast furnace slag on pore solution composition and alkali-silica reaction	Incorporation of 60–70% slag reduced expansions from nine times the permissible expansion to safe values ranging from one-tenth to one-half the allowable expansion. Blast furnace slag was shown to be an active remover of alkalis and was especially effective in medium-alkali cements, where for equal alkali contents, the performance of 60% slag cement was comparable with that of 10% microsilica cement. However, the effectiveness of the slag decreased as alkali content of the cement increases.

Use of Natural Pozzolan to reduce ASR

Different types of natural pozzolan used in cements to mitigate the ASR. Table 1.8 summarizes the major findings of some of the research studies done on natural pozzolan to mitigate ASR.

Table 1.8: Summary and subjects of previous studies related to the effect of natural pozzolans on ASR

Author/Authors, Year	Subject of study	Major findings of study
Ramjan et al., 2017	Effects of Binary and Ternary Blended Cements Made from Palm Oil Fuel Ash and Rice Husk Ash on Alkali–Silica Reaction of Mortar	Alkali–silica reaction (ASR) of binary and ternary blended cement mortars made from fine particles of palm oil fuel ash (PA) and rice husk ash (RA) was investigated. Portland cement type I was replaced by PA, RA, and RA mixed with PA at rates of 10, 20, 30, and 40% by weight of binder and was used for casting mortar to investigate compressive strength and expansion due to ASR. the expansions of PA mortars due to ASR were lower than control mortar, while the mortars containing RA had very high expansion and many cracks.
Karakurt and Topcu, 2011	Effect of blended cements produced with natural zeolite and industrial by-products on alkali-silica reaction and sulfate resistance of concrete	In this study, influence of blended cements produced with different types of pozzolans on alkali-silica reaction (ASR) and sulfate resistance of concrete was investigated. natural zeolite (clinoptilolite) was used to produce the blended cement and compared with the ordinary cement. The length changes and microstructure investigations of the mortar specimens with natural zeolite (clinoptilolite) blended cement showed that zeolite reduced ASR and sulfate damages when compared with Portland cement reference specimen.

Author/Authors, Year	Subject of study	Major findings of study
Bektas et al., 2005	Use of perlite powder to suppress the alkali–silica reaction	This study aimed at mitigating the deleterious alkali–silica reaction by using natural perlite powder as an admixture. The results showed that natural perlite powder (NPP) had potential to suppress the deleterious alkali–silica expansion.
Hossain, 2005	Volcanic ash and pumice as cement additives: pozzolanic, alkali-silica reaction and autoclave expansion characteristics	This study reported the results of investigation to assess the suitability of volcanic ash (VA) and pumice (VP) powder to be used as cement additives. It recommended the use of 20% volcanic ash or volcanic pumice as a cement additive.
Ramlochan et al., 2000	The effect of metakaolin on alkali–silica reaction in concrete	This article reports on a study to evaluate the efficacy of high-reactivity metakaolin (HRM) in controlling expansion due to alkali–silica reaction (ASR). The expansion of concretes and mortars containing 0–20% HRM as a partial replacement for OPC was studied. The amount of HRM required to control the expansion to <0.04% at 2 years was found to be between 10% and 15% depending on the aggregate.

Research Objectives

The objective of this study was to evaluate the extent of reactivity, in the form of expansion, of the aggregates acquired from seven distinct quarries within the State of Nevada. The loss in compressive strength due to alkali-silica reactions was also evaluated. This research investigation included a technical literature review, laboratory experimentations, discussions of results, and conclusions.

Chapter 1 provides the background and a basic overview of alkali-aggregate reactivity (ASR/ACR), including history, gel formation, mechanisms of reactivity, crack development, and symptoms, and factors influencing ASR.

Chapter 2 deals with the materials preparation and the experimental program used to identify and control ASR-induced expansion of reactive aggregates. Testing methodologies, and matrix constituents and proportions are also discussed.

Chapter 3 discusses the ASR-induced expansions of the ASTM C 1260 for the studied reactive aggregates in the virgin form (control) and for the mortars prepared using four sources of natural pozzolans. The minimum dosages of the studied natural pozzolans as a partial replacement of Portland cement for the mortars prepared with the reactive aggregates are also presented.

Chapter 4 reports the loss in strength of the studied natural pozzolan mortars alkali-silica reactivity.

Chapter 5 compares the effect of natural and industrial pozzolans on the ASR-induced expansion and loss in strength of the studied mortars.

Chapter 6 reports the conclusions of the research investigation.

Research significance

The impending environmental regulations/restrictions have created uncertainty in the supply of coal-burning fly ash (particularly Class F). These environmental regulations aimed at decreasing air pollution; i.e., Clean Air Interstate Rule and Cross State Air Pollution Rule; have forced coal burning electric generating industry to adopt emission reduction techniques that have led to a lower quality of fly ash. Many contractors are finding it difficult to obtain quality fly ash for construction projects. Moreover, the environmental regulations have forced many coal-producing corporations into bankruptcy. These situations have made it imperative to find and evaluate alternative sources of supplementary cementitious materials that can provide similar strength and ASR-mitigation benefit to concrete as fly ash. This study aims to evaluate the performance of commercially available Nevada's natural pozzolans to assess their effectiveness in mitigating ASR of reactive aggregates. The outcomes of this study can lead to various benefits, including:

- Improvement in the quality and longevity of pavements and bridges,
- Elimination of the need for frequent repair and rehabilitation activities,
- Reduction in the overall costs associated with highway maintenance and traffic delays.

Chapter 2

Experimental Program

The focus of this chapter is to present the experimental program; including materials preparation, sample preparation and curing, laboratory test procedures, and equipment used during this investigation.

Experimental Program

The experimental program of this study consisted of three major phases. Phase I dealt with the preparation of raw materials; such as collecting, washing, drying, crushing, sieving and grading of aggregates per ASTM C 1260. In Phase II, a variety of laboratory test methods, such as ASTM C 1260 and C 109, were conducted to identify the extent of reactivity of the studied aggregates. Phase III of the experimental program dealt with the comparison of the utilized mitigation techniques to control excess expansion of the reactive aggregates. The breakdown of each phase of this investigation is shown in the following flow chart (Figure 2.1) and described in the sections to follow.

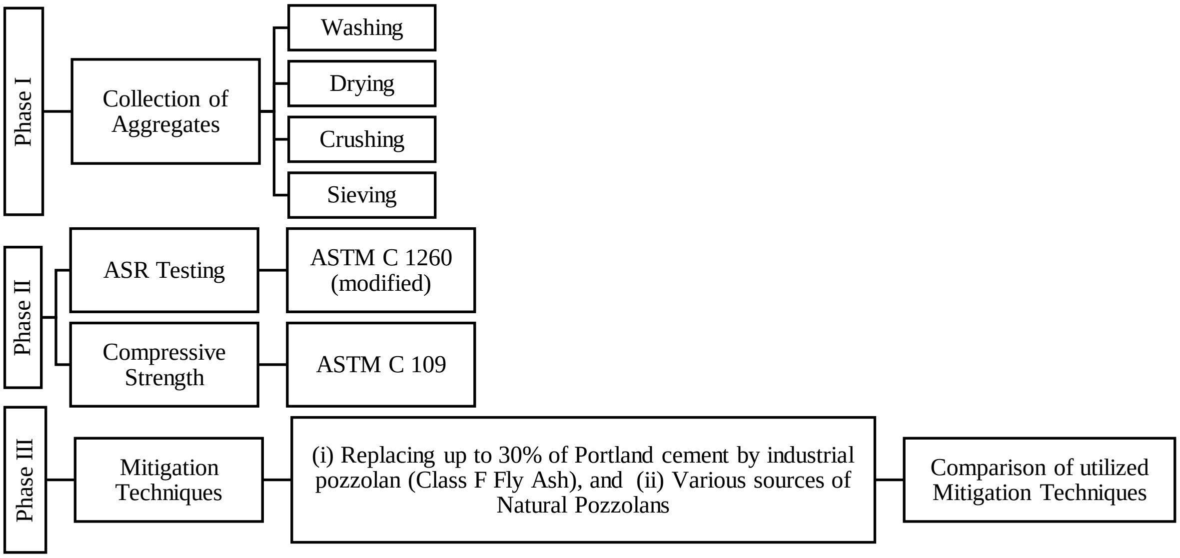


Figure 2.1: Flow chart of experimental program for alkali-aggregate detection and mitigation

Properties of Aggregates

Acquiring Aggregates

Sufficient amounts of coarse and fine aggregates were procured from seven different quarries within the State of Nevada. Based on the prior history, the aggregates belonging to these quarries were suspected to be reactive or potentially reactive.

Washing and Drying of Aggregates

During the washing process, the coarse aggregates were first soaked in a bucket of water for about 24 hours, and then placed on large trays and hand-washed with water sprays as shown in Figure 2.2. Once the dirt (suspended fine solid matters) was washed off and the water running over the aggregates was clear, they were placed on aluminum trays and then put in the preheated oven at 100°C for 24 hours to fully dry off. Afterward, they were stored in clean and dry buckets for the crushing operation. Additionally, the fine aggregates were dried in horse troughs under the sun in order to remove moisture. Sufficient amounts of material from each of the quarries were prepared for the anticipated testing. During the washing process, the utmost care was taken to avoid any cross contamination of the aggregates.

Figure 2.2: Washing coarse aggregates

Crushing of Aggregates

A badger rock crusher, shown in Figure 2.3, was used to crush the coarse aggregates to obtain the required amount of graded aggregates. The badger crusher crushed the aggregates into very fine particles. Once the aggregate was crushed, it was collected in clean and dry buckets. The containers and rock crusher was wiped clean before and after crushing to avoid contamination.

Figure 2.3: Equipment (badger crusher) used to crush the coarse aggregate in to smaller sizes

Sieving Aggregates

The aggregate gradation of the crushed aggregates was performed in accordance with ASTM C 136, "Sieve or screen analysis of fine and coarse aggregates." The crushed aggregates were sieved for the preparation of the specimens, the mortar bars and the cubes, as per requirements of ASTM C 1260. For the mortar bars and cubes (ASTM C 1260), the aggregates were separated into #8, #16, #30, #50, and #100 US sieve sizes. The gradation of each aggregate source consisted of about three pounds of the crushed aggregate that was two directionally sieved for a period of 8 minutes. If needed, additional time was given until the source was fully exhausted. The separated fractions of aggregate were placed in plastic zip-lock bags and stored inside clean buckets. Lastly, the sieves were washed and dried before the next aggregate source was graded to avoid cross contamination.

Grading Aggregates

Once the crushing of the seven aggregate sources was completed, they were graded to meet the gradation requirement of the ASTM C1260. Table 2.1 and Figure 2.4 show the aggregate gradation used to prepare mortar bars and cubes. The fineness modulus (FM) of the gradation of the combined aggregate sizes was 2.90.

Table 2.1: Crushed aggregate gradation for mortar bar specimens

Sieve size		Mass (%)
Passing	Retained on	
4.75 mm (No. 4)	2.36 mm (No. 8)	10
2.36 mm (No. 8)	1.18 mm (No. 16)	25
1.18 mm (No. 16)	600 µm (No. 30)	25
600 µm (No. 30)	300 µm (No. 50)	25
300 µm (No. 50)	150 µm (No.100)	15

Note: 1 mm = 0.03937 in

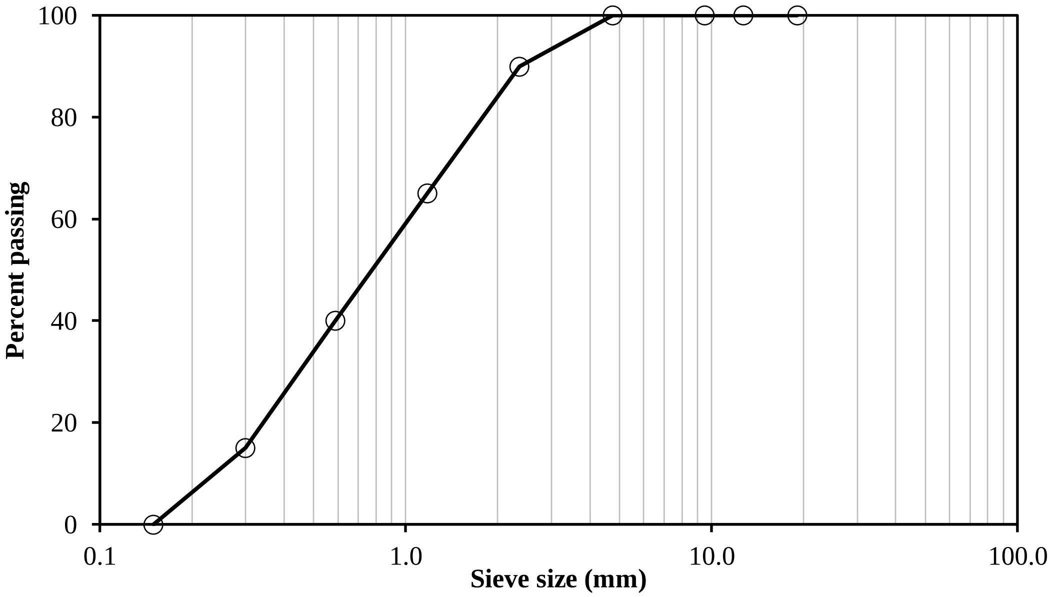


Figure 2.4: Gradation of aggregate

Materials

Sodium Hydroxide Pallet

A sodium hydroxide (NaOH) pellet is a white particle approximately 4 mm in diameter and 2 mm in width. The weight of each particle was approximately 0.1 grams. Sodium hydroxide pellets were soluble and generated heat when mixed with water. The containers of NaOH pellets were kept in a tightly closed container to prevent the conversion of NaOH to sodium carbonate by the CO_2 in air. Its purity was 99% (by acidimetry test) and among the other ingredients, sodium carbonate (Na_2CO_3) was 0.4%. Sodium hydroxide was added to distilled water to prepare concentrations of soak solutions by adding 160g of sodium hydroxide per 1 gallon of distilled water.

Portland Cement

Type V Portland cement with alkali content of 0.6% Na_2O_{eq} meeting the requirements of ASTM C 1507 was used to prepare the studied mortar cubes and prisms (Figure 2.5). It had a very low C_3A composition, which accounts for its high sulfate resistance. The physico-chemial properties of the Portland cement utilized is presented in Table 2.2.

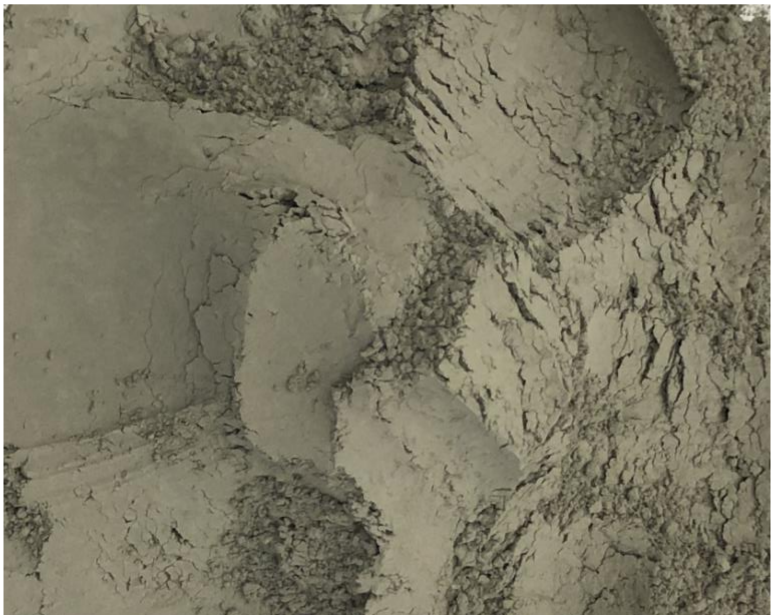


Figure 2.5: Type V Portland cement

Class F Fly Ash

One source of Class F fly ash with CaO content of 5.59% that complied with the requirements of ASTM C 618 was used to reduce ASR-induced expansion (Figure 2.6). Four different dosages of Class F fly ash as a partial replacement of Portland cement by weight were blended with cement. The physico-chemical properties of the Class F fly ash are presented in Table 2.3.

Table 2.2: Chemical compositions of Type V cement

Component	Type V Cement (%)
Silicon Dioxide (SiO_2)	8.2
Calcium Oxide (CaO)	47.8
Aluminum Oxide (Al_2O_3)	2.3
Ferric Oxide (Fe_2O_3)	0.7
Magnesium Oxide (MgO),	6
Sulfur Trioxide (SO_3),	2.7
Total Alkali (Na_2O+ K_2O)	0.6
Loss on Ignition (LOI)	3.5
C_3S	54
C_2S	19
C_3A	4
C_4AF	11
Physical Properties of Type V Cement	
Blaine Fineness (m^2/Kg)	260
Autoclave Expansion (%)	0.8
Time of set initial Vicat (Minutes)	45/375 (Min/Max)
Air Entrainment (%volume)	12
False set (%)	50

Figure 2.6: Class F fly ash

Table 2.3: Chemical compositions and physical properties of Class F fly ash

Component	Class F Fly Ash (%)	ASTM Limit Class F/C
Silicon Dioxide (SiO_2)	63.05	
Aluminum Oxide (Al_2O_3)	17.48	
Ferric Oxide (Fe_2O_3)	4.53	
Sum(SiO_2 +Al_2O_3 +Fe_2O_3)	85.06	70.0/50.0 min
Sulfur Trioxide (SO_3),	0.84	5.0 max
Calcium Oxide (CaO)	5.59	
Magnesium Oxide (MgO),	2.06	
Sodium Oxide (Na_2O)	2.97	
Potassium Oxide K_2O)	4.16	
Moisture	0.04	3.0 max
Loss on Ignition (LOI)	0.38	6.0 max
Physical Properties of class F fly ash		
Fineness	21.69	
Strength Activity Index (7 days)	83	
Strength Activity Index (28 days)	97	
Water requirement	96	
Autoclave Soundness	0.01	
Density	2.34	

Natural Pozzolans

Four different sources of natural pozzolans were used. For the purpose of this study, they were designated as “N1 through N4.” Four different dosages of natural pozzolans as a partial replacement of Portland cement by weight were blended with cement (Figure 2.7). The chemical properties of the four natural pozzolan sources are presented in Table 2.4.

Figure 2.7: Natural pozzolan

Table 2.4: Chemical compositions of natural pozzolans

Component	N1 (%)	N2 (%)	N3 (%)	N4 (%)
Silicon Dioxide (SiO_2)	68.8	57.15	73.74	72.97
Calcium Oxide (CaO)	3.2	10.21	0.54	0.80
Aluminum Oxide (Al_2O_3)	8.5	13.46	12.20	12.27
Ferric Oxide (Fe_2O_3)	1.1	3.17	1.11	2.21
Magnesium Oxide (MgO),	-	1.61	0.13	0.34
Sulfur Trioxide (SO_3),	-	4.37	<0.01	0.02
Total Alkali (Na_2O+ K_2O)	6.4	4.79	5.87	6.62
Loss on Ignition (LOI)	3.7	2.59	4.15	2.65

Physical Properties of Sieved Aggregates

The physical properties of the seven aggregates sources are shown in table 2.5. For the purpose of this study they are designated as A, B, C, D, E, F, G.

Table 2.5: Physical properties of the aggregates

Agg. ID	Specific Gravity (SSD)	Absorption Capacity (%)	Unit Weight Kg/m^3 (lb/ft^3)
A	2.58	3.41	1527.20 (95.34)
B	2.63	0.93	1576.70 (98.43)
C	2.71	1.23	1561.00 (97.45)
D	2.67	1.75	1548.19 (96.65)
E	2.65	1.02	1559.08 (97.33)
F	2.59	2.87	1516.47 (94.67)
G	2.69	0.76	1586.15 (99.02)

Mixture Constituents and Proportions, Mixing and Curing

Mixture Constituents and Proportions

In order to meet the objective of this study, a total of 131 different mortar mixtures was prepared. This number of mixtures constituted 7 control-, 28 Class F fly ash contained-, and 118 natural pozzolan contained mortars. Industrial and natural pozzolans replaced a portion of Portland cement at four levels of 15, 20, 25, and 30% by weight. Their mixture identification, matrix ingredients and proportions by weight, water-to-cementitious materials ratio, flow dimension, and one-day demolded unit weight are shown in Table 2.6 for control and fly ash contained mixtures, as well as in Tables 2.7A through 2.7D for the natural pozzolan contained mortars.

Table 2.6: Mixture constituents and proportion of mortars containing control and Class F fly ash

Mix ID	Cement Replacement (%)	Graded Agg. (gm)	Cement (gm)	Class F fly ash (gm)	W/C	Water (gm)	Unit Weight (kg/m^3)	Flow (mm)
AF-0	0	1385	615	0	0.47	289	2162	151
AF-15	15	1385	523	92	0.47	289	2142	153
AF-20	20	1385	492	123	0.47	289	2144	159
AF-25	25	1385	462	154	0.47	289	2163	162
AF-30	30	1385	431	185	0.47	289	2165	172
BF-0	0	1385	615	0	0.47	289	2299	135
BF-15	15	1385	523	92	0.47	289	2304	140
BF-20	20	1385	492	123	0.47	289	2279	145
BF-25	25	1385	462	154	0.47	289	2249	147
BF-30	30	1385	431	185	0.47	289	2260	152
CF-0	0	1385	615	0	0.47	289	2292	141
CF-15	15	1385	523	92	0.47	289	2260	145
CF-20	20	1385	492	123	0.47	289	2257	149
CF-25	25	1385	462	154	0.47	289	2202	151
CF-30	30	1385	431	185	0.47	289	2228	157

Mix ID	Cement Replacement (%)	Graded Agg. (gm)	Cement (gm)	Class F fly ash (gm)	W/C	Water (gm)	Unit Weight (kg/m^3)	Flow (mm)
DF-0	0	1385	615	0	0.47	289	2290	161
DF-15	15	1385	523	92	0.47	289	2289	169
DF-20	20	1385	492	123	0.47	289	2265	175
DF-25	25	1385	462	154	0.47	289	2284	179
DF-30	30	1385	431	185	0.47	289	2317	182
EF-0	0	1385	615	0	0.47	289	2291	149
EF-15	15	1385	523	92	0.47	289	2273	152
EF-20	20	1385	492	123	0.47	289	2288	158
EF-25	25	1385	462	154	0.47	289	2272	160
EF-30	30	1385	431	185	0.47	289	2287	163
FF-0	0	1385	615	0	0.47	289	2285	179
FF-15	15	1385	523	92	0.47	289	2282	184
FF-20	20	1385	492	123	0.47	289	2289	191
FF-25	25	1385	462	154	0.47	289	2264	198
FF-30	30	1385	431	185	0.47	289	2301	210
GF-0	0	1385	615	0	0.47	289	2293	188
GF-15	15	1385	523	92	0.47	289	2277	196
GF-20	20	1385	492	123	0.47	289	2253	204
GF-25	25	1385	462	154	0.47	289	2261	208
GF-30	30	1385	431	185	0.47	289	2274	215

Note: 1 gm = 0.0022046 lb; 1 mm = 0.03937 in; 1 kg/m^3 =0.0624 lb/ft^3

Table 2.7A: Mixture constituents and proportion of mortars containing natural pozzolan N1

Mix ID	Cement replacement (%)	Graded Agg. (gm)	Cement (gm)	Nat. pozz. N1 (gm)	W/C	Water (gm)	Unit Weight (kg/m^3)	Flow (mm)
AN1-15	15	1385	523	92	0.47	289	2192	155
AN1-20	20	1385	492	123	0.47	289	2170	157
AN1-25	25	1385	462	154	0.47	289	2143	161
AN1-30	30	1385	431	185	0.47	289	2166	165
BN1-15	15	1385	523	92	0.47	289	2270	138
BN1-20	20	1385	492	123	0.47	289	2278	141
BN1-25	25	1385	462	154	0.47	289	2276	141
BN1-30	30	1385	431	185	0.47	289	2258	143
CN1-15	15	1385	523	92	0.47	289	2260	146
CN1-20	20	1385	492	123	0.47	289	2268	150
CN1-25	25	1385	462	154	0.47	289	2275	155
CN1-30	30	1385	431	185	0.47	289	2247	163
DN1-15	15	1385	523	92	0.47	289	2311	169
DN1-20	20	1385	492	123	0.47	289	2303	175
DN1-25	25	1385	462	154	0.47	289	2284	177
DN1-30	30	1385	431	185	0.47	289	2287	183
EN1-15	15	1385	523	92	0.47	289	2260	150
EN1-20	20	1385	492	123	0.47	289	2281	152
EN1-25	25	1385	462	154	0.47	289	2278	155
EN1-30	30	1385	431	185	0.47	289	2263	156
FN1-15	15	1385	523	92	0.47	289	2279	182
FN1-20	20	1385	492	123	0.47	289	2301	183

Mix ID	Cement replacement (%)	Graded Agg. (gm)	Cement (gm)	Nat. pozz. N1 (gm)	W/C	Water (gm)	Unit Weight (kg/m^3)	Flow (mm)
FN1-25	25	1385	462	154	0.47	289	2270	184
FN1-30	30	1385	431	185	0.47	289	2270	187
GN1-15	15	1385	523	92	0.47	289	2292	194
GN1-20	20	1385	492	123	0.47	289	2267	201
GN1-25	25	1385	462	154	0.47	289	2268	207
GN1-30	30	1385	431	185	0.47	289	2294	211

Note: 1 gm = 0.0022046 lb; 1 mm = 0.03937 in; 1 kg/m^3 =0.0624 lb/ft^3

Table 2.7B: Mixture constituents and proportion of mortars containing natural pozzolan N2

Mix ID	Cement Replacement (%)	Graded Agg. (gm)	Cement (gm)	Nat. Pozz. N2 (gm)	W/C	Water (gm)	Unit Weight (kg/m^3)	Flow (mm)
AN2-15	15	1385	523	92	0.47	289	2157	152
AN2-20	20	1385	492	123	0.47	289	2187	157
AN2-25	25	1385	462	154	0.47	289	2171	160
AN2-30	30	1385	431	185	0.47	289	2171	163
BN2-15	15	1385	523	92	0.47	289	2286	139
BN2-20	20	1385	492	123	0.47	289	2324	142
BN2-25	25	1385	462	154	0.47	289	2299	143
BN2-30	30	1385	431	185	0.47	289	2303	148
CN2-15	15	1385	523	92	0.47	289	2269	145
CN2-20	20	1385	492	123	0.47	289	2264	146
CN2-25	25	1385	462	154	0.47	289	2286	149
CN2-30	30	1385	431	185	0.47	289	2220	152
DN2-15	15	1385	523	92	0.47	289	2319	163
DN2-20	20	1385	492	123	0.47	289	2319	164
DN2-25	25	1385	462	154	0.47	289	2325	167
DN2-30	30	1385	431	185	0.47	289	2324	167
EN2-15	15	1385	523	92	0.47	289	2293	150
EN2-20	20	1385	492	123	0.47	289	2303	151
EN2-25	25	1385	462	154	0.47	289	2296	155
EN2-30	30	1385	431	185	0.47	289	2256	157
FN2-15	15	1385	523	92	0.47	289	2308	181
FN2-20	20	1385	492	123	0.47	289	2314	189
FN2-25	25	1385	462	154	0.47	289	2295	193
FN2-30	30	1385	431	185	0.47	289	2254	197
GN2-15	15	1385	523	92	0.47	289	2282	193
GN2-20	20	1385	492	123	0.47	289	2307	194
GN2-25	25	1385	462	154	0.47	289	2268	198
GN2-30	30	1385	431	185	0.47	289	2266	203

Note: 1 gm = 0.0022046 lb; 1 mm = 0.03937 in; 1 kg/m^3 =0.0624 lb/ft^3

Table 2.7C: Mixture constituents and proportion of mortars containing natural pozzolan N3

Mix ID	Cement replacement (%)	Graded Agg. (gm)	Cement (gm)	Nat. Pozz. N3 (gm)	W/C	Water (gm)	Unit Weight (kg/m³)	Flow (mm)
AN3-15	15	1385	523	92	0.47	289	2231	158
AN3-20	20	1385	492	123	0.47	289	2211	161
AN3-25	25	1385	462	154	0.47	289	2147	163
AN3-30	30	1385	431	185	0.47	289	2120	166
BN3-15	15	1385	523	92	0.47	289	2285	139
BN3-20	20	1385	492	123	0.47	289	2293	140
BN3-25	25	1385	462	154	0.47	289	2315	143
BN3-30	30	1385	431	185	0.47	289	2278	143
CN3-15	15	1385	523	92	0.47	289	2300	142
CN3-20	20	1385	492	123	0.47	289	2336	142
CN3-25	25	1385	462	154	0.47	289	2219	145
CN3-30	30	1385	431	185	0.47	289	2316	147
DN3-15	15	1385	523	92	0.47	289	2326	163
DN3-20	20	1385	492	123	0.47	289	2407	166
DN3-25	25	1385	462	154	0.47	289	2307	170
DN3-30	30	1385	431	185	0.47	289	2318	171
EN3-15	15	1385	523	92	0.47	289	2382	150
EN3-20	20	1385	492	123	0.47	289	2397	153
EN3-25	25	1385	462	154	0.47	289	2328	153
EN3-30	30	1385	431	185	0.47	289	2296	156
FN3-15	15	1385	523	92	0.47	289	2331	182
FN3-20	20	1385	492	123	0.47	289	2294	184
FN3-25	25	1385	462	154	0.47	289	2343	187
FN3-30	30	1385	431	185	0.47	289	2282	189
GN3-15	15	1385	523	92	0.47	289	2253	191
GN3-20	20	1385	492	123	0.47	289	2279	194
GN3-25	25	1385	462	154	0.47	289	2246	197
GN3-30	30	1385	431	185	0.47	289	2234	202

Note: 1 gm = 0.0022046 lb; 1 mm = 0.03937 in; 1 kg/m^3 =0.0624 lb/ft^3

Table 2.7D: Mixture constituents and proportion of mortars containing natural pozzolan N4

Mix ID	Cement replacement (%)	Graded Agg. (grams)	Cement (gm)	Nat. Pozz. N3 (gm)	W/C	Water (gm)	Unit Weight (kg/m³)	Flow (mm)
AN4-15	15	1385	523	92	0	289	2286	155
AN4-20	20	1385	492	123	0	289	2182	158
AN4-25	25	1385	462	154	0	289	2218	159
AN4-30	30	1385	431	185	0	289	2169	162
BN4-15	15	1385	523	92	0	289	2257	136
BN4-20	20	1385	492	123	0	289	2275	138
BN4-25	25	1385	462	154	0	289	2304	139
BN4-30	30	1385	431	185	0	289	2247	142
CN4-15	15	1385	523	92	0	289	2301	144
CN4-20	20	1385	492	123	0	289	2304	147
CN4-25	25	1385	462	154	0	289	2282	149
CN4-30	30	1385	431	185	0	289	2291	152
DN4-15	15	1385	523	92	0	289	2398	163

Mix ID	Cement replacement (%)	Graded Agg. (grams)	Cement (gm)	Nat. Pozz. N3 (gm)	W/C	Water (gm)	Unit Weight (kg/m³)	Flow (mm)
DN4-20	20	1385	492	123	0	289	2372	167
DN4-25	25	1385	462	154	0	289	2391	168
DN4-30	30	1385	431	185	0	289	2410	173
EN4-15	15	1385	523	92	0	289	2398	151
EN4-20	20	1385	492	123	0	289	2412	153
EN4-25	25	1385	462	154	0	289	2306	154
EN4-30	30	1385	431	185	0	289	2269	158
FN4-15	15	1385	523	92	0	289	2402	181
FN4-20	20	1385	492	123	0	289	2381	183
FN4-25	25	1385	462	154	0	289	2310	186
FN4-30	30	1385	431	185	0	289	2357	188
GN4-15	15	1385	523	92	0	289	2321	190
GN4-20	20	1385	492	123	0	289	2351	192
GN4-25	25	1385	462	154	0	289	2360	194
GN4-30	30	1385	431	185	0	289	2296	197

Note: 1 gm = 0.0022046 lb; 1 mm = 0.03937 in; 1 kg/m^3 =0.0624 lb/ft^3

Flow

The flow spread of each batched mortars is shown in Table 2.6 and Tables 2.7A through 2.7D. The average flow of the control mortars using seven aggregate sources was 193.25 mm. The average flow as functions of the five pozzolan sources (one industrial (Class F fly ash) and four natural pozzolans) and as functions of cement replacement by weight percentage are shown in Figures 2.8 and 2.9, respectively. As can be seen, at all cement replacement levels, Class F fly ash produced higher workability than the natural pozzolans used in this study. Amongst the four natural pozzolan sources, N1 natural pozzolan displayed highest average flow followed by N2, N3, and N4 in descending order.

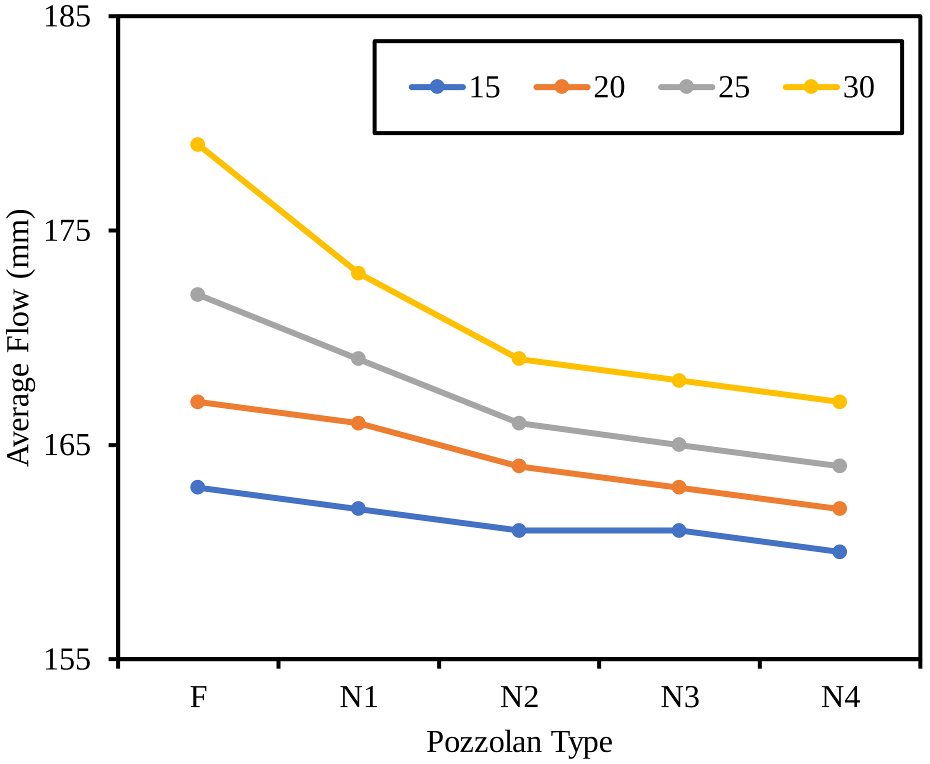


Figure 2.8: Effect of pozzolan type on average flow

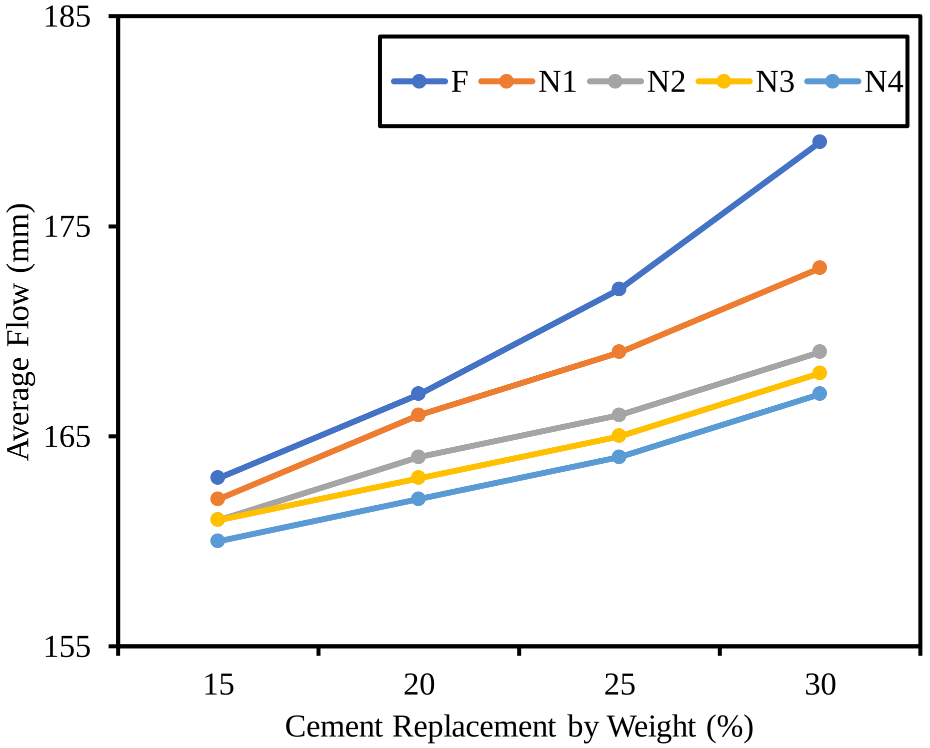


Figure 2.9: Effect of cement replacement on average flow

Mixer and Mixing Procedure

A mortar mixer is a device that homogeneously combines cement, fine aggregate and water to form plastic mortar. An electric bowl mixer with a capacity of 0.27 ft^3 and a speed of 50 rpm was used to blend the mortar constituents as shown in Figure 2.10. A bowl mixer was preferred because it is particularly efficient for mixing small quantities of mortar in a laboratory. The laboratory room condition was maintained at 25±5% relative humidity and a temperature of 71±3°F (20±1°C). Aggregates, cement, water, fly ash, and NaOH solutions were all kept in the same laboratory room to maintain consistency.

The mixing sequence, conducted in accordance with ASTM C305, consisted of: (i) placing all the mixing water in the pan, (ii) adding the cementitious materials and mixing for 45 seconds, (iii) adding the selected gradation of crushed aggregate and mixing for 30 seconds, and (iv) scraping the paste from bottom of the pan, and mixing for additional 45 seconds.

Figure 2.10: Mortar mixer

Preparation of Test Specimens

As shown in Figure 2.11, a mortar cube mold consisted of three 50 x 50 x 50 mm (2 x 2 x 2 in) with a cross-sectional area of 25.8 cm^2 (4 in^2) and a twin 25 x 25 x 286 mm (1 x 1 x 1 in) beam-shaped mold with a 6.45 cm^2 (1 in^2) cross section. These molds were used to produce mortar bars and cubes.

Figure 2.11: Mortar cube and bar molds

Curing of Test Specimens

Upon casting, mortar prisms and cubes (while in mold) were transferred to a curing chamber having 100% relative humidity and temperature of 23±1°C for a period of 1 day (Figure 2.12). Once demolded, the four mortar bars were placed in a sealed plastic container filled with water and kept inside an oven, which maintained the temperature of 80±2°C, for 24 hours. Afterward, the four mortar bars were transferred to another sealed plastic container filled with 1N sodium hydroxide (NaOH) solution and kept in an oven of 80±2°C temperature for the test duration of 56 days. The test cubes were divided into two equal groups. 3 cubes were placed inside a sealed plastic container filled with 1N NaoH solution and stored in on oven having temperature of 80±2°C for the duration of 90 days. The remaining cubes were kept in a water curing chamber for the same period of 90 days.

Equipment

Flow Table

Once mixing was completed, workability, expressed in flow spread, of mortar was measured according to ASTM C807 (Figure 2.13). The flow Table, as shown in table 2.10, was used to provide flow of the studied mortars. Upon batching, a predetermined volume of mortar was placed inside the flow mold. The mold was then removed and the table was subjected to 25 drops using the flow table crank handle. The flow spread was measured in four directions and averaged. The flow spreads, reported in mm, of the 131 studied mortars are shown in Table 2.6 and Tables 2.7A through 2.7D.

Figure 2.12: Specimens in curing chamber

Figure 2.13: Flow table

Oven

A number of ovens was built and used to maintain an inside temperature of 80 ±2°C as shown in Figure 2.14. The ovens were continuously monitored via a temperature control device with ten thermocouples placed inside the oven at different locations including three in the solution containers. The average temperature of the thermocouples was recorded at 80 ±2°C and the maximum temperature difference among the thermocouples was at ±2°C. To protect the oven from or any external sources, plywood boards were glued onto the exposed areas of the oven. The steel frames were installed to maintain the shape and stability of the oven.

(a) Oven (b) Oven Temperature

Figure 2.14: Oven along with the heating units and temperature controller

Length Comparator

A digital length comparator allowed for measurements of the change in length of mortar bars. ASTM C 490 is the standard practice for using this apparatus in determination of length change of hardened cement paste, mortar, and concrete. Figure 2.15 shows the length comparator used in this study. The length change value for each bar was calculated to the nearest 0.0254 mm (0.001 in) and the average expansion of four bars was reported to the nearest 0.0254 mm (0.001 in). The calculation of the length change at any age was performed as follows:

$$\Delta L = \frac{L_x - L_i}{L_g} \times 100 \qquad \text{Equation 2.1}$$

Where:

ΔL = change in length at x age, %

L_x = difference between the specimen and the reference bar readings at x age

L_i = difference between the specimen and the reference bar readings, usually taken before storing in the respective test environment

L_g = nominal gage length.

Figure 2.15: Digital length comparator

Compression Machine

Compressive strength is one of the most important physical properties used in design of concrete structure. A classic concrete compression machine (Model# MC-500CL) with the capacity of 226796 kg (500,000 pounds) was used to evaluate the cube compressive strength in accordance with the ASTM C 109. Before each test, the surfaces of the upper and lower platens of the compression machine were wiped clean. As the upper platen was brought to bear on the top of the specimen, the spherically seated platen was moved by hand and adjusted to seat uniformly over the specimen. The specimen was then subjected to a uniaxial centroidal compressive force. The compression machine used in this study is shown in Figure 2.16.

Figure 2.16: Compression machine

Assessing Alkali-Silica Reactivity

The following testing methods were conducted to determine the extent of alkali-silica reactivity of the studied aggregates.

ASTM C 1260

ASTM C 1260 is a recommended test method for assessing ASR. It is recognized as a very severe test method because of the extreme test conditions such as highly alkaline storage solution and high temperature. The test is considered as a screening tool for aggregates. Most researchers have agreed that this test is a good predictor of ASR; however, it may give overestimated results for some aggregates. For each aggregate source, four mortar bars and six cubes were cast. Mortar bars and cubes were molded within a total elapsed time of not more than 2 min and 15 sec after completing of the original mixing of the mortar batch. After 24 hours of moist curing, the bars were demolded and initial readings were taken. Afterward, the submerged specimens were stored in an oven at 80±2°C for 24 hours after which the zero readings were recorded. The test specimens were then submerged in 1N NaOH solution in an air-tight plastic container, as shown in Figure 2.17, and kept in an oven maintaining temperature of 80±2°C for 56 days. Subsequent readings were taken at the age of 3, 6, 10, 14 days and thereafter one reading per week until the immersion age of 56 days was reached.

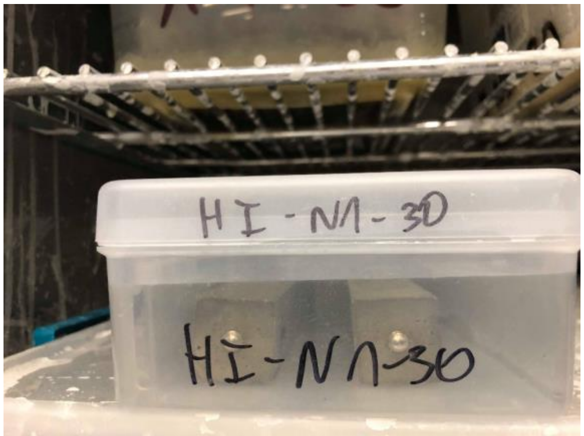


Figure 2.17: Mortar bars stored in NaOH solution at 80°C

ASTM C 109

Three cubes were removed from curing chamber, they were submerged in 1N NaOH solution and placed in an oven for a period of 90 days prior to testing. In addition, three companion cubes were kept in the curing chamber for the same period of time. Once 90-day curing age was reached, test cubes were removed from oven and water curing chamber and kept in the laboratory (73±2ºC) for 30 minutes prior to testing. Cubes were tested in compression in accordance with ASTM C 109.

Chapter 3

ASR-Induced Expansion of Control and Natural Pozzolan Contained Mortars

The goal of this chapter is to examine the extent of reactivity of the control mortars made with 7 different aggregate sources. Additionally, the effectiveness of using four natural pozzolan sources to replace a portion of Portland cement at the four levels of 15, 20, 25, and 30% by weight to mitigate ASR is examined. The minimum amount of natural pozzolan to mitigate the ASR concern of the reactive aggregates, using each of the four natural pozzolan sources, is also discussed.

3.1 ASR-Induced Expansion of Control Mortars

The ASR-induced expansions of the mortar bars belonging to seven aggregate sources as a function of immersion age is shown in figure 3.1. As can be seen, the expansion of the mortar bars continuously increased with an increase in the test duration. However, the expansion behavior varied depending on the aggregate source. During first 10 days, aggregate source G had the lowest expansion, whereas aggregate source D displayed the highest expansion. Once immersion age extended to 56 days, these two aggregate sources maintained the same status for the lowest and highest expansions. At 14 days, with the exception of aggregate source G, the remaining aggregate sources exhibited ASR-induced expansions well above the failure limit of 0.1% as prescribed by the ASTMC 1260.

The classification of the studied aggregate based on the ASTM classification of C1260 at 14 days, based on the failure criteria of 0.33% at 28 days and 0.48% at 56 days as suggested by Rogers and Hooton (1993), and based on the failure criteria of 0.28% at 28 days and 0.47% at 56 days as suggested by Islam (2010) are given in Table 3.1. As can be seen, aggregate source A through F are highly reactive based on the failure criteria of ASTM C 1260 (expansion percentage of greater than 0.1%) and are reactive based on the failure criteria at the extended age of 28 and 56 days. The aggregate source G was found to be innocuous per criterial limits of ages 14, 28, and 56 days. Therefore, this source was precluded from further studies. The aggregate groups A through F did require corrective measures to control alkali-aggregate reactivity.

The average ASR-induced expansion of the six reactive aggregate sources (A through F) as a function of immersion age is shown in Figure 3.2. The best fit curve between average expansions of the six reactive aggregates and immersion age at the confidence level of 95% is shown in Equation 3.1. The R^2 value of 0.9984 and the values of *prob(F)* of the regression curve and *prob(T)* of the regression parameters of zero are all indicative of the suitable relationship as proposed by Equation 3.1.

$$\textit{Average Expansion } (y) = 0.5054 \ln(t') - 0.4362 \qquad \text{Equation 3.1}$$

Where,

$$t' = \frac{t}{\ln(t)}$$

t = number of immersion days and $3 \leq t \leq 56$ days

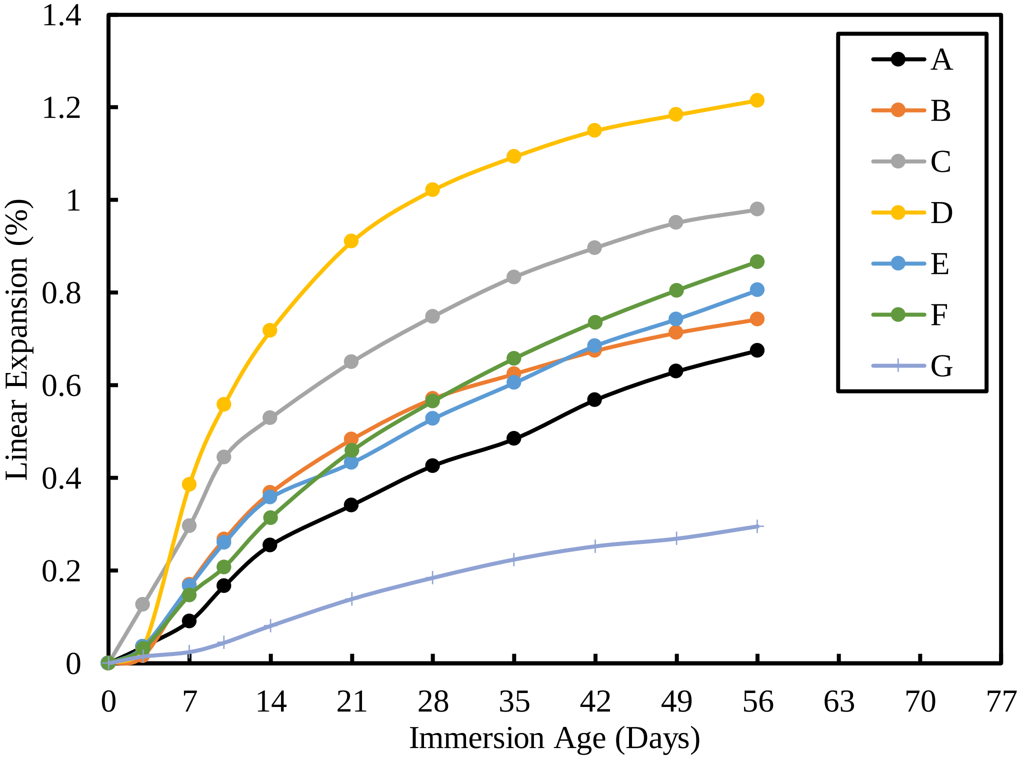


Figure 3.1: Expansion of control mortars with all aggregate sources

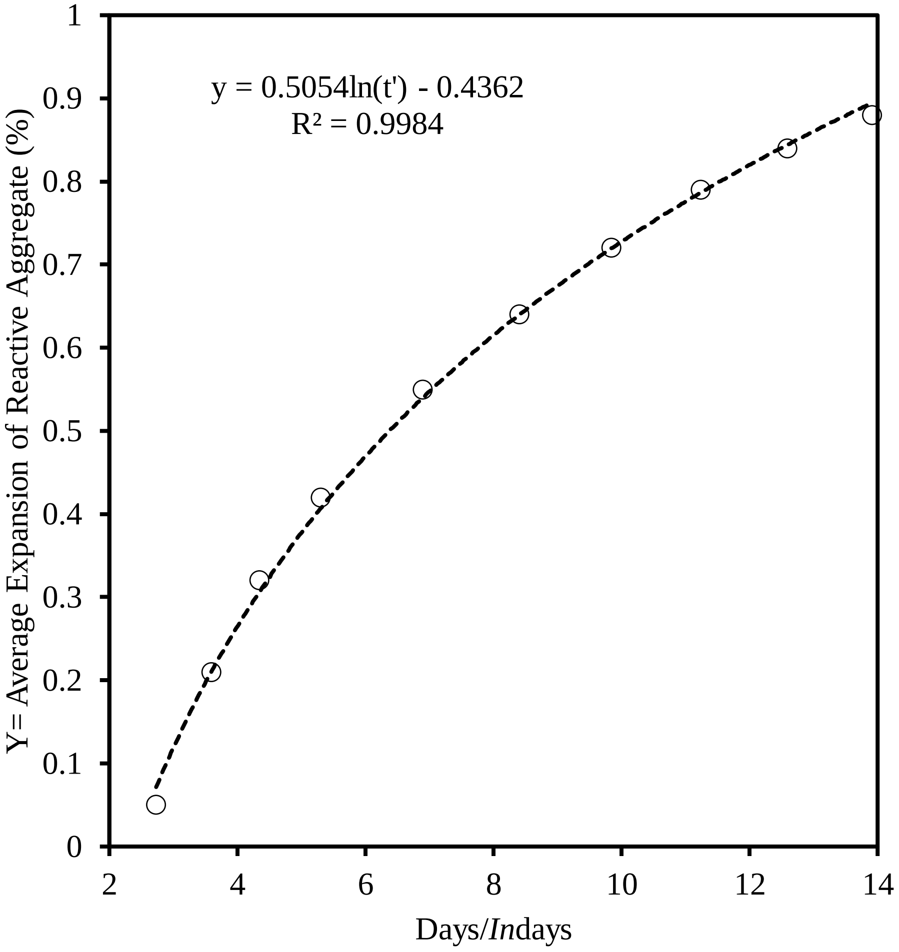


Figure 3.2: Average expansion of reactive aggregate as a function of age

Table 3.1: Aggregate classification based on ASTM C 1260 at ages 14, 28 and 56 days

Aggregate ID	14-day (0-10%)	28-day		56-day	
		0.28%[2]	0.33%[3]	0.47%[2]	0.48%[3]
Agg- A	HR	R	R	R	R
Agg-B	HR	R	R	R	R
Agg-C	HR	R	R	R	R
Agg-D	HR	R	R	R	R
Agg-E	HR	R	R	R	R
Agg-F	HR	R	R	R	R
Agg-G	I	I	I	I	I

I = Innocuous, R=Reactive, HR= Highly Reactive

[1] Aggregates are classified on ASTM C1260, I ≤ 0.10% and HR ≥ 0.20%

[2] Aggregates are classified based on failure limits proposed by Islam

[3] Aggregates are classified based on failure limits proposed by Hooton (1991) and Rogers and Hooton (1993)

3.2 ASR-Induced Expansion of Mortars using Aggregate Source A

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source A are depicted in Figures 3.3 through 3.6 and Tables 3.2 through 3.5, respectively. As can be seen, control mortar exhibited significantly higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansions of the control mortars were 0.2550, 0.4263 and .6750, respectively, all well above the respective prescribed failure limits. Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

When N1 natural pozzolan was used, the 14-day ASR-induced expansion of the mortars reduced by 70, 88, 90 and 95%, as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansion were 43, 71, 77, and 91%; and 21, 44, 55 and 71%; respectively; for the four cement replacement levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortars (Figure 3.4). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansions of the N2 natural pozzolan contained mortars reduced by 77, 78, 79 and 92%, respectively, as compared to that of the control mortar. After 28 and 56 immersion ages, the decreases in expansion were 30, 50, 79, and 79%; and 22, 30, 49 and 61; respectively.

As shown in Figures 3.5 and 3.6, the mortars cast with the N3 and N4 natural pozzolans also exhibited a trend similar to that of the mortars containing N1 and N2 natural pozzolans. The reductions in expansion, as compared to that of the control mortar, at the immersion ages of 14, 28, and 56 days were 73, 79, 89, and 90%; 48, 58, 72, and 73%; and 29, 45, 65, and 66% for the N3 natural pozzolan contained mortars and 88, 92, 93, and 94%; 87, 90, 91, and 92%; and 62, 63, 64, and 71% for the N4 natural pozzolan contained mortars.

On the whole, based on the failure limit of ASTM C1260, the ASR mitigation of the aggregate source A required only 15% of Portland cement substitution by any of the N1, N2, N3, and N4 natural pozzolans.

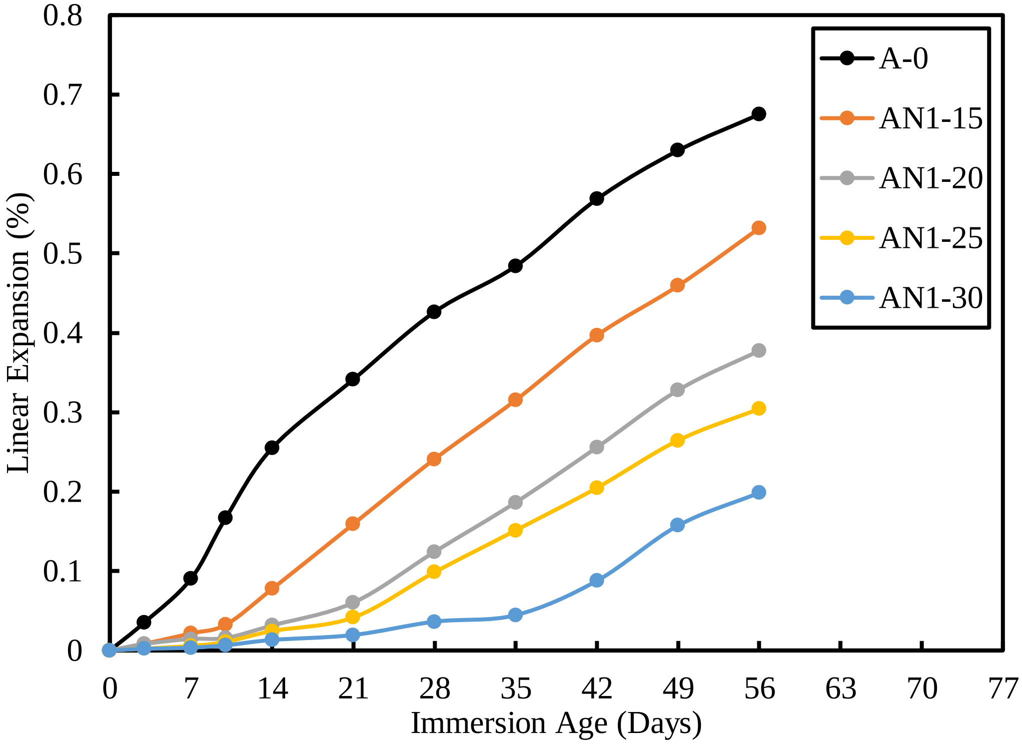


Figure 3.3: Expansion of N1 natural pozzolan mortars using aggregate source A

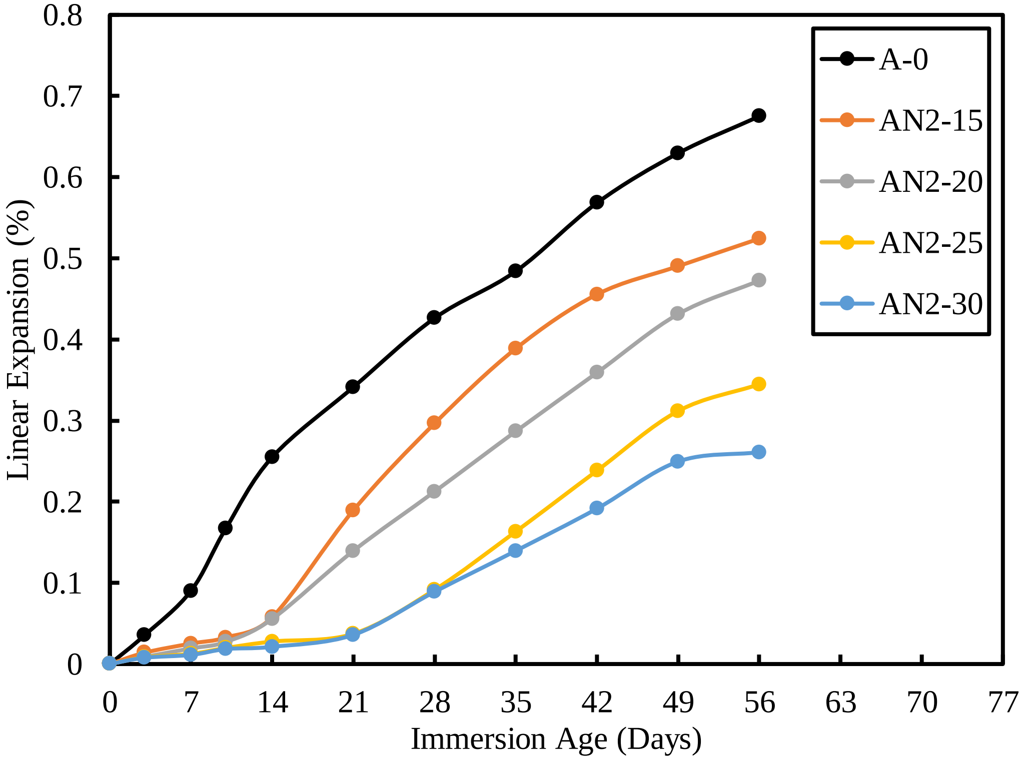


Figure 3.4: Expansion of N2 natural pozzolan mortars using aggregate source A

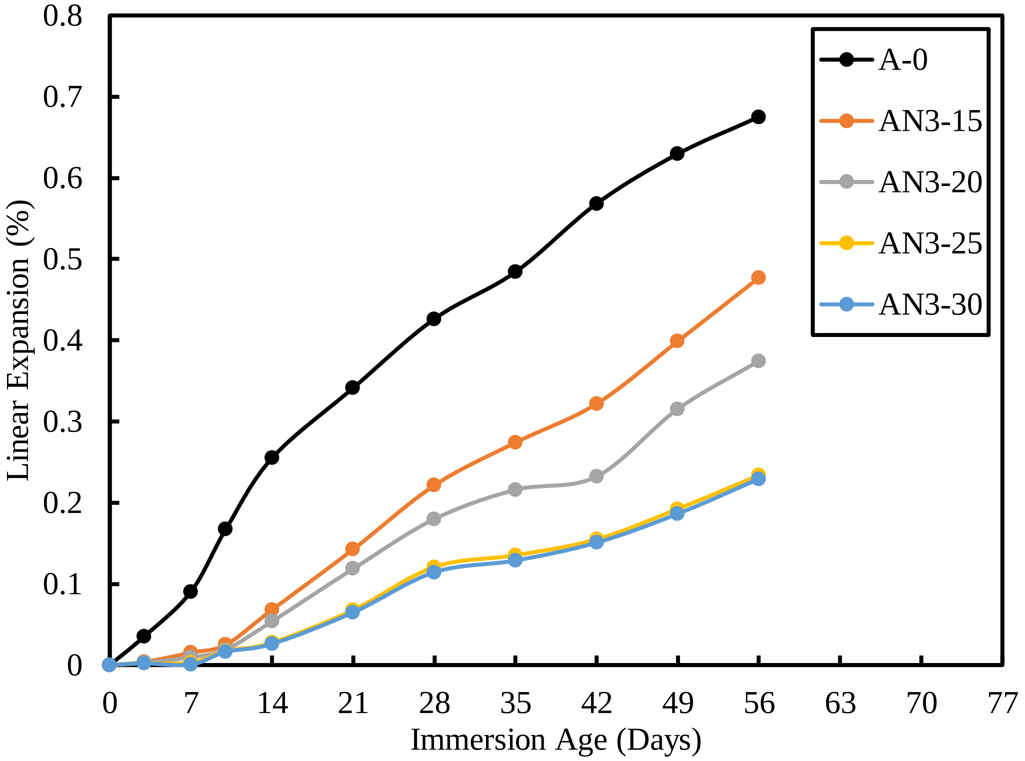


Figure 3.5: Expansion of N3 natural pozzolan mortars using aggregate source A

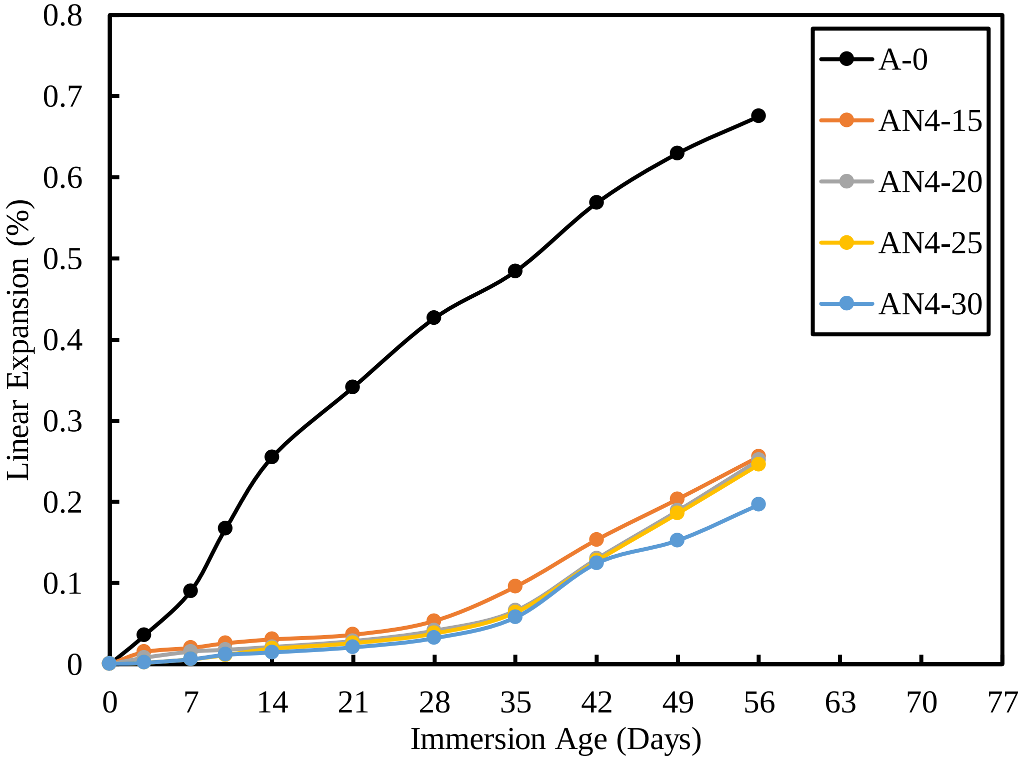


Figure 3.6: Expansion of N4 natural pozzolan mortars using aggregate source A

Table 3.2: Expansion of N1 natural pozzolan mortars using aggregate source A

Imm. Ages	Expansion (%)				
(Days)	A-0	AN1-15	AN1-20	AN1-25	AN1-30
14	0.2550	0.0775	0.0315	0.0245	0.0133
28	0.4263	0.2410	0.1243	0.0985	0.0363
56	0.6750	0.5318	0.3775	0.3043	0.1985

Table 3.3: Expansion of N2 natural pozzolan mortars using aggregate source A

Imm. Ages	Expansion (%)				
(Days)	A-0	AN2-15	AN2-20	AN2-25	AN2-30
14	0.2550	0.0578	0.0555	0.0278	0.0212
28	0.4263	0.2965	0.2125	0.0915	0.0890
56	0.6750	0.5243	0.4725	0.3448	0.2610

Table 3.4: Expansion of N3 natural pozzolan mortars using aggregate source A

Imm. Ages	Expansion (%)				
(Days)	A-0	AN3-15	AN3-20	AN3-25	AN3-30
14	0.2550	0.0680	0.0538	0.0275	0.0260
28	0.4263	0.2213	0.1798	0.1208	0.1143
56	0.6750	0.4770	0.3745	0.2338	0.2293

Table 3.5: Expansion of N4 natural pozzolan mortars using aggregate source A

Imm. Ages	Expansion (%)				
(Days)	A-0	AN4-15	AN4-20	AN4-25	AN4-30
14	0.2550	0.0305	0.0212	0.0190	0.0145
28	0.4263	0.0533	0.0413	0.0378	0.0320
56	0.6750	0.2558	0.2515	0.2460	0.1965

3.3 ASR-Induced Expansion of Mortars using Aggregate Source B

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source B are presented in Figures 3.7 through 3.10 and Tables 3.6 through 3.9, respectively. As can be seen, control mortar exhibited significantly higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansions of the control mortars were 0.3683, 0.5708 and .7423, respectively, all well above the respective respective failure limits.

Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

When N1 natural pozzolan was used, the 14-day ASR-induced expansion of the mortars reduced by 67, 71, 72 and 93%, as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansion were 49, 60, 62, and 78%; and 20, 37, 48 and 48%; respectively; for the four cement replacement levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortar (Figure 3.8). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansion of the N2 natural pozzolan contained mortars reduced by 87, 88, 92 and 93%, respectively as compare to that of the control mortar. After 28 and 56 immersion ages the decreases in expansion were 74, 75, 78, and 89%; and 57, 58, 58 and 70; respectively.

As presented in Figures 3.9 and 3.10, the mortars cast with the N3 and N4 natural pozzolans also displayed a trend similar to that of the mortars containing N1 and N2 natural pozzolans. The reductions in expansion, as compared to that of the control mortar, at the immersion ages of 14, 28, and 56 days, were 90, 91, 92, and 92%; 80, 82, 87, and 90%; and 59, 59, 64, and 65%; for N3 natural pozzolan mortars and 63, 70, 85, and 87%; and 59, 67, 75, and 87%; and 45, 50, 64, and 71%; for N4 natural pozzolan contained mortars.

In summary, based on the failure limit of ASTM C1260, the ASR mitigation of the aggregate source B required only 15% by weight of Portland cement substitution by any of the N1, N2, N3, and N4 natural pozzolans.

Table 3.6: Expansion of N1 natural pozzolan mortars using aggregate source B

Imm. Ages	Expansion (%)				
(Days)	B-0	BN1-15	BN1-20	BN1-25	BN1-30
14	0.3683	0.1225	0.1078	0.1023	0.0250
28	0.5708	0.2905	0.2278	0.2173	0.1270
56	0.7423	0.5933	0.4703	0.3890	0.3888

Table 3.7: Expansion of N2 natural pozzolan mortars using aggregate source B

Imm. Ages	Expansion (%)				
(Days)	B-0	BN2-15	BN2-20	BN2-25	BN2-30
14	0.3683	0.0467	0.0425	0.0300	0.0265
28	0.5708	0.1485	0.1435	0.1265	0.0655
56	0.7423	0.3180	0.3153	0.3150	0.2243

Table 3.8: Expansion of N3 natural pozzolan mortars using aggregate source B

Imm. Ages	Expansion (%)				
(Days)	B-0	BN3-15	BN3-20	BN3-25	BN3-30
14	0.3683	0.0362	0.0345	0.0303	0.0285
28	0.5708	0.1140	0.1020	0.0715	0.0543
56	0.7423	0.3065	0.3010	0.2653	0.2635

Table 3.9: Expansion of N4 natural pozzolan mortars using aggregate source B

Imm. Ages	Expansion (%)				
(Days)	B-0	BN4-15	BN4-20	BN4-25	BN4-30
14	0.3683	0.1345	0.1105	0.0555	0.0478
28	0.5708	0.2325	0.1880	0.1415	0.0748
56	0.7423	0.4103	0.3683	0.2675	0.2145

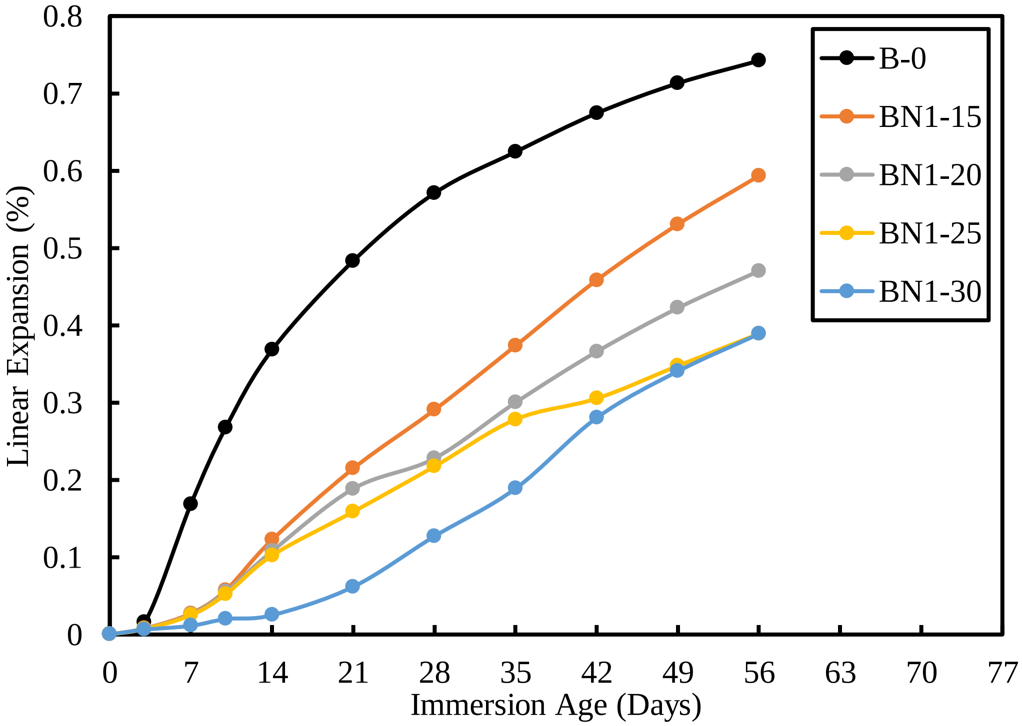


Figure 3.7: Expansion of N1 natural pozzolan mortars using aggregate source B

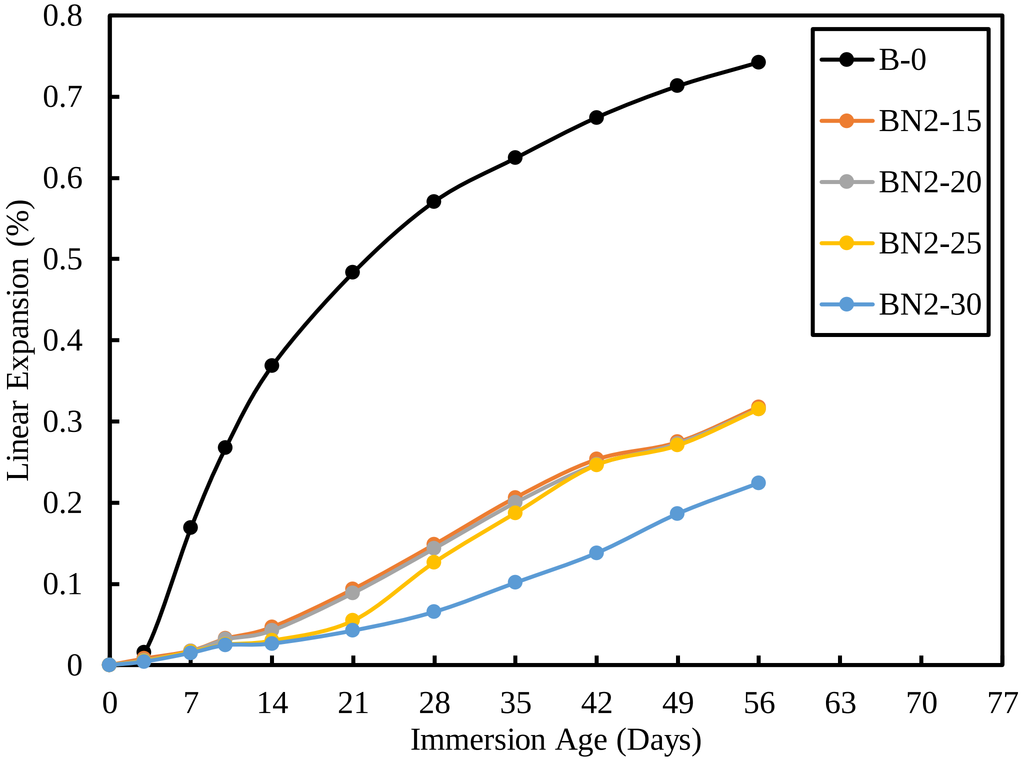


Figure 3.8: Expansion of N2 natural pozzolan mortars using aggregate source B

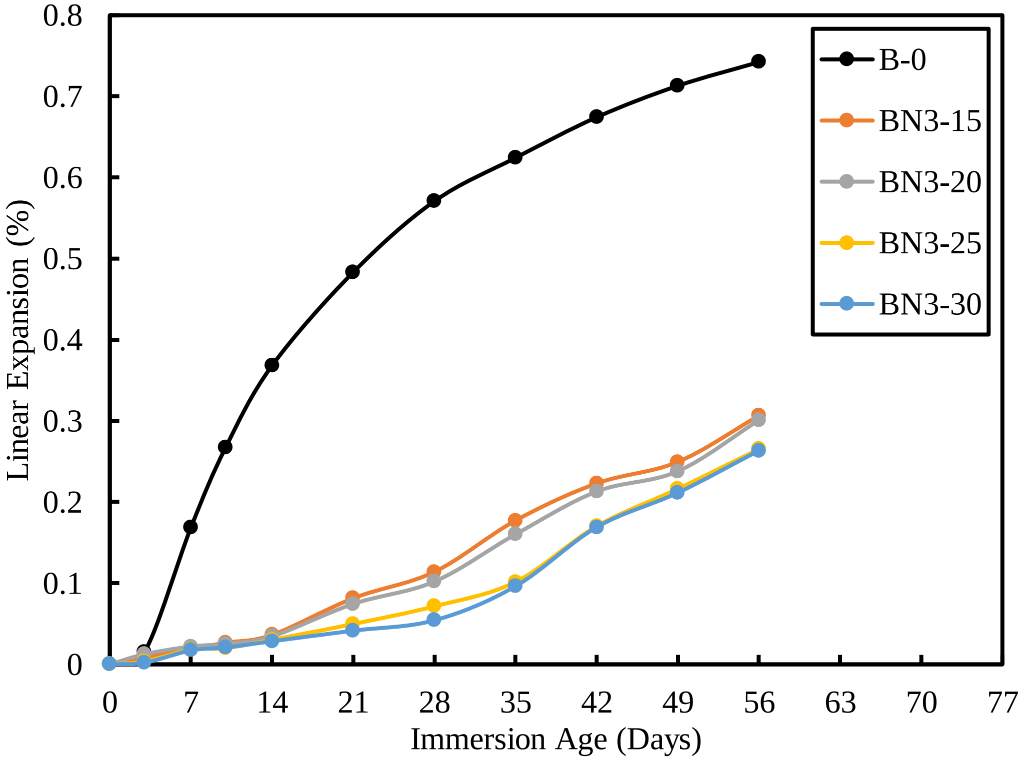


Figure 3.9: Expansion of N3 natural pozzolan mortars using aggregate source B

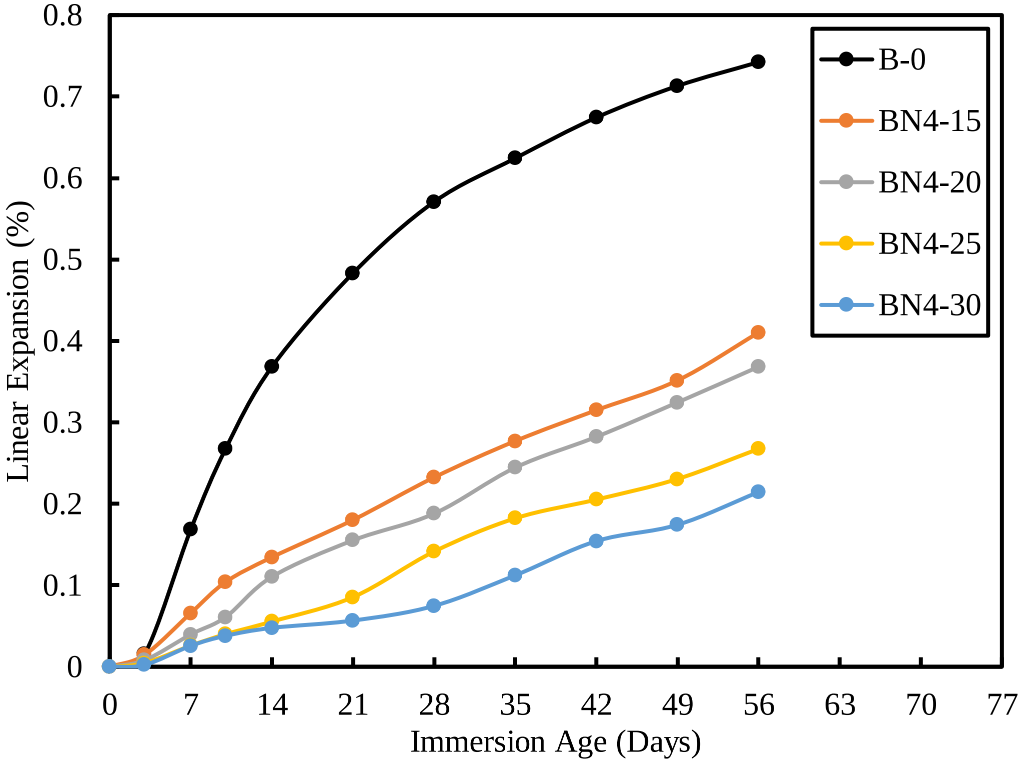


Figure 3.10: Expansion of N4 natural pozzolan mortars using aggregate source B

3.4 ASR-Induced Expansion of Mortars using Aggregate Source C

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source C are presented in Figures 3.11 through 3.14 and Tables 3.10 through 3.13, respectively. As can be seen, control mortar exhibited significantly higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansion of the control mortars were 0.5298, 0.7485 and 0.9793, respectively, all well above the respective prescribed failure limits. Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

Once N1 natural pozzolan was used, the 14-day ASR-induced expansion of the mortars reduced by 56, 79, 82, and 95%, as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansion were 41, 62, 65, and 87%; and 20, 41, 43 and 66%; respectively; for the four cement replacement levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortar shown in (Figure 3.12). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansions of the N2 natural pozzolan contained mortars reduced by 62, 67, 89 and 94%, respectively, as compare to that of control mortar. After 28 and 56 immersion ages, the decreases in expansion were 49, 50, 70, and 78%; and 29, 29, 51 and 52%; respectively.

As presented in Figures 3.13 and 3.14, the mortars cast with the N3 and N4 natural pozzolans also displayed a similar trend to that of the N1 and N2 natural pozzolans. The reductions in expansion, as compared to that of the control mortar, at the immersion ages of 14, 28, and 56 days were 63, 69, 92, and 96%; 46, 54, 79, and 85%; and 36, 37, 67, and 71% for the N3 natural pozzolan contained mortars and 92, 93, 93, and 94%; 77, 81, 88, and 89%; and 56, 63, 71, and 76% for the N4 natural pozzolan contained mortars.

On the whole, based on the failure limit of ASTM C1260, the ASR mitigation of the aggregate source C required 25% substitution of Portland cement by any of the N1, N2, and N3 natural pozzolans, and 15% of cement replacement by the N4 natural pozzolan.

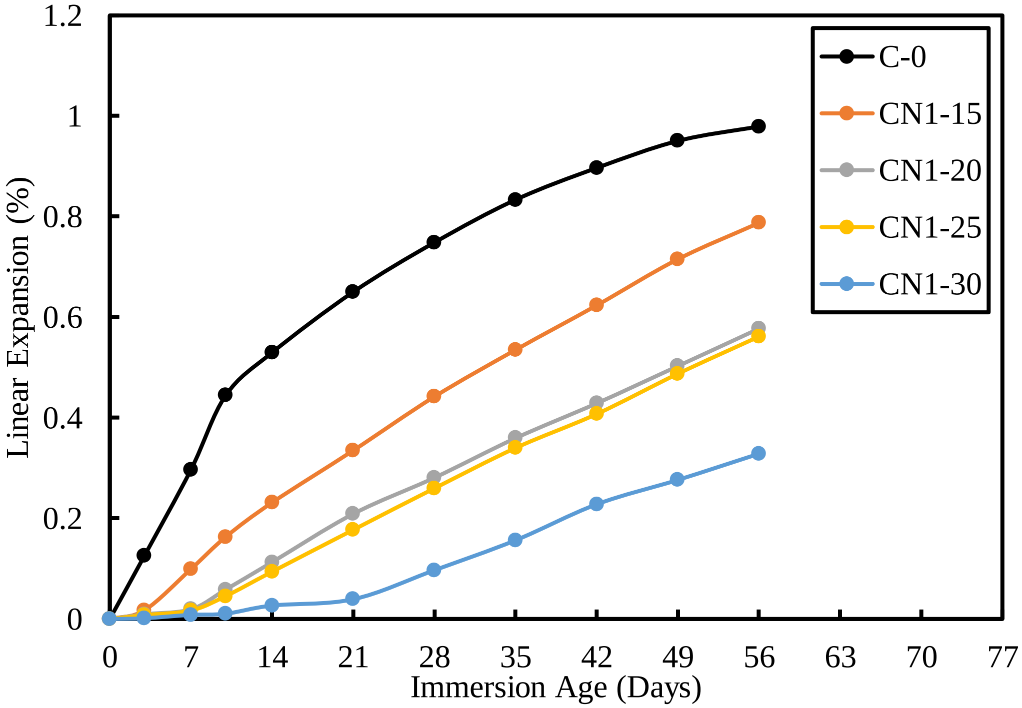


Figure 3.11: Expansion of N1 natural pozzolan mortars using aggregate source C

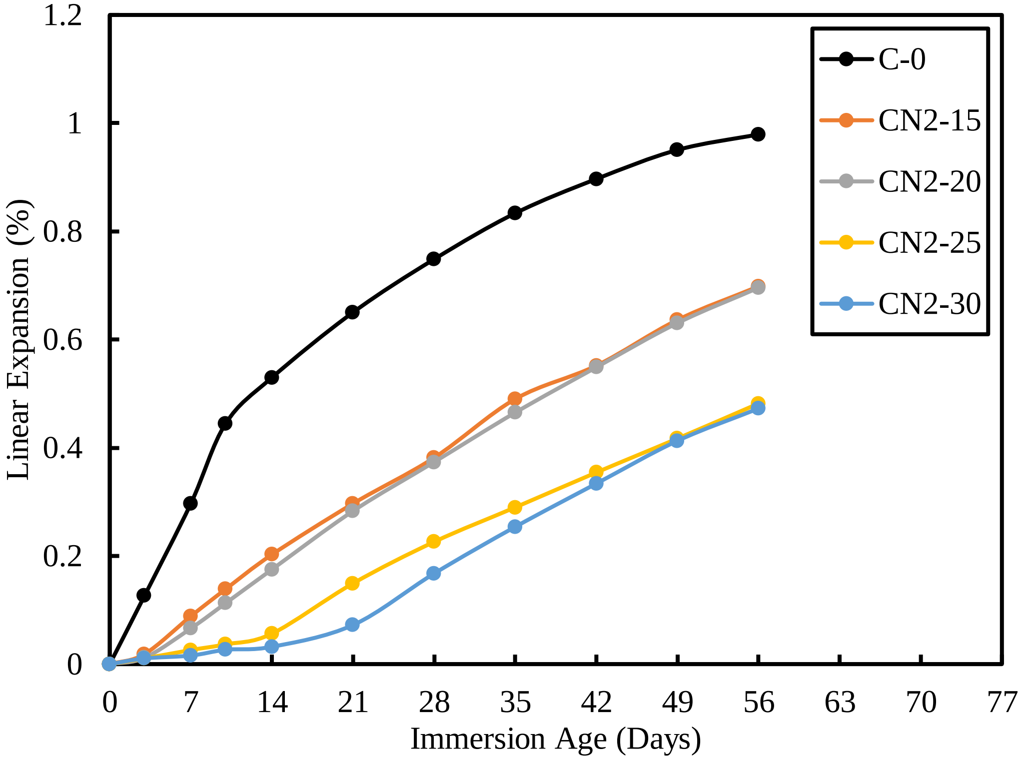


Figure 3.12: Expansion of N2 natural pozzolan mortars using aggregate source C

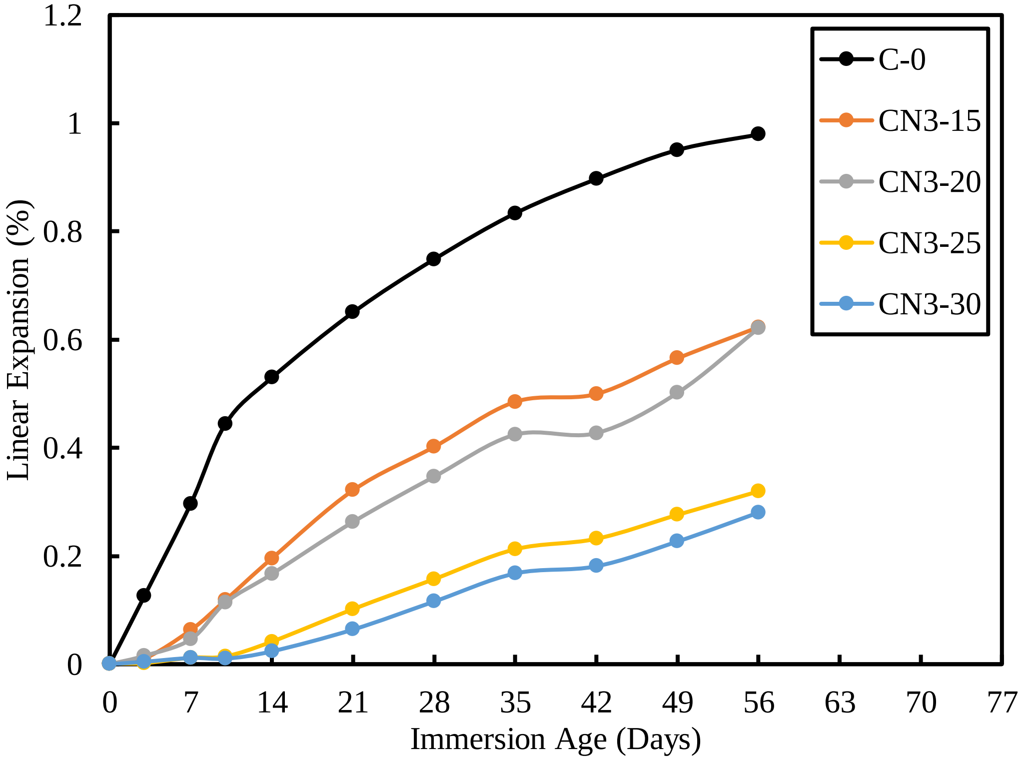


Figure 3.13: Expansion of N3 natural pozzolan mortars using aggregate source C

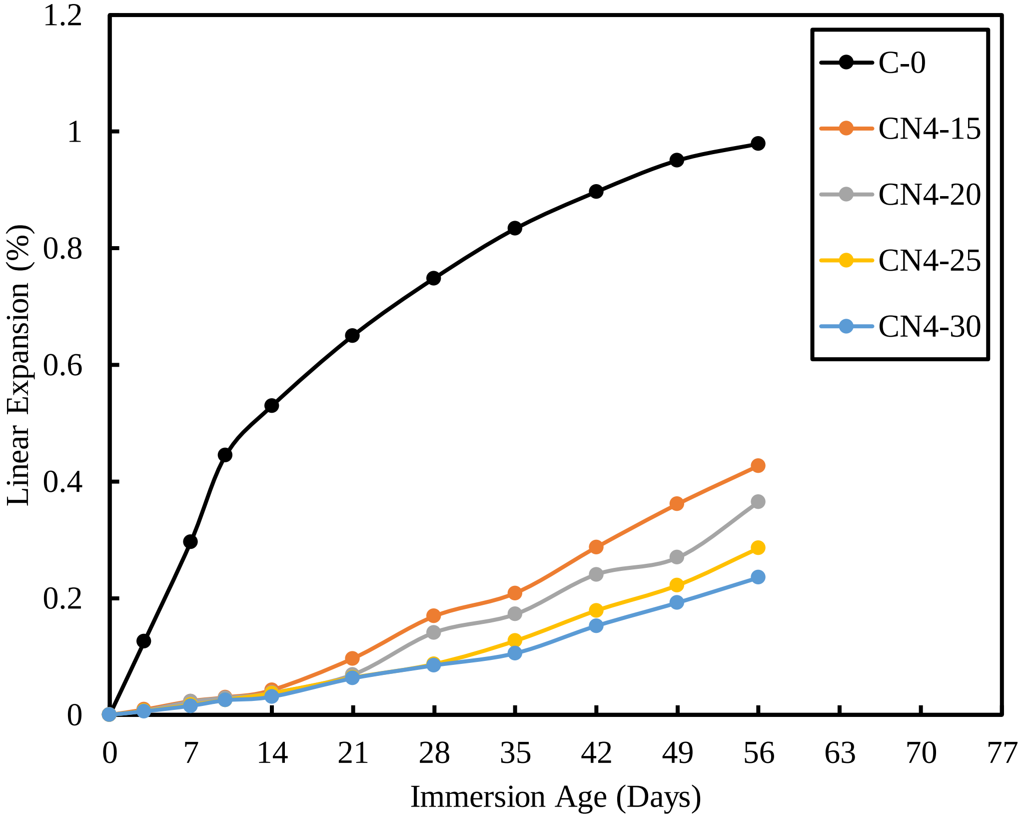


Figure 3.14: Expansion of N4 natural pozzolan mortars using aggregate source C

Table 3.10: Expansion of N1 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)				
	C-0	CN1-15	CN1-20	CN1-25	CN1-30
14	0.5298	0.2315	0.1130	0.0940	0.0268
28	0.7485	0.4420	0.2808	0.2598	0.0970
56	0.9793	0.7875	0.5773	0.5615	0.3285

Table 3.11: Expansion of N2 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)				
	C-0	CN2-15	CN2-20	CN2-25	CN2-30
14	0.5298	0.2025	0.1750	0.0563	0.0320
28	0.7485	0.3815	0.3735	0.2260	0.1675
56	0.9793	0.6983	0.6958	0.4818	0.4725

Table 3.12: Expansion of N3 natural pozzolan mortars using aggregate source C

Imm. Ages	Expansion (%)				
(Days)	C-0	CN3-15	CN3-20	CN3-25	CN3-30
14	0.5298	0.1958	0.1668	0.0418	0.0238
28	0.7485	0.4018	0.3465	0.1573	0.1158
56	0.9793	0.6230	0.6210	0.3195	0.2803

Table 3.13: Expansion of N4 natural pozzolan mortars using aggregate source C

Imm. Ages	Expansion (%)				
(Days)	C-0	CN4-15	CN4-20	CN4-25	CN4-30
14	0.5298	0.0425	0.0375	0.0370	0.0310
28	0.7485	0.1690	0.1410	0.0870	0.0847
56	0.9793	0.4270	0.3648	0.2858	0.2353

3.5

3.6 ASR-Induced Expansion of Mortars using Aggregate Source D

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source D are presented in Figures 3.15 through 3.18 and Tables 3.14 through 3.17, respectively. As can be seen, control mortar exhibited significantly higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansions of the control mortars were 0.7178, 1.021 and 1.215, respectively, all well above the respective prescribed failure limits. Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

Once N1 natural pozzolan was used, the 14-day ASR-induced expansion for the mortars reduced by 86, 90, 90, and 92% as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansion were 66, 74, 76, and 78%; and 32, 50, 51 and 52%; respectively; for the four cement replacement levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortar (Figure 3.16). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansion of the N2 natural pozzolan contained mortars reduced by 72, 76, 92 and 96%, respectively, as compare to that of control mortar. After 28 and 56 immersion ages, the decreases in expansion were 63, 63, 78, and 84%; and 43, 43, 60 and 61; respectively.

As presented in Figures 3.17 and 3.18, the mortars cast with the N3 and N4 natural pozzolans also displayed a trend comparable to that of the mortars containing N1 and N2 natural pozzolans. The reduction in expansion, as compared to that of the control mortar, at the immersion ages of 14, 28, and 56 days, were 73, 77, 94, and 97%; 61, 66, 85, and 89%; and 49, 49, 74, and 77% for the N3 natural pozzolan contained mortars and 94, 95, 95, and 96%; 83, 86, 91, and 92%; and 65, 70, 76, and 81% for the N4 natural pozzolan contained mortars.

In summary, based on the failure limit of ASTM C1260, the ASR mitigation of the aggregate source D required 15% Portland cement substitution by any of the N1, and N4 natural pozzolans, and 25% cement replacement by any of N2 and N3 natural pozzolans.

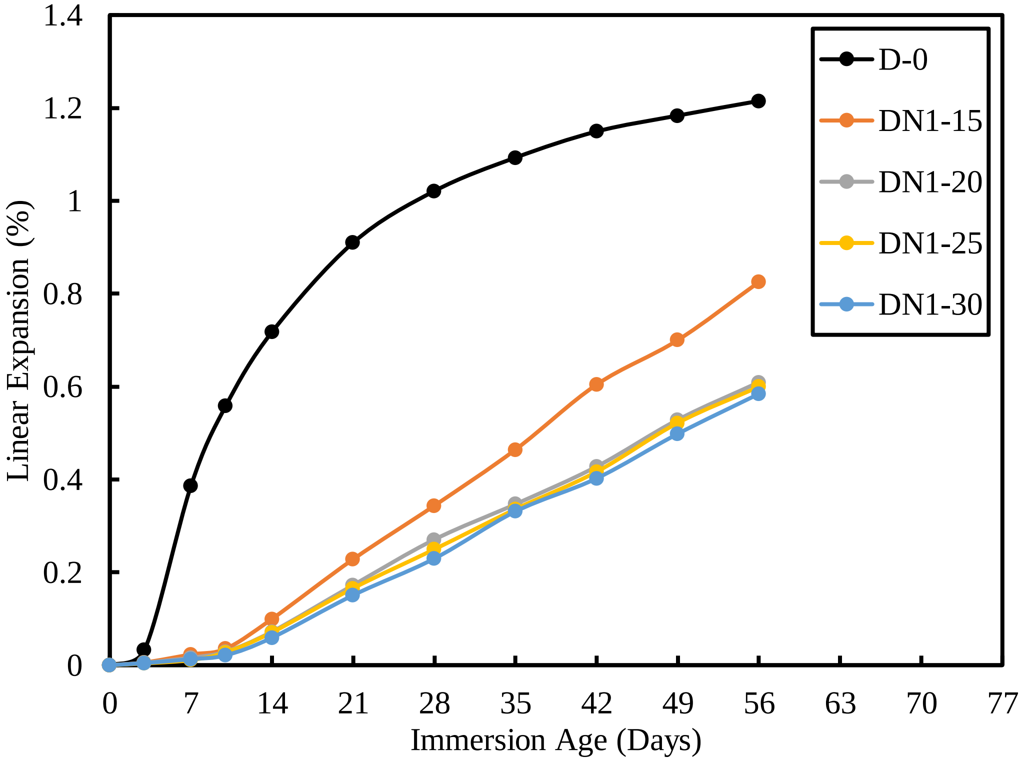


Figure 3.15: Expansion of N1 natural pozzolan mortars using aggregate source D

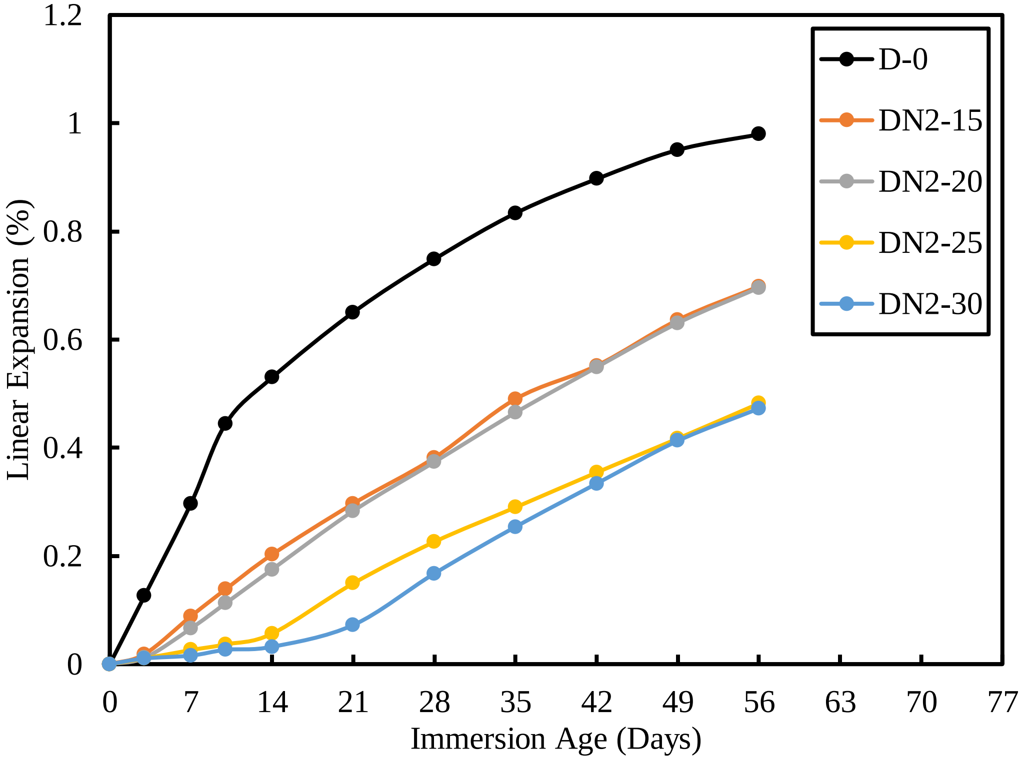


Figure 3.16: Expansion of N2 natural pozzolan mortars using aggregate source D

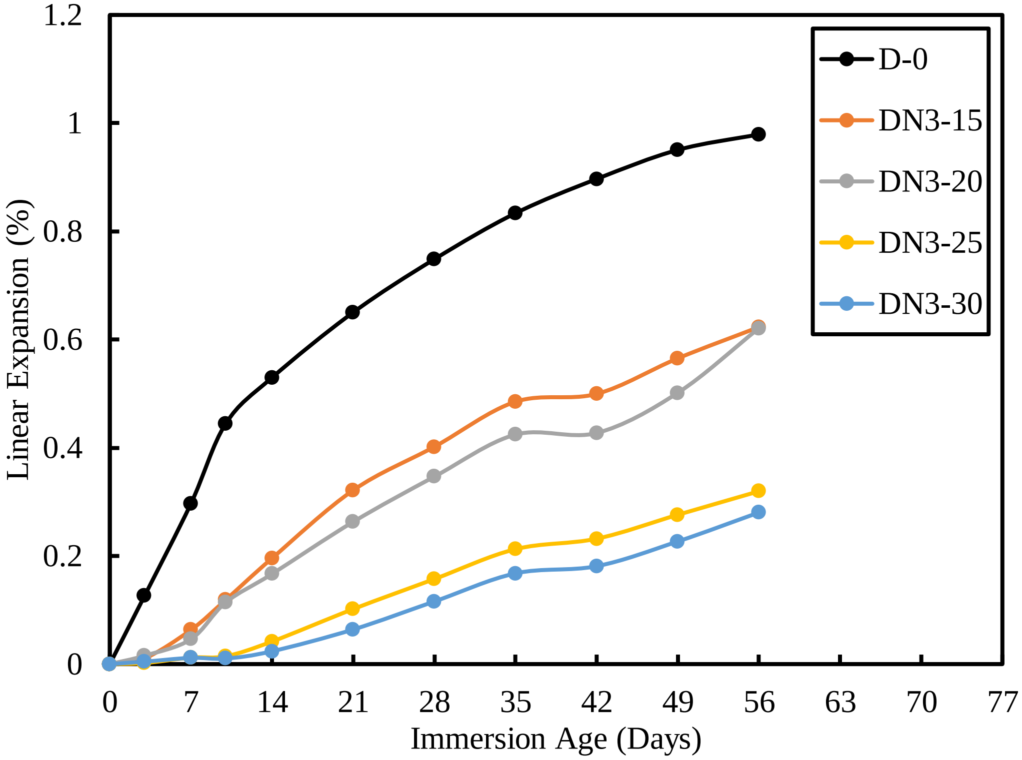


Figure 3.17: Expansion of N3 natural pozzolan mortars using aggregate source D

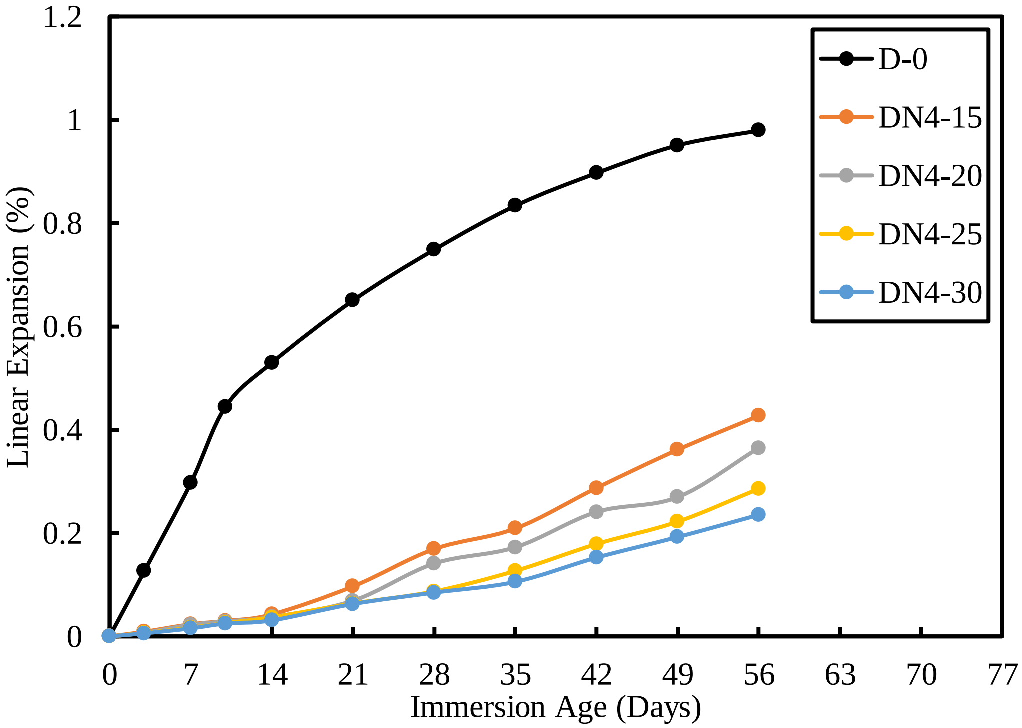


Figure 3.18: Expansion of N4 natural pozzolan mortars using aggregate source D

Table 3.14: Expansion of N1 natural pozzolan mortars using aggregate source D

Imm. Ages	Expansion (%)				
(Days)	D-0	DN1-15	DN1-20	DN1-25	DN1-30
14	0.7178	0.0997	0.0723	0.0708	0.0593
28	1.0210	0.3435	0.2705	0.2495	0.2295
56	1.2150	0.8250	0.6093	0.5995	0.5843

Table 3.15: Expansion of N2 natural pozzolan mortars using aggregate source D

Imm. Ages	Expansion (%)				
(Days)	D-0	DN2-15	DN2-20	DN2-25	DN2-30
14	0.7178	0.2025	0.1750	0.0563	0.0320
28	1.0210	0.3815	0.3735	0.2260	0.1675
56	1.2150	0.6983	0.6958	0.4818	0.4725

Table 3.16: Expansion of N3 natural pozzolan mortars using aggregate source D

Imm. Ages	Expansion (%)				
(Days)	D-0	DN3-15	DN3-20	DN3-25	DN3-30
14	0.7178	0.1958	0.1668	0.0418	0.0238
28	1.0210	0.4018	0.3465	0.1573	0.1158
56	1.2150	0.6230	0.6210	0.3195	0.2803

Table 3.17: Expansion of N4 natural pozzolan mortars using aggregate source D

Imm. Ages	Expansion (%)				
(Days)	D-0	DN4-15	DN4-20	DN4-25	DN4-30
14	0.7178	0.0425	0.0375	0.0370	0.0310
28	1.0210	0.1690	0.1410	0.0870	0.0847
56	1.2150	0.4270	0.3648	0.2858	0.2353

3.7 ASR-Induced Expansion of Mortars using Aggregate Source E

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source E are presented in Figures 3.19 through 3.22 and Tables 3.18 through 3.21, respectively. As can be seen, control mortar exhibited higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansions of the control mortars were 0.3575, 0.5275 and 0.8050, respectively, all well above the respective prescribed failure limits.

Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

Once N1 natural pozzolan was used, the 14-day ASR-induced expansion of the mortars reduced by 79, 82, 79, and 89%, as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansions were 33, 46, 50, and 57%; and 1, 10, 14 and 15%; respectively; for the four cement replacement levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortar (Figure 3.20). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansions of the N2 natural pozzolan contained mortars reduced by 82, 87, 87 and 88%, respectively, as compare to that of the control mortar. After 28 and 56 immersion ages the decreases in expansion were 55, 79, 79, and 80%; and 7, 32, 33 and 43; respectively.

As presented in Figures 3.21 and 3.22, the mortars cast with N3 and N4 natural pozzolans also displayed a trend similar to that of the mortars containing N1 and N2 natural pozzolans. The reductions in expansion, as compared to that of the control mortar, at the immersion age of 14, 28, and 56 days, were 63, 63, 86, and 85%; 19, 21, 43, and 50%; and 2, 5, 8, and 27% for the N3 natural pozzolan contained mortars and 86, 88, 89, and 89%; and 75, 77, 82, and 87%; 38, 39, 47, and 66% for the N4 natural pozzolan mortars.

On the whole, based on the ASTM C1260 failure limit, the ASR mitigation of the aggregate source E required 15% Portland cement replacement by any of the N1, N2, and N4 natural pozzolans, and 25% Portland cement substitution by N3 natural pozzolan.

Table 3.18: Expansion of N1 natural pozzolan mortars using aggregate source E

Imm. Ages	Expansion (%)				
(Days)	E-0	EN1-15	EN1-20	EN1-25	EN1-30
14	0.3575	0.0738	0.0643	0.0742	0.0390
28	0.5275	0.3515	0.2858	0.2638	0.2250
56	0.8050	0.7955	0.7220	0.6898	0.6880

Table 3.19: Expansion of N2 natural pozzolan mortars using aggregate source E

Imm. Ages	Expansion (%)				
(Days)	E-0	EN2-15	EN2-20	EN2-25	EN2-30
14	0.3575	0.0647	0.0470	0.0450	0.0420
28	0.5275	0.2360	0.1120	0.1090	0.1067
56	0.8050	0.7507	0.5463	0.5433	0.4613

Table 3.20: Expansion of N3 natural pozzolan mortars using aggregate source E

Imm. Ages	Expansion (%)				
(Days)	E-0	EN3-15	EN3-20	EN3-25	EN3-30
14	0.3575	0.1320	0.1310	0.0508	0.0550
28	0.5275	0.4293	0.4155	0.3010	0.2630
56	0.8050	0.7915	0.7680	0.7413	0.5905

Table 3.21: Expansion of N4 natural pozzolan mortars using aggregate source E

Imm. Ages	Expansion (%)				
(Days)	E-0	EN4-15	EN4-20	EN4-25	EN4-30
14	0.3575	0.0483	0.0430	0.0390	0.0385
28	0.5275	0.1323	0.1200	0.0975	0.0660
56	0.8050	0.4958	0.4940	0.4295	0.2723

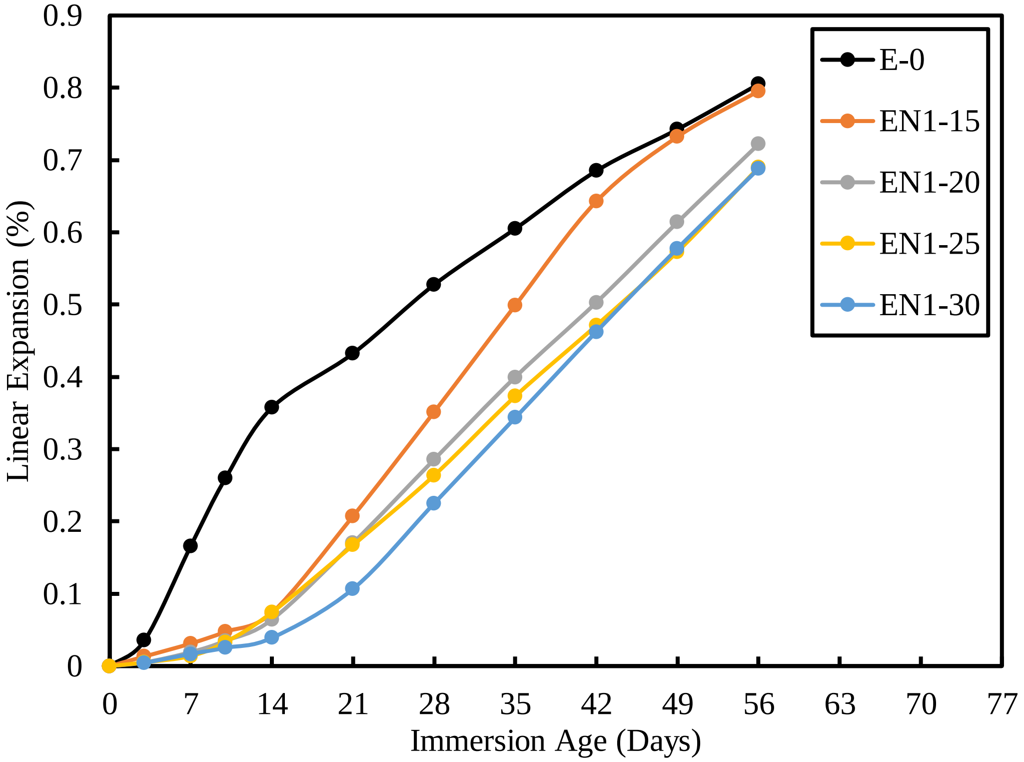


Figure 3.19: Expansion of N1 natural pozzolan mortars using aggregate source E

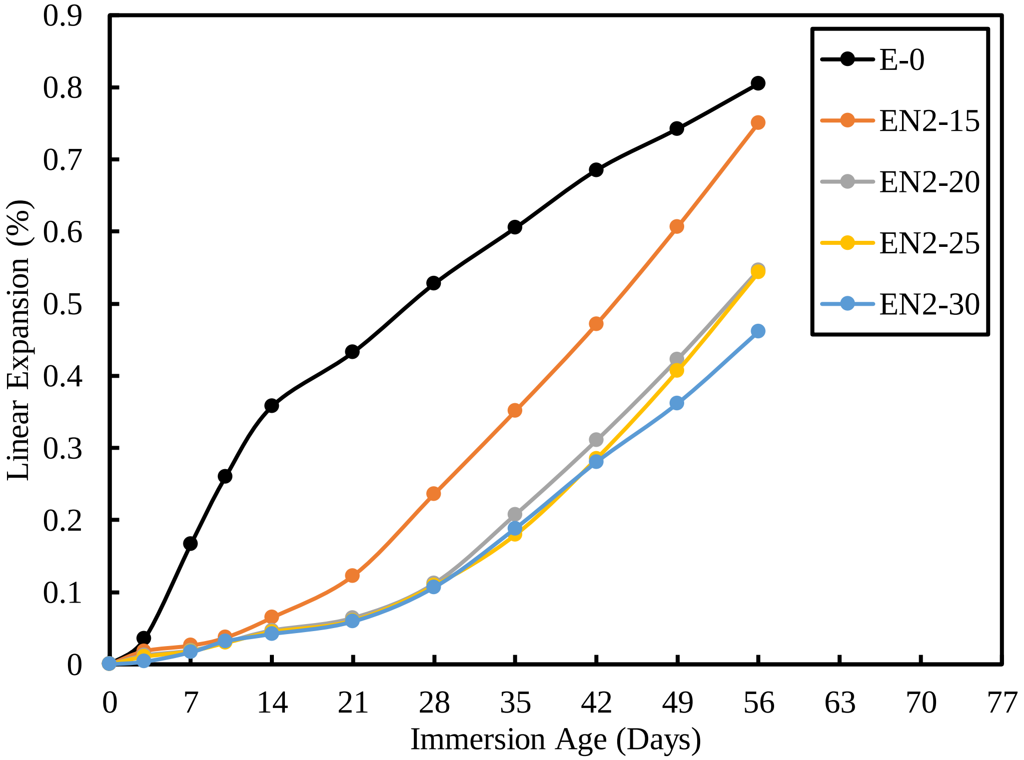


Figure 3.20: Expansion of N2 natural pozzolan mortars using aggregate source E

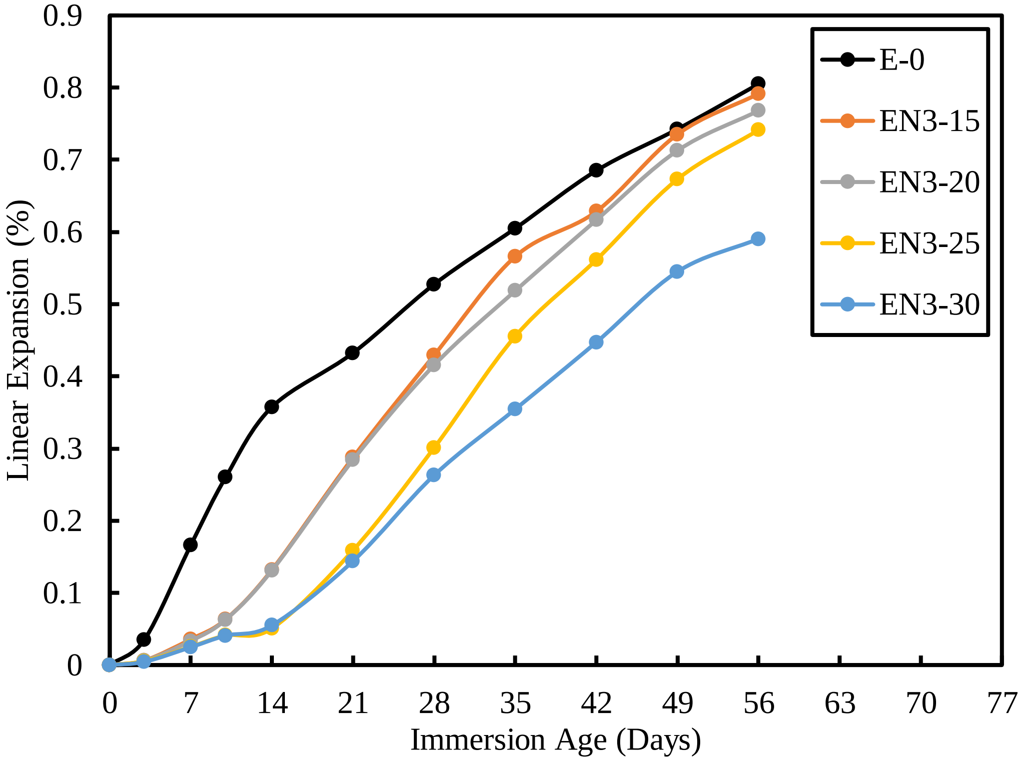


Figure 3.21: Expansion of N3 natural pozzolan mortars using aggregate source E

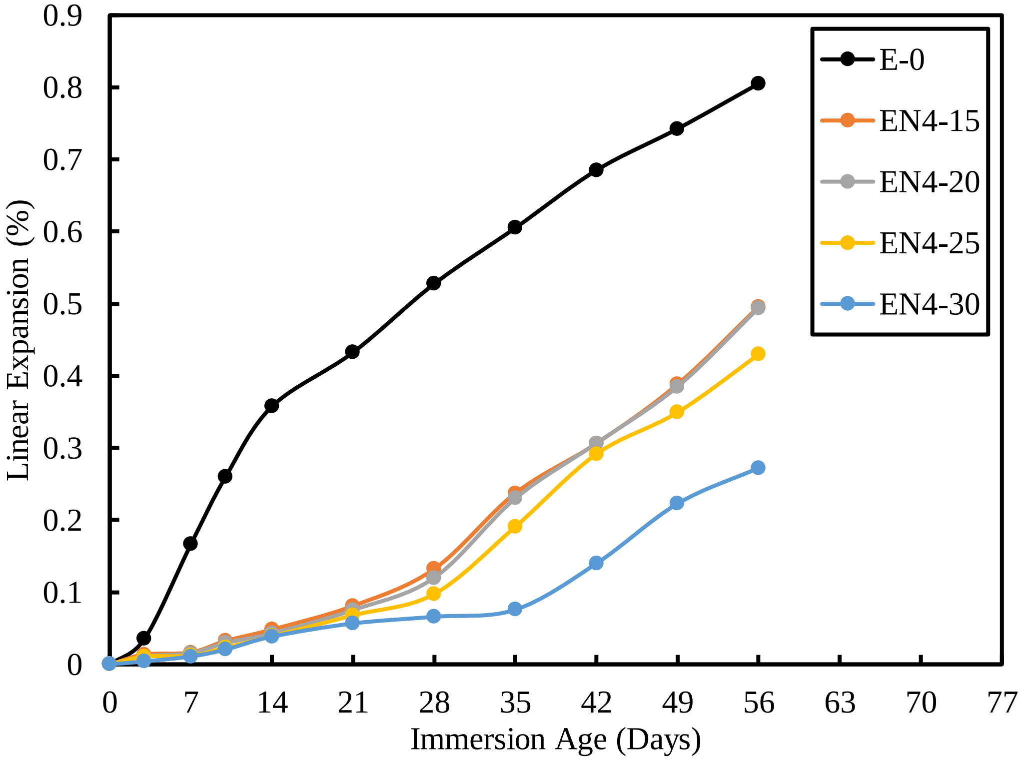


Figure 3.22: Expansion of N4 natural pozzolan mortars using aggregate source E

3.8 ASR-Induced Expansion of Mortars using Aggregate Source F

The expansions of the control and natural pozzolan contained mortar prisms at different immersion ages (up to 56 days) using N1, N2, N3, and N4 natural pozzolans and aggregate source F are presented in Figures 3.23 through 3.26 and Tables 3.22 through 3.25, respectively. As can be seen, control mortar exhibited higher expansion than the companion natural pozzolan contained mortars. The 14, 28, and 56 days expansions of the control mortars were 0.3143, 0.5655 and 0.8670, respectively, all are above the respective prescribed failure limits. Incorporation of the natural pozzolan to replace a portion of Portland cement successfully mitigated the excessive expansion of the control mortar.

When N1 natural pozzolan was used, the 14-day ASR-induced expansion of the mortars reduced by 78, 95, 95, and 96%, as compared to that of control mortar, for cement substitutions of 15, 20, 25, and 30% by weight. Once immersion age was extended to 28 and 56 days, the decreases in expansion were 65, 93, 94, and 97%; and 48, 67, 67 and 85%; respectively; for the four cement replacements levels.

The mortars containing N2 natural pozzolan produced a similar trend as N1 natural pozzolan, reducing the ASR-induced expansion when compared to that of the control mortar (Figure 3.24). For the Portland cement substitution levels of 15 through 30%, the 14-day ASR-induced expansions of the N2 natural pozzolan contained mortars reduced by 71, 85, 94 and 95%, respectively, as compared to that of control mortar. After 28 and 56 immersion ages, the decreases in expansion were 65, 74, 95, and 95%; and 56, 62, 87 and 89; respectively.

As presented in Figures 3.25 and 3.26, the mortars cast with the N3 and N4 natural pozzolans also displayed a similar trend as did the mortars containing N1 and N2 natural pozzolans. The reductions in expansion, as compared to that of the control mortar, at the immersion ages of 14, 28, and 56 days were 89, 89, 94, and 95%; 76, 78, 95, and 95%; and 67, 69, 87, and 87% for the N3 natural pozzolan mortars and 93, 94, 94, and 94%; 94, 95, 95, and 95%; and 81, 84, 87, and 88 for the N4 natural pozzolan mortars.

On the whole, based on the failure criteria of ASTM C1260 the ASR mitigation of the aggregate source F required only 15% Portland cement replacement by any of the N1, N2, N3, and N4 natural pozzolans.

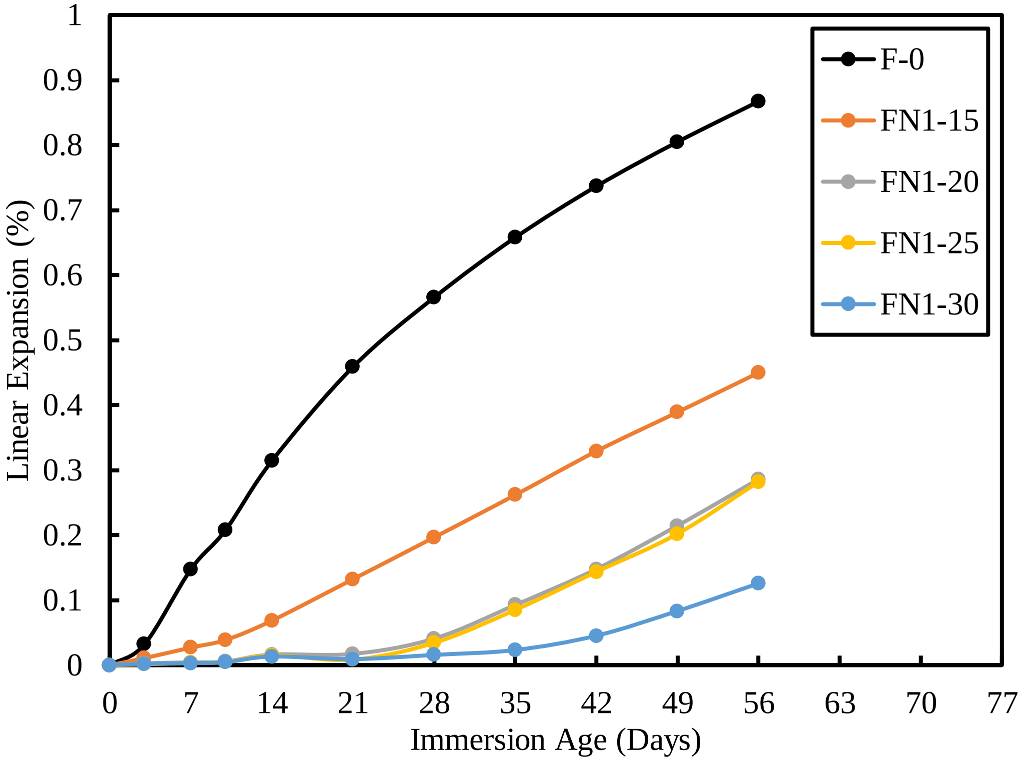


Figure 3.23: Expansion of N1 natural pozzolan mortars using aggregate source F

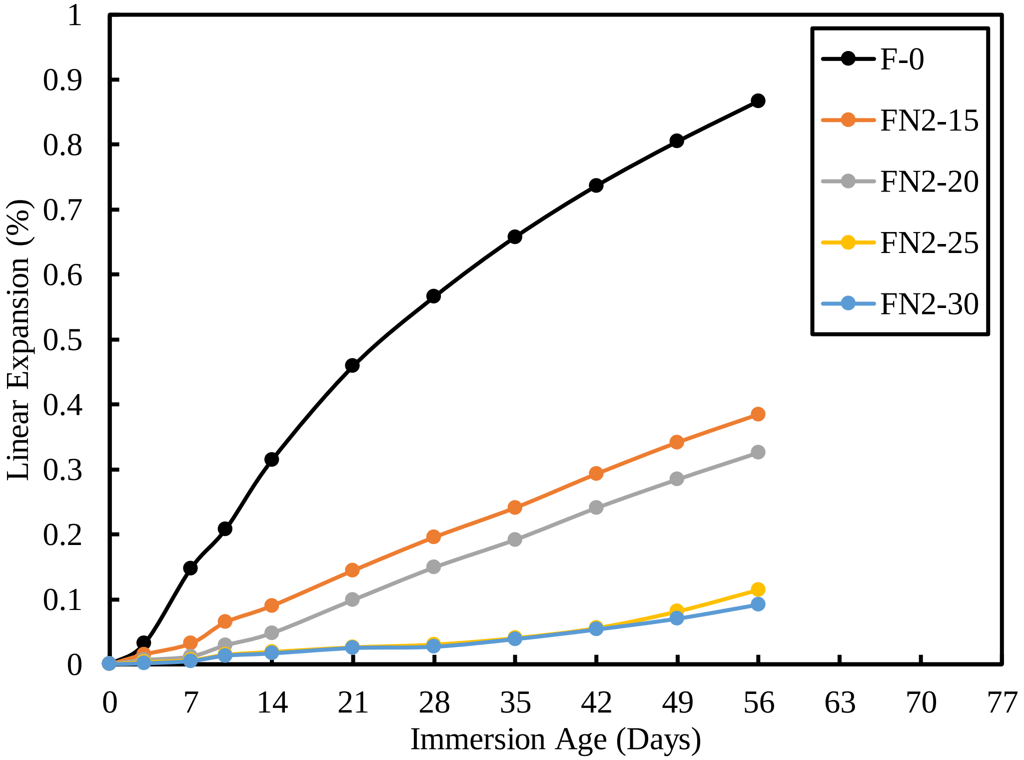


Figure 3.24: Expansion of N2 natural pozzolan mortars using aggregate source F

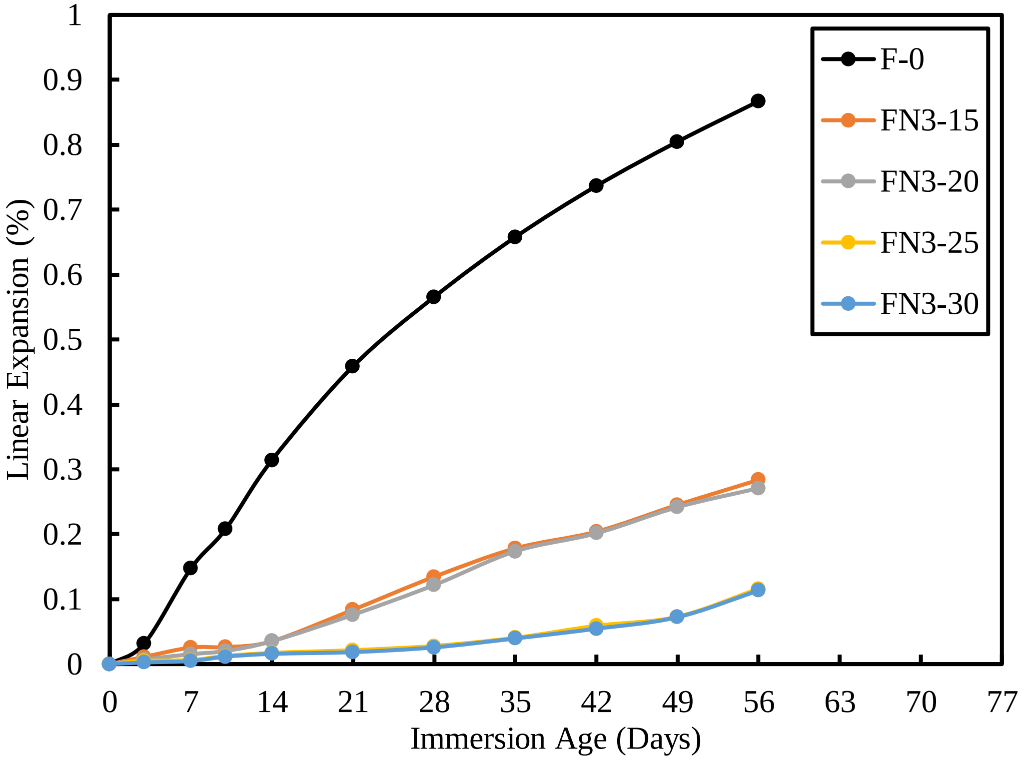


Figure 3.25: Expansion of N3 natural pozzolan mortars using aggregate source F

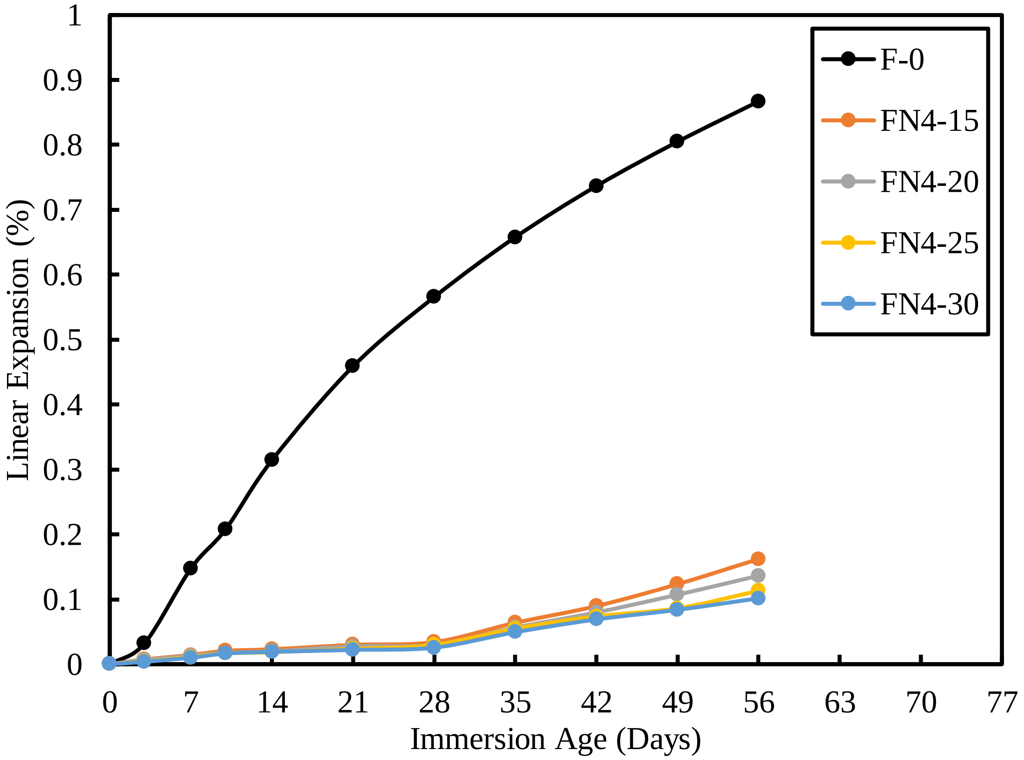


Figure 3.26: Expansion of N4 natural pozzolan mortars using aggregate source F

Table 3.22: Expansion of N1 natural pozzolan mortars using aggregate source F

Imm. Ages	Expansion (%)				
(Days)	F-0	FN1-15	FN1-20	FN1-25	FN1-30
14	0.3143	0.0685	0.0162	0.0150	0.0133
28	0.5655	0.1965	0.0408	0.0343	0.0158
56	0.8670	0.4498	0.2860	0.2820	0.1258

Table 3.23: Expansion of N2 natural pozzolan mortars using aggregate source F

Imm. Ages	Expansion (%)				
(Days)	F-0	FN2-15	FN2-20	FN2-25	FN2-30
14	0.3143	0.0900	0.0480	0.0190	0.0168
28	0.5655	0.1955	0.1490	0.0303	0.0270
56	0.8670	0.3848	0.3258	0.1145	0.0918

Table 3.24: Expansion of N3 natural pozzolan mortars using aggregate source F

Imm. Ages	Expansion (%)				
(Days)	F-0	FN3-15	FN3-20	FN3-25	FN3-30
14	0.3143	0.0353	0.0353	0.0173	0.0158
28	0.5655	0.1345	0.1218	0.0280	0.0258
56	0.8670	0.2838	0.2710	0.1160	0.1133

Table 3.25: Expansion of N4 natural pozzolan mortars using aggregate source F

Imm. Ages	Expansion (%)				
(Days)	F-0	FN4-15	FN4-20	FN4-25	FN4-30
14	0.3143	0.0230	0.0198	0.0185	0.0190
28	0.5655	0.0340	0.0300	0.0298	0.0255
56	0.8670	0.1620	0.1363	0.1130	0.1015

Chapter 4

Loss in Strength Due to Alkali-Silica Reactivity

This chapter describes the ASR-induced loss in strength of the control and natural pozzolan contained cubes made with the mortars of the six reactive aggregate sources used in this investigation. As part of this study, upon demolding, three cubes were immersed in 1N sodium hydroxide solution and kept inside an oven (temperature of 80±2°C) for a period of 90 days. In addition, three companion cubes were also maintained in a water-curing chamber (relative humidity of 100% and room temperature of 23±2°C) for a 90-day period. At the end of 90 days, cubes were removed and tested in compression. The loss in strength (LIS) were calculated by subtracting the average loss in compressive strength of the salt-cured cubes from the average loss in compressive strength of water-cured samples. The test results pertinent to loss in strength of each reactive aggregate source are discussed in the paragraphs to follow.

[redacted] 4.1 Aggregate Source A

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source A are shown in Table 4.1. As can be seen, the loss in compressive strength of the four-source natural pozzolan mortars was below that of the control mortar for all four cement replacement levels. When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of natural pozzolan contained mortars reduced averagely by 9, 22, 42, and 58%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, the loss in compressive strength decreased by averagely 33%.

Figure 4.1 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source A. In consideration of natural pozzolan source and in comparison with the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% of Portland cement replacement levels were approximately 6, 21, 42, and 61%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by 4, 9, 25, and 31%, respectively, for the similar replacement levels of Portland cement. The N3 and N4 natural pozzolans reduced the LIS by nearly 8, 23, 48, and 68%; and 20, 36, 54, 70%; respectively; as compared to the LIS of the control mortar.

On the whole, the loss in strength of the four-source natural pozzolan mortars made with the reactive aggregate source A were below that of the control mortar at all four Portland cement substitution levels used in this study.

Table 4.1: Loss in strength of mortars using aggregate source A

Portland Cement Sub. (%)	Control (%)	AN1 (%)	AN2 (%)	AN3 (%)	AN4 (%)
15	20.03	18.91	19.27	18.52	13.23
20	20.03	15.86	18.14	15.38	10.10
25	20.03	11.58	15.06	10.48	9.25
30	20.03	7.80	13.75	6.48	7.11

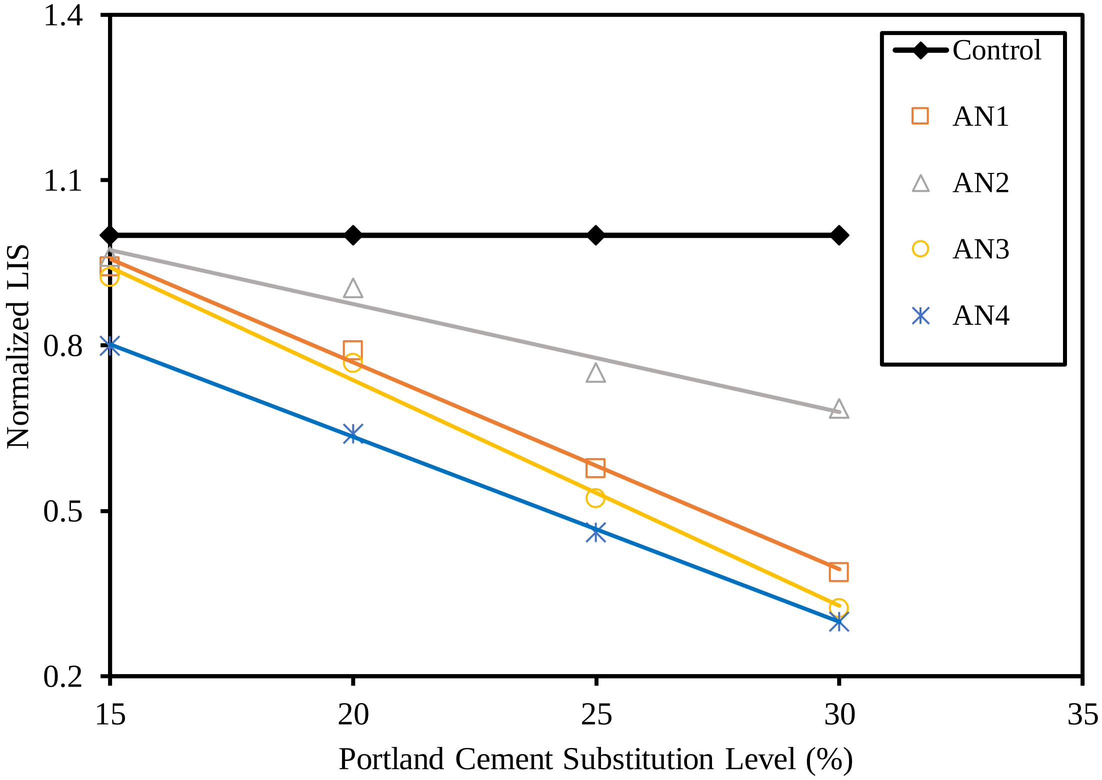


Figure 4.1: Loss in strength of mortars using aggregate source A

[redacted]4.2 Aggregate Source B

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source B are shown in Table 4.2. As can be seen, the loss in the compressive strength of the four-source natural pozzolan mortars showed mixed results when compared to that of the control mortar When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of natural pozzolan contained mortars reduced averagely by -43, -19, -3, and 14%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, loss in compressive strength decreased by nearly 13%.

Figure 4.2 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source B. In consideration of natural pozzolan source and in comparison the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% of Portland cement replacement levels were nearly -78, -40, -16, and 2%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by 8, 12, 29, and 38% respectively, for the similar replacements of Portland cement. The N3 and N4 natural pozzolans reduced the LIS by nearly -86, -51, -35, and -10%; and -18, 3, 12, 28%; respectively; as compared to the LIS of the control mortar.

On the whole, natural pozzolan sources N2 and N4 mortars produced losses in strength below that of the control mortars, whereas the mortars containing natural pozzolan sources N1 and N3 did the contrary.

Table 4.2: Loss in strength of mortars using aggregate source B

Portland Cement Sub. (%)	Control (%)	BN1 (%)	BN2 (%)	BN3 (%)	BN4 (%)
15	19.75	35.15	18.08	36.64	23.26
20	19.75	27.61	17.29	29.82	19.22
25	19.75	22.87	14.11	26.74	17.34
30	19.75	19.42	12.19	21.74	14.27

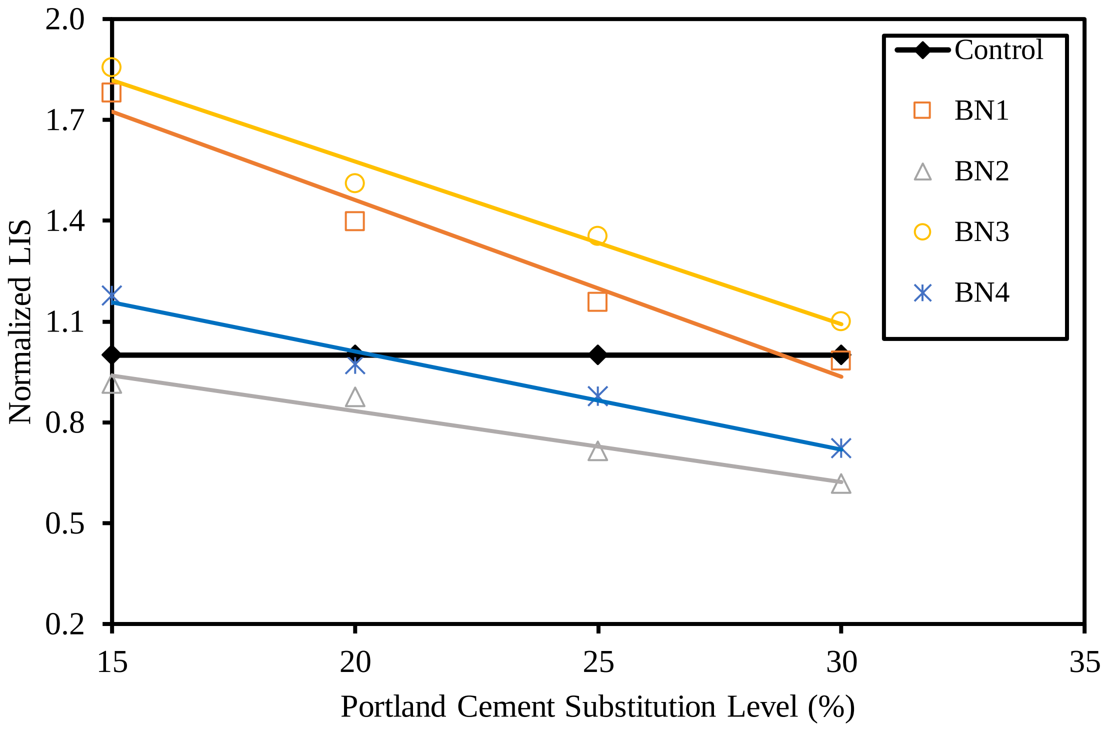


Figure 4.2: Loss in strength of mortars using aggregate source B

[redacted] 4.3 Aggregate Source C

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with reactive aggregate source C are shown in Table 4.3. As can be seen, the loss in compressive strength of the four-source natural pozzolan mortars showed mixed results when compared to that of the control mortar which was 28%. When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of the natural pozzolan contained mortars reduced averagely by -19, -11, 1, and 13%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, the loss in compressive strength increased by approximately -4%.

Figure 4.3 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source C. In consideration of natural pozzolan source and in comparison with the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% Portland cement replacement levels were lower by averagely -30, -22, -13, and 5%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by -15, -6, 5, and 15% respectively, for the similar replacements levels of Portland cement. The N3 and N4 natural pozzolan reduced the LIS by nearly 14, 22, 37, and 54%; and -45, -38, -25, -24%; respectively; as compared to the LIS of the control mortar.

On the whole, natural pozzolan source N4 generated LIS below that of the control at all levels of Portland cement replacement. On the other hand, control mortar mostly produced lower loss in strength as compared to those of the mortars containing natural pozzolan sources N1, N2, or N3.

Table 4.3: Loss in strength of mortars using aggregate source C

Portland Cement Sub. (%)	Control (%)	CN1 (%)	CN2 (%)	CN3 (%)	CN4 (%)
15	28.00	36.40	32.31	23.94	40.49
20	28.00	34.07	29.67	21.76	38.68
25	28.00	31.61	26.64	17.66	35.05
30	28.00	26.60	23.73	12.99	34.61

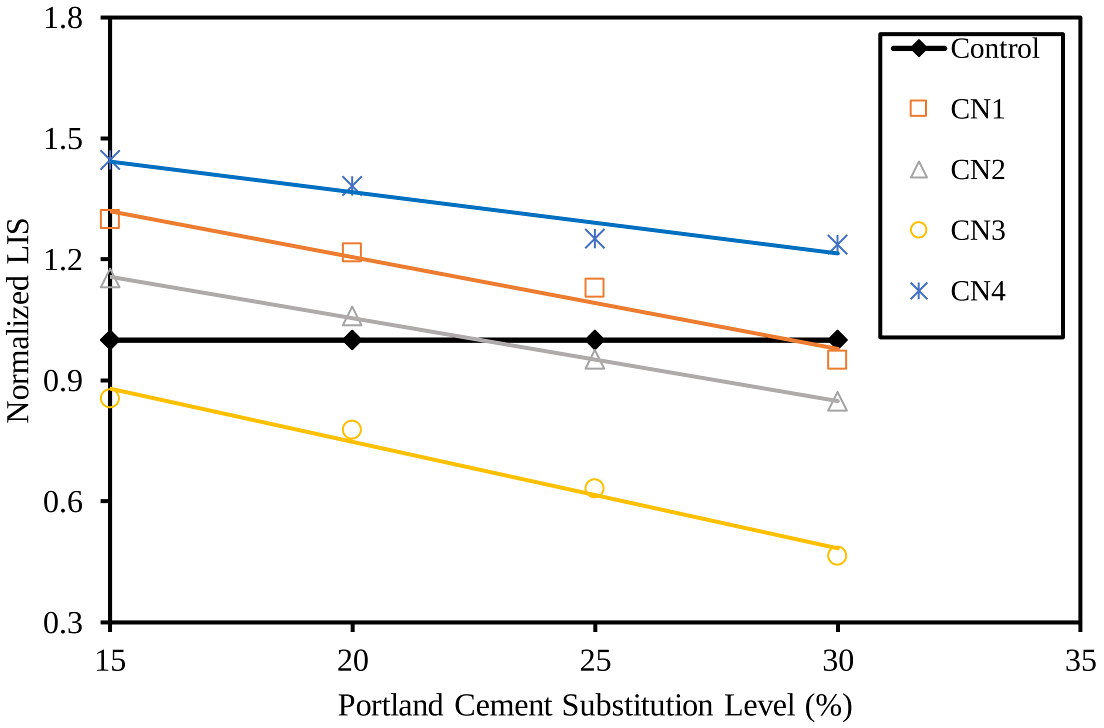


Table 4.3: Loss in strength of mortars using aggregate source C

[redacted]4.4 Aggregate Source D

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source D are shown in Table 4.4. As can be seen, the loss in compressive strength of the four-source natural pozzolan mortars was below that of the control mortar for nearly all four cement substitution levels used in this study. When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of natural pozzolan contained mortars reduced averagely by 3, 21, 31, and 42%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, the loss in compressive strength decreased by averagely 24%.

Figure 4.4 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source D. In consideration of natural pozzolan source and in comparison with the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% Portland cement replacement were lower by nearly 30, 38, 44, and 58%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by -15, 7, 16, and 27%, respectively, for the similar replacement level of Portland cement. The N3 and N4 natural pozzolan reduced the LIS by nearly 1, 20, 40, and 45%; and -5, 17, 25, 38%; respectively; as compared to the LIS of the control mortar.

On the whole with the exception of DN2 at 15% by weight of cement replacement, the loss in strength of the four-source natural pozzolan mortars made with the reactive aggregate source D were all below that of the control mortar for the four Portland cement substitution levels used in this study.

Table 4.4: Loss in strength of mortars using aggregate source D

Portland Cement Sub. (%)	Control (%)	DN1 (%)	DN2 (%)	DN3 (%)	DN4 (%)
15	33.23	23.26	38.22	32.98	34.76
20	33.23	20.51	30.77	26.59	27.69
25	33.23	18.74	27.91	20.02	25.07
30	33.23	13.97	24.30	18.28	20.66

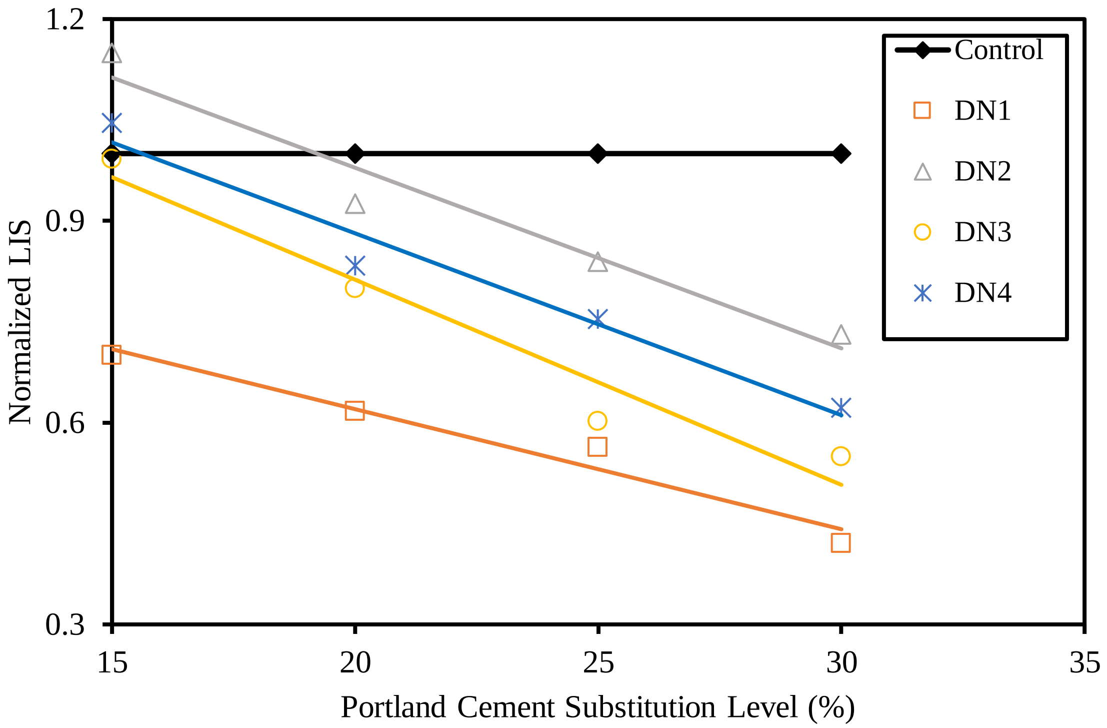


Figure 4.4: Loss in strength of mortars using aggregate source D

[redacted] 4.5 Aggregate Source E

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source E are shown in Table 4.5. As can be seen, the loss in compressive strength of the four- source natural pozzolan mortars was below that of the control mortar recorded at the LIS of 58%. When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of the four-source natural pozzolan contained mortars reduced averagely by 1, 10, 20, and 26%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, the loss in compressive strength decreased by an average of 14%.

Figure 4.5 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source E. In consideration of natural pozzolan source and in comparison with the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% Portland cement replacement levels were lower by nearly -5, -4, 11, and 17%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by 2, 5, 10, and 20%, respectively, for the similar replacements of Portland cement. The N3 and N4 natural pozzolans reduced the LIS by nearly 14, 23, 35, and 44%; and -5, 14, 22, 23%; respectively; as compared to the LIS of the control mortar.

On the whole, the loss in strength of the four-source natural pozzolan mortars made with the reactive aggregate E were below that of the control mortar for the four Portland cement substitution levels used in this investigation.

Table 4.5: Loss in strength of mortars using aggregate source E

Portland Cement Sub. (%)	Control (%)	EN1 (%)	EN2 (%)	EN3 (%)	EN4 (%)
15	58.40	61.42	57.46	50.22	61.32
20	58.40	60.63	55.27	44.97	49.95
25	58.40	51.77	52.56	38.05	45.53
30	58.40	48.47	46.72	32.68	44.97

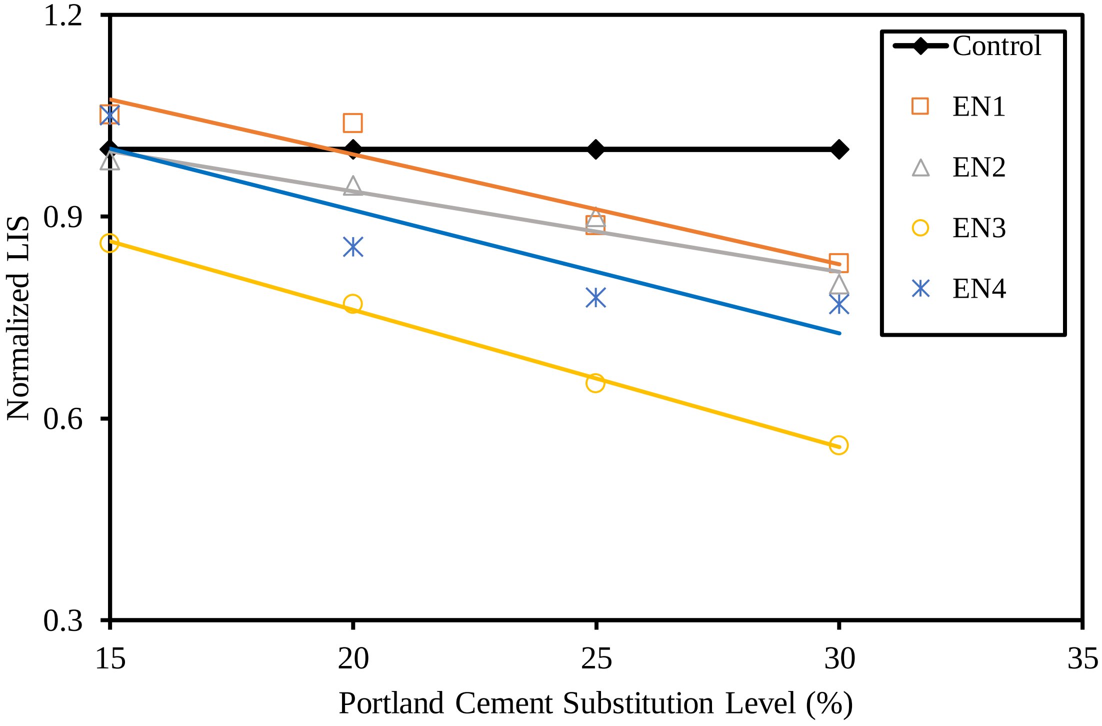


Figure 4.5: Loss in strength of mortars using aggregate source E

[redacted]4.6 Aggregate Source F

The losses in strength (LIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source F are shown in Table 4.6. As can be seen, the loss in the compressive strength of the four-source natural pozzolan mortars was below that of the control mortar for nearly all four Portland amount substitution levels. When natural pozzolan replaced 15, 20, 25, and 30% of Portland cement, the losses in compressive strength of natural pozzolan contained mortars reduced averagely by 12, 20, 31, and 48%, respectively. On the whole, for every 5% increase in substitution of Portland cement, from 15 to 30%, the loss in compressive strength decreased by averagely 28%.

Figure 4.6 represents the normalized loss in strength (NLIS) of the control and natural pozzolan contained cubes made with the reactive aggregate source F. In consideration of natural pozzolan source and in comparison, with the control mortar, the decreases of loss in compressive strength at the levels of 15, 20, 25, and 30% Portland cement replacement levels were lower by approximately 27, 35, 48, and 57%, respectively, when N1 natural pozzolan was used. The use of N2 natural pozzolan resulted in the reduced LIS by -23, -6, 5, and 32%, respectively, for the similar replacements of Portland cement. The N3 and N4 natural pozzolans reduced the LIS by nearly 40, 45, 60, and 68%; and 2, 8, 12, 33%; respectively; as compared to the LIS of the control mortar.

With the exception of the natural pozzolan contained mortars FN2 at 15 and 20% by weight of Portland cement substitutions, on the whole, the loss in strength of the four-source natural pozzolan mortars made with the reactive aggregate F were below that of the control mortar for the remaining four Portland cement substitution levels used in this study.

Table 4.6: Loss in strength of mortars using aggregate source F

Portland Cement Sub. (%)	Control (%)	FN1 (%)	FN2 (%)	FN3 (%)	FN4 (%)
15	30.07	21.81	37.11	17.94	29.54
20	30.07	19.62	31.78	16.67	27.68
25	30.07	15.64	28.54	11.93	26.47
30	30.07	12.93	20.43	9.51	20.10

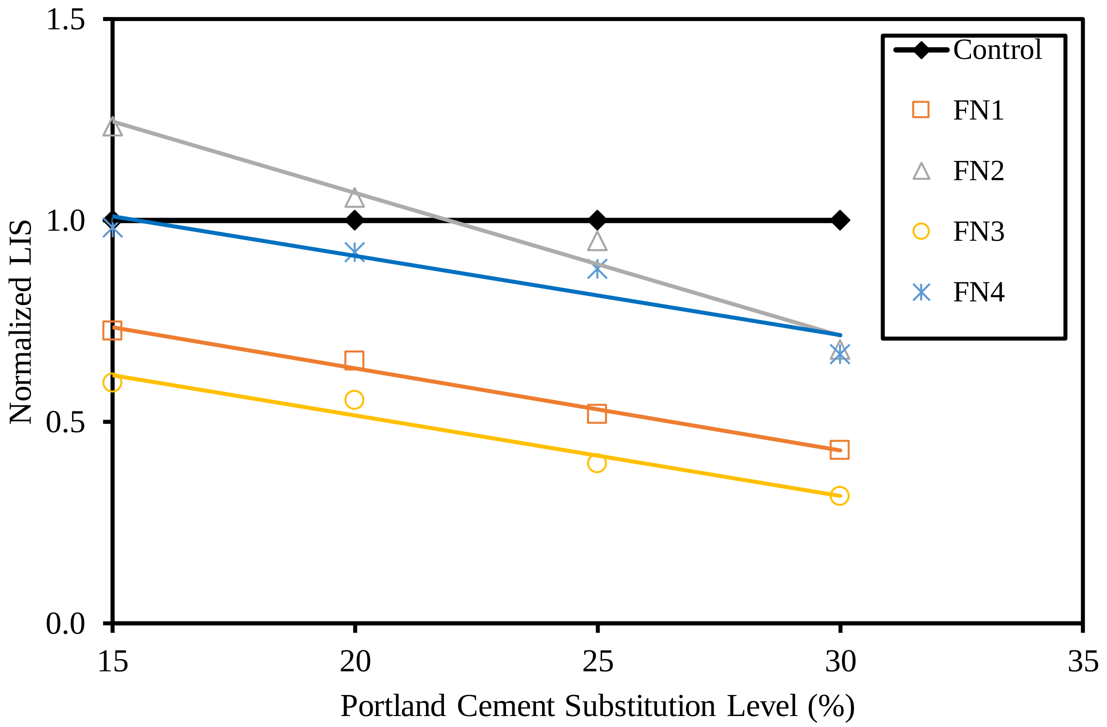


Figure 4.6: Loss in strength of mortars using aggregate source F

[redacted] 4.7 Effect of Pozzolan Type and Replacement Level on LIS

The average loss in strength (LIS) of the natural pozzolan contained cubes made with the reactive aggregate of all sources are shown in Table 4.7. As can be seen, the loss in the compressive strength of the four-source natural pozzolan mortars was mainly similar with the standard deviations of 1.87%, 2.04, 2.93, and 3.08%, respectively, when Portland cement was replaced at the levels of 15, 20, 25, and 30%. For all four natural pozzolans at the 20, 25, and 30% replacement level of Portland cement, the average loss in compressive strength of the four-source natural pozzolan mortars were lower than that of the control irrespective of the natural pozzolan source. On the other hand, no significant differences were observed when 15% Portland cement was replaced with the four natural pozzolans.

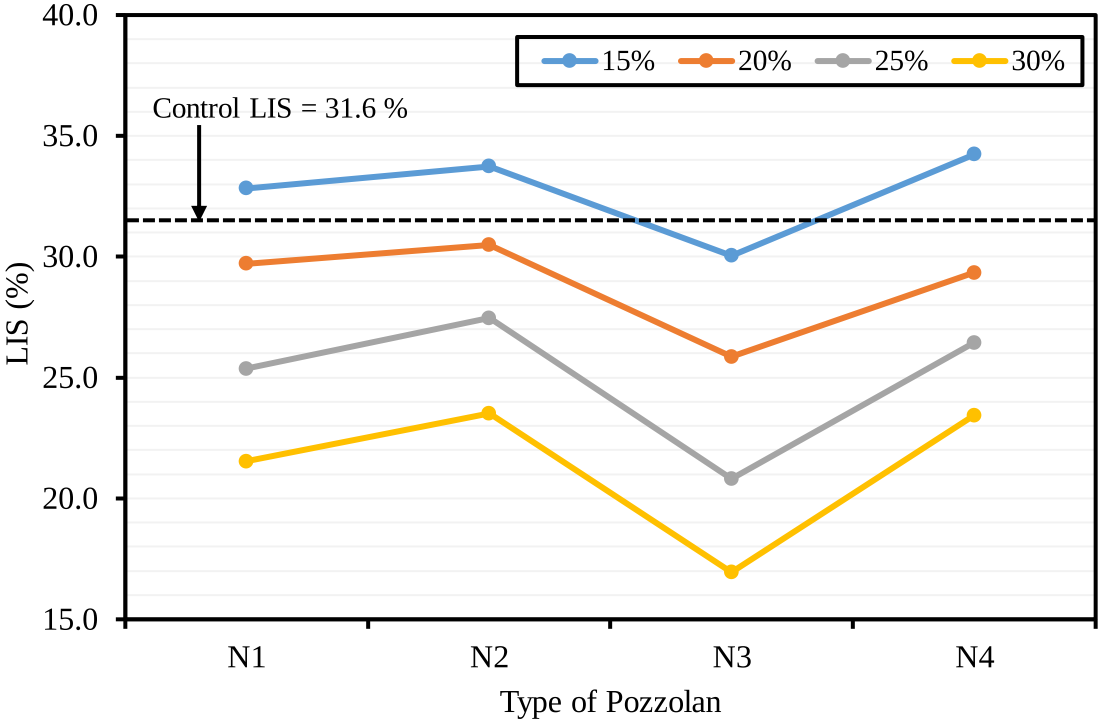


Figure 4.7: Effect of pozzolan type on average loss in strength

Chapter 5

Comparison of Industrial and Natural Pozzolans

The goal of this chapter is to compare the effectiveness of the utilized industrial (Class F fly Ash) and natural pozzolans in mitigating alkali-silica reactivity. The discussion of each reactive aggregates sources are characterized by both ASR-induced expansion and 90-day loss in compressive strength.

5.1 Comparison of ASR-Induced Expansions

5.1.1 Aggregate Source A

The expansions due to alkali-silica reactivity of the aggregate source A mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.1 through 5.4 and Figures 5.1 through 5.4. As can be seen, both Class F fly ash and 4-source natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. Overall, the four natural pozzolan sources utilized in this study were more effective in the reduction of alkali-silica reactivity of mortars made with aggregate source A when compared to that of the companion mortars containing Class F fly ash.

In the case of natural pozzolan N1, the expansions due to alkali-silica reactivity of the natural pozzolan contained mortars were lower than that of the fly ash contained mortars using the four levels of cement substitution. As shown in Table 5.1, at 14-day immersion age, natural pozzolan N1 reduced ASR-induced expansion averagely by 26, 38, 20, and 47% for cement substitution levels of 15, 20, 25, and 30%, respectively, when compared to the companion Class F fly ash mortars. The superior performance of N1 natural pozzolan mortars, over that of Class F fly ash mortars, in mitigating alkali-silica reactivity was also evident at the immersion ages of 28 and 56 days. The reduction of expansion at these two immersion ages were averagely 18, 40, 20, and 64%; and 14, 23, 24, and 49%; respectively.

The incorporation of N2 natural pozzolan in the mortars containing aggregate source A resulted in an overall better performance in reducing ASR expansion than when Class F fly ash was used. As cement substitution level increased, the gap between the expansions of the two pozzolan types increased. On the average and in comparison with the Class F fly ash, N2 natural pozzolan reduced ASR-induced expansion of the mortars containing aggregate source A by nearly 45, -9, 9, and 15%; -1, -2, 26, and, 11%; and 15, 3, 14, and 33% at the immersion ages of 14, 28 and 56 days; respectively.

Once N3 natural pozzolan was used, both of these two pozzolan types displayed nearly similar results in mitigating the ASR expansion of the studied mortars made with aggregate source A at the immersion age of 14 days. When immersion age was extended to 28 and 56 days, the expansion of N3 natural pozzolan mortars were lower averagely, than the equivalent Class F fly ash mortars, by approximately 24, 13, 2, and -14%; and 23, 23, 41, and 41%; respectively; for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

When N4 natural pozzolan was used to prepare mortars containing aggregate source A, the resulting ASR-induced expansions were well below that of Class F fly ash mortars at the three critical immersion ages. At 14 days, N4 natural pozzolan mitigated the alkali silica reactivity of the reactive aggregate source A better than the Class F fly ash by averagely 71, 58, 38, and 42% for the Portland cement replacement levels of 15, 20, 25, and 30%, respectively. For the immersion ages of 28 and 56 days, these reductions were 82, 80, 69, and 68%; and 59, 49, 38, and 50%; respectively.

Table 5.1: Expansion of industrial and N1 natural pozzolan mortars using aggregate source A

Imm. Ages (Days)	Expansion (%)								
	A-0	AF-15	AF-20	AF-25	AF-30	AN1-15	AN1-20	AN1-25	AN1-30
14	0.2550	0.1043	0.0508	0.0307	0.0250	0.0775	0.0315	0.0245	0.0133
28	0.4263	0.2923	0.2078	0.1238	0.1000	0.2410	0.1243	0.0985	0.0363
56	0.6750	0.6190	0.4893	0.3988	0.3908	0.5318	0.3775	0.3043	0.1985

Table 5.2: Expansion of industrial and N2 natural pozzolan mortars using aggregate source A

Imm. Ages (Days)	Expansion (%)								
	A-0	AF-15	AF-20	AF-25	AF-30	AN2-15	AN2-20	AN2-25	AN2-30
14	0.2550	0.1043	0.0508	0.0307	0.0250	0.0578	0.0555	0.0278	0.0212
28	0.4263	0.2923	0.2078	0.1238	0.1000	0.2965	0.2125	0.0915	0.0890
56	0.6750	0.6190	0.4893	0.3988	0.3908	0.5243	0.4725	0.3448	0.2610

Table 5.3: Expansion of industrial and N3 natural pozzolan mortars using aggregate source A

Imm. Ages (Days)	Expansion (%)								
	A-0	AF-15	AF-20	AF25	AF-30	AN3-15	AN3-20	AN3-25	AN3-30
14	0.2550	0.1043	0.0508	0.0307	0.0250	0.0680	0.0538	0.0275	0.0260
28	0.4263	0.2923	0.2078	0.1238	0.1000	0.2213	0.1798	0.1208	0.1143
56	0.6750	0.6190	0.4893	0.3988	0.3908	0.4770	0.3745	0.2338	0.2293

Table 5.4: Expansion of industrial and N4 natural pozzolan mortars using aggregate source A

Imm. Ages (Days)	Expansion (%)								
	A-0	AF-15	AF-20	AF-25	AF-30	AN4-15	AN4-20	AN4-25	AN4-30
14	0.2550	0.1043	0.0508	0.0307	0.0250	0.0305	0.0212	0.0190	0.0145
28	0.4263	0.2923	0.2078	0.1238	0.1000	0.0533	0.0413	0.0378	0.0320
56	0.6750	0.6190	0.4893	0.3988	0.3908	0.2558	0.2515	0.2460	0.1965

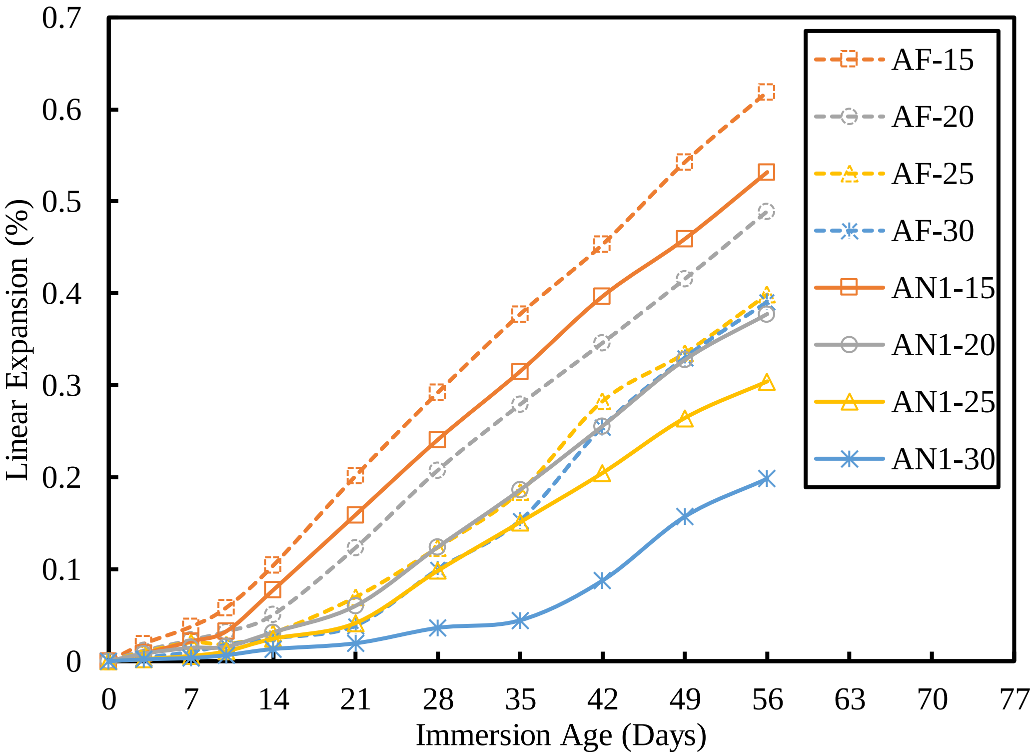


Figure 5.1: Expansion of industrial and N1 natural pozzolan mortars using aggregate source A

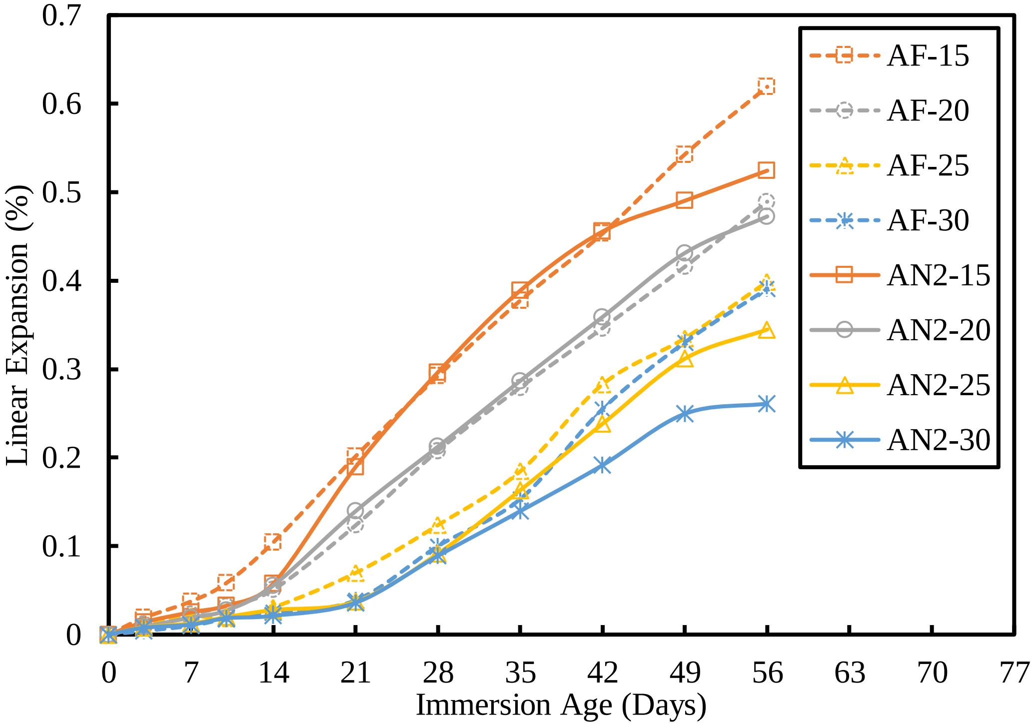


Figure 5.2: Expansion of industrial and N2 natural pozzolan mortars using aggregate source A

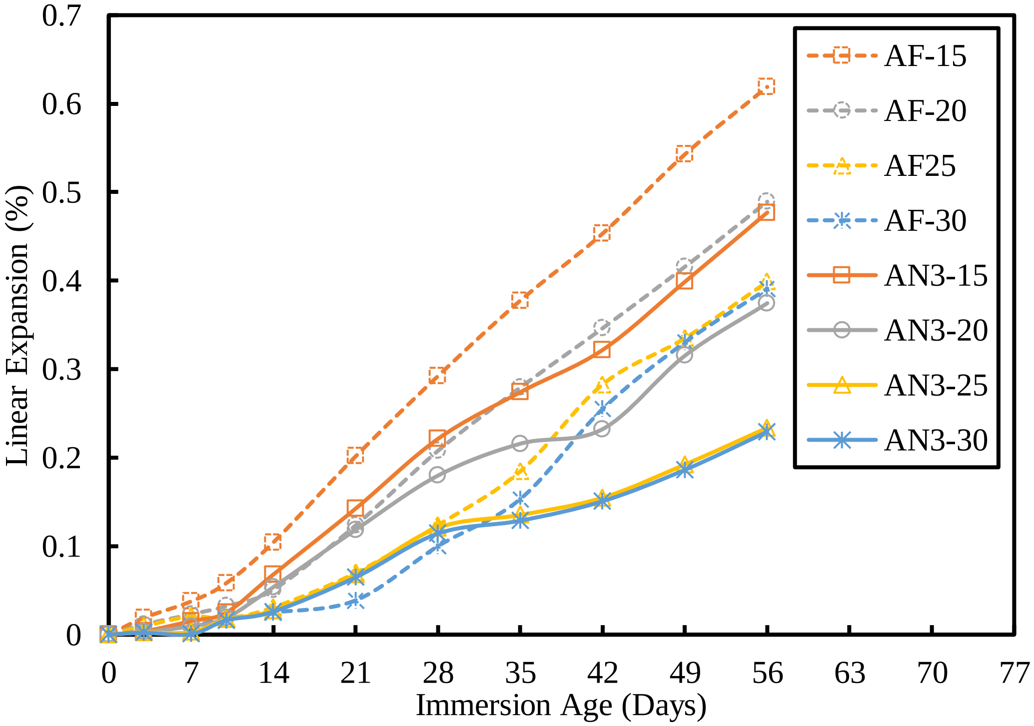


Figure 5.3: Expansion of industrial and N3 natural pozzolan mortars using aggregate source A

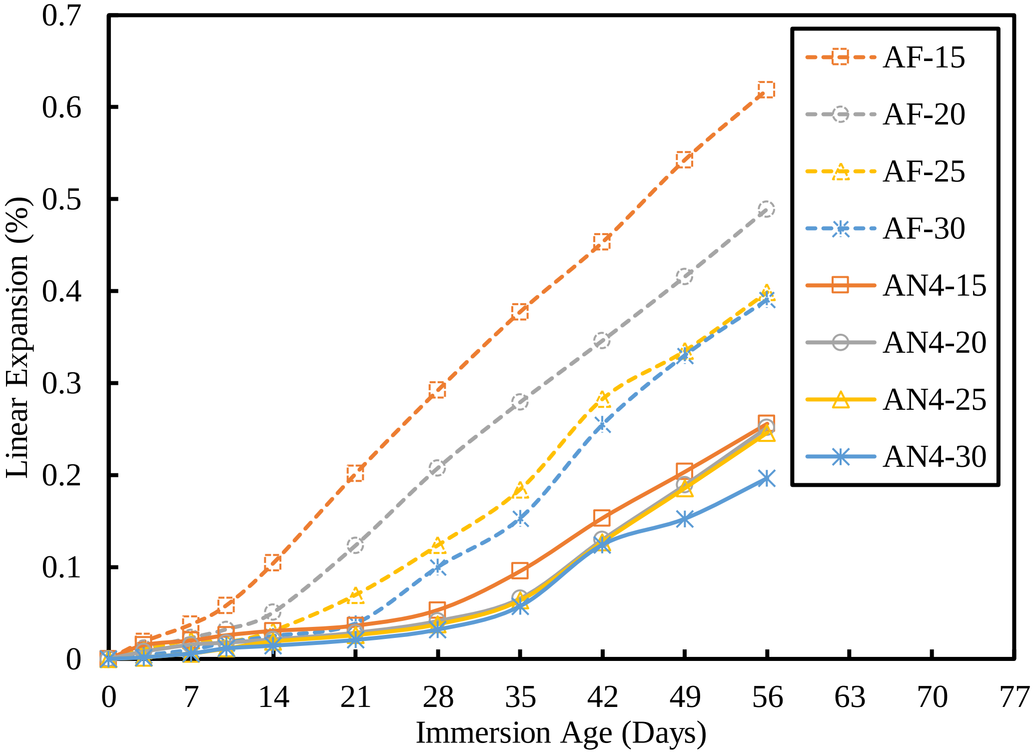


Figure 5.4: Expansion of industrial and N4 natural pozzolan mortars using aggregate source A

5.1.2 Aggregate Source B

The expansions due to alkali-silica reactivity of the aggregate source B mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.5 through 5.8 and Figures 5.5 through 5.8. As can be seen, both Class F fly ash and natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. Overall, the four natural pozzolan sources utilized in this study were slightly less effective as Class F fly ash in the reduction of alkali-silica reactivity of the mortars made with aggregate source B.

For natural pozzolan N1, the expansions due to alkali-silica reactivity of natural pozzolan contained mortars were much higher than that of the fly ash contained mortars at nearly all Portland cement substitution levels. As shown in Table 5.5, at 14-day immersion age, natural pozzolan N1 increased ASR-induced expansion averagely by 70, 81, 80, and 29% for cement substitution levels of 15, 20, 25, and 30%, respectively, when compared to that of the companion Class F fly ash mortars. The superior performance of Class F fly ash mortars over that of the N1 natural pozzolan mortars, in mitigating alkali-silica reactivity was also evident at the immersion ages of 28 and 56 days. The increase in expansions at these two immersion ages were averagely 43, 45, 49, and 21%; and 37, 25, 15, and 28%; respectively, when compared to that of the companion fly ash mortars.

Incorporation of the Class F fly ash in the mortars containing aggregate source B resulted in better performance in reducing ASR expansion at 14-day immersion age than when N2 natural pozzolan was used. On the average, N2 natural pozzolan increased ASR-induced expansions of the mortars containing aggregate source B by nearly 21, 52, 32, and 33%. However with an increase in immersion age, the performance was mostly reversed. When immersion age was extended to 28 and 56 days, the expansion of N2 natural pozzolan mortars were lower averagely, than the equivalent Class F fly ash mortars, by approximately 11, -15, -13, and, 35%; and 15, 10, 5, and 20%; respectively; for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

Once N3 natural pozzolan was used, Class F fly ash and natural pozzolan mortars showed comparable 14-day expansions and thus similar performance in mitigating alkali-silica reactivity. However, when immersion ages was extended to 28 and 56 days, N3 natural pozzolan performed better to mitigate ASR as compared to the studied Class F fly ash mortars made with aggregate source B by approximately 31, 18, 36, and 46%; and 18, 14, 20, and 6%; respectively; for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

When N4 natural pozzolan was used to prepare mortars containing aggregate source B, the resulting ASR-induced expansions were higher than that of Class F fly ash mortars at the three critical immersion ages. At 14 days immersion, Class F fly ash mitigated the alkali silica reactivity of reactive aggregate source B better than the N4 natural pozzolan by averagely 73, 81, 63, and 63% for the Portland cement replacement levels of 15, 20, 25, and 30%, respectively. For immersion ages of 28 and 56 days, Class F fly ash performed better than N4 natural pozzolan by approximately 28, 34, 21, and -26%; and 9, 5, -19, and -24%; respectively.

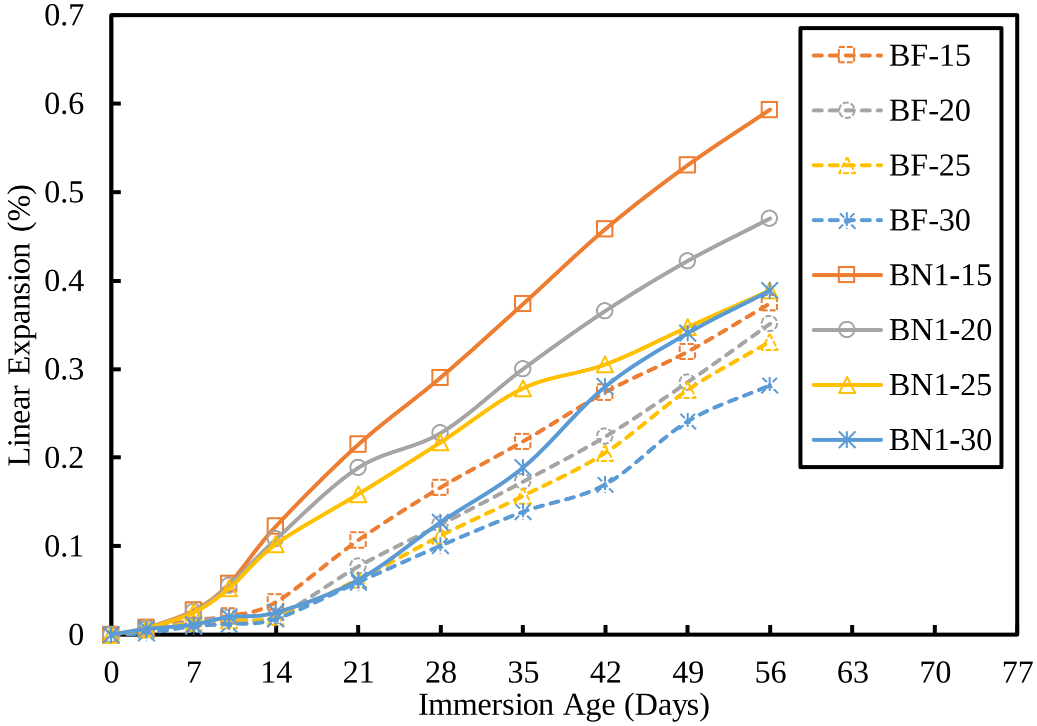


Figure 5.5: Expansion of industrial and N1 natural pozzolan mortars using aggregate source B

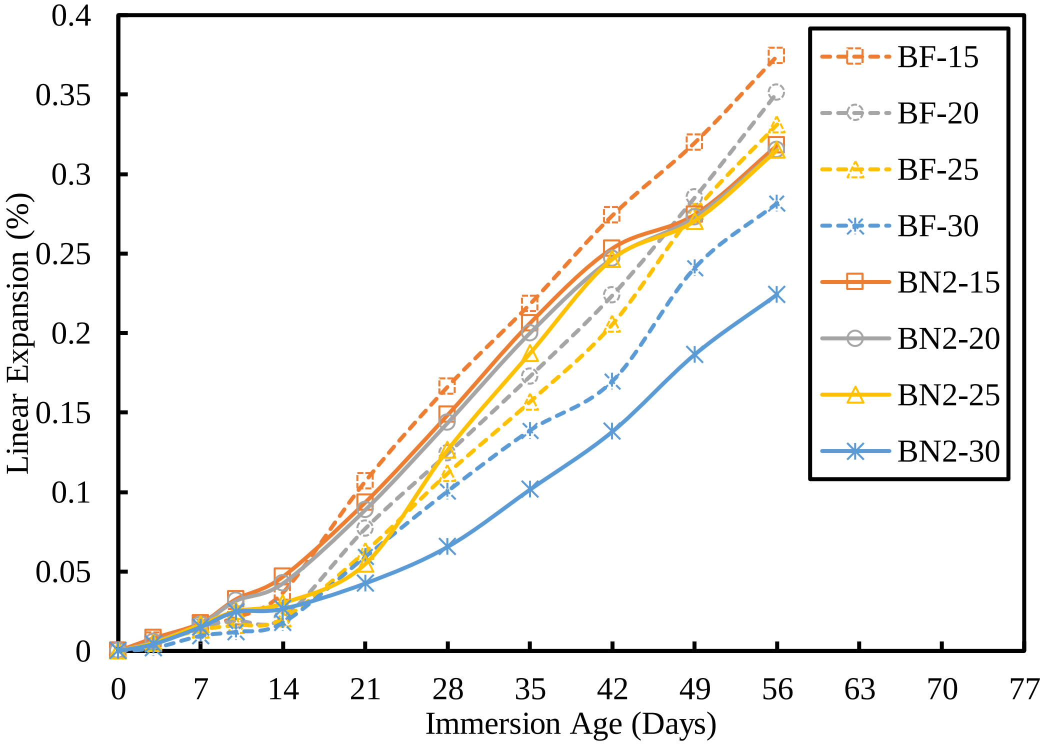


Figure 5.6: Expansion of industrial and N2 natural pozzolan mortars using aggregate source B

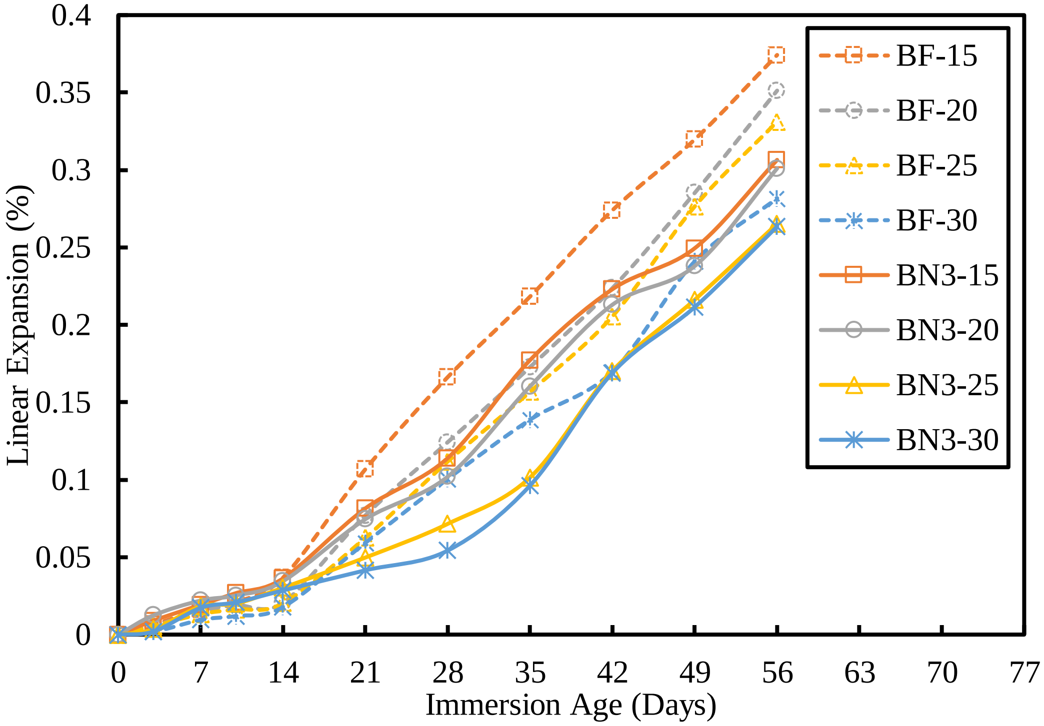


Figure 5.7: Expansion of industrial and N3 natural pozzolan mortars using aggregate source B

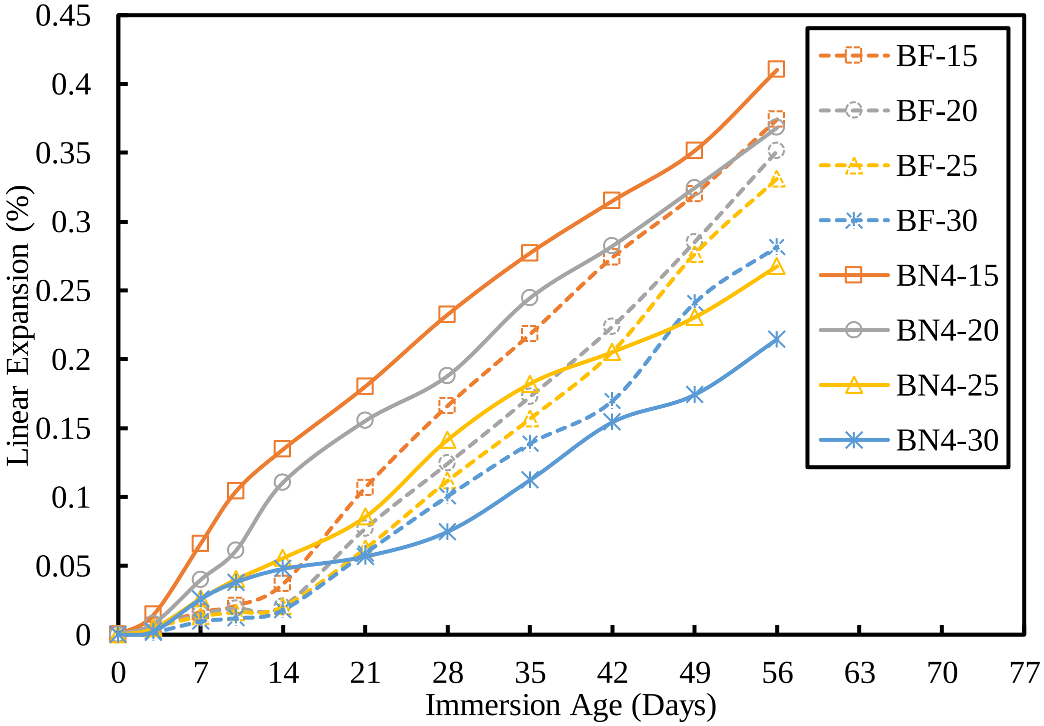


Figure 5.8: Expansion of industrial and N4 natural pozzolan mortars using aggregate source B

Table 5.5: Expansion of industrial and N1 natural pozzolan mortars using aggregate source B

Imm. Ages (Days)	Expansion (%)								
	B-0	BF-15	BF-20	BF-25	BF-30	BN1-15	BN1-20	BN1-25	BN1-30
14	0.3683	0.0368	0.0205	0.0203	0.0178	0.1225	0.1078	0.1023	0.0250
28	0.5708	0.1663	0.1243	0.1118	0.1005	0.2905	0.2278	0.2173	0.1270
56	0.7423	0.3743	0.3513	0.3313	0.2818	0.5933	0.4703	0.3890	0.3888

Table 5.6: Expansion of industrial and N2 natural pozzolan mortars using aggregate source B

Imm. Ages (Days)	Expansion (%)								
	B-0	BF-15	BF-20	BF-25	BF-30	BN2-15	BN2-20	BN2-25	BN2-30
14	0.3683	0.0368	0.0205	0.0203	0.0178	0.0467	0.0425	0.0300	0.0265
28	0.5708	0.1663	0.1243	0.1118	0.1005	0.1485	0.1435	0.1265	0.0655
56	0.7423	0.3743	0.3513	0.3313	0.2818	0.3180	0.3153	0.3150	0.2243

Table 5.7: Expansion of industrial and N3 natural pozzolan mortars using aggregate source B

Imm. Ages (Days)	Expansion (%)								
	B-0	BF-15	BF-20	BF-25	BF-30	BN3-15	BN3-20	BN3-25	BN3-30
14	0.3683	0.0368	0.0205	0.0203	0.0178	0.0362	0.0345	0.0303	0.0285
28	0.5708	0.1663	0.1243	0.1118	0.1005	0.1140	0.1020	0.0715	0.0543
56	0.7423	0.3743	0.3513	0.3313	0.2818	0.3065	0.3010	0.2653	0.2635

Table 5.8: Expansion of industrial and N4 natural pozzolan mortars using aggregate source B

Imm. Ages (Days)	Expansion (%)								
	B-0	BF-15	BF-20	BF-25	BF-30	BN4-15	BN4-20	BN4-25	BN4-30
14	0.3683	0.0368	0.0205	0.0203	0.0178	0.1345	0.1105	0.0555	0.0478
28	0.5708	0.1663	0.1243	0.1118	0.1005	0.2325	0.1880	0.1415	0.0748
56	0.7423	0.3743	0.3513	0.3313	0.2818	0.4103	0.3683	0.2675	0.2145

5.1.3 Aggregate Source C

The expansions due to alkali-silica reactivity of the aggregate source C mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.9 through 5.12 and Figures 5.9 through 5.12. As can be seen, both Class F fly ash and natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. Overall, the four natural pozzolan sources utilized in this study were less effective in the reduction of alkali-silica reactivity of mortars made with aggregate source C when compared to the companion mortars containing Class F fly ash.

Incorporation of the Class F fly ash in the mortars containing aggregate source C resulted in an overall better performance in reducing ASR expansion than when N1 natural pozzolan was used. This trend held true at the critical immersion age of 14, 28 and 56 days, as well as for the three cement substitution levels (20, 25, and 30%). On the average, Class F fly ash reduced ASR-Induced expansion of the mortars containing aggregate source C by nearly -11, 49, 45, and 3%; -9, 24, 19, and, 24%; and -9, 13, 15, and 15% at the immersion age of 14, 28 and 56 days, respectively, when compared to that of the comparison N1 natural pozzolan contained mortars.

For natural pozzolan N2, the expansions due to alkali-silica reactivity of fly ash contained mortars were also higher than that of natural pozzolan contained mortars. As shown in Table 5.10, at 14-day immersion age, natural pozzolan N2 mortars exhibited higher ASR-induced expansions averagely by -23, 67, 8, and 19% for cement substitution of 15, 20, 25, and 30%, respectively, when compared to that of the companion fly ash mortars. The superior performance of Class F fly ash mortars over that of N2 natural pozzolan mortars, in mitigating alkali-silica reactivity was also evident at the immersion ages of 28 and 56 days. The reduction of expansions of the Class F fly ash mortars at these two immersion ages were averagely -22, 43, 7, and 56%; and -19, 28, 1, and 41%; respectively, when compared to that of the comparison N2 natural pozzolan contained mortars for cement substitution of 15, 20, 25, and 30% by weight.

Once N3 natural pozzolan was used, with the exception of cement substitution level 20%, it showed better performance in expansion reduction as compared to Class F fly ash. The reduction of expansion for N3 natural pozzolan at 14, 28, and 56 days were averagely by 25, -65, 20, and 8%; 17, -38, 25, and -36%; and 28, -20, 33, and -1%; respectively, for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

When N4 natural pozzolan was used to prepare mortars containing reactive aggregate source C, the resulting ASR-induced expansions were lower than that of Class F fly ash mortars at the three critical immersion ages for 15, 20, and 25% Portland cement replacement levels. However, for 30% Portland cement replacement, Class F fly ash mortars showed comparable result with that of N4 natural pozzolan mortars at 14 and 28 days immersion ages. At 14 days immersion, N4 natural pozzolan mitigated the alkali silica reactivity of the reactive aggregate source C better than the Class F fly ash by averagely 84, 35, and 29% for the Portland cement replacement of 15, 20, and 25%, respectively. For immersion age of 28 and 56 days, these expansion reduction were lower by approximately 65, 34,and 59, %; and 51, 27, and 40%; respectively.

Table 5.9: Expansion of industrial and N1 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)								
	C-0	CF-15	CF-20	CF-25	CF-30	CN1-15	CN1-20	CN1-25	CN1-30
14	0.5298	0.2615	0.0578	0.0520	0.0260	0.2315	0.1130	0.0940	0.0268
28	0.7485	0.4865	0.2143	0.2100	0.0740	0.4420	0.2808	0.2598	0.0970
56	0.9793	0.8658	0.4995	0.4778	0.2788	0.7875	0.5773	0.5615	0.3285

Table 5.10: Expansion of industrial and N2 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)								
	C-0	CF-15	CF-20	CF-25	CF-30	CN2-15	CN2-20	CN2-25	CN2-30
14	0.5298	0.2615	0.0578	0.0520	0.0260	0.2025	0.1750	0.0563	0.0320
28	0.7485	0.4865	0.2143	0.2100	0.0740	0.3815	0.3735	0.2260	0.1675
56	0.9793	0.8658	0.4995	0.4778	0.2788	0.6983	0.6958	0.4818	0.4725

Table 5.11: Expansion of industrial and N3 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)								
	C-0	CF-15	CF-20	CF-25	CF-30	CN3-15	CN3-20	CN3-25	CN3-30
14	0.5298	0.2615	0.0578	0.0520	0.0260	0.1958	0.1668	0.0418	0.0238
28	0.7485	0.4865	0.2143	0.2100	0.0740	0.4018	0.3465	0.1573	0.1158
56	0.9793	0.8658	0.4995	0.4778	0.2788	0.6230	0.6210	0.3195	0.2803

Table 5.12: Expansion of industrial and N4 natural pozzolan mortars using aggregate source C

Imm. Ages (Days)	Expansion (%)								
	C-0	CF-15	CF-20	CF-25	CF-30	CN4-15	CN4-20	CN4-25	CN4-30
14	0.5298	0.2615	0.0578	0.0520	0.0260	0.0425	0.0375	0.0370	0.0310

Imm. Ages (Days)	Expansion (%)								
	C-0	CF-15	CF-20	CF-25	CF-30	CN4-15	CN4-20	CN4-25	CN4-30
28	0.7485	0.4865	0.2143	0.2100	0.0740	0.1690	0.1410	0.0870	0.0847
56	0.9793	0.8658	0.4995	0.4778	0.2788	0.4270	0.3648	0.2858	0.2353

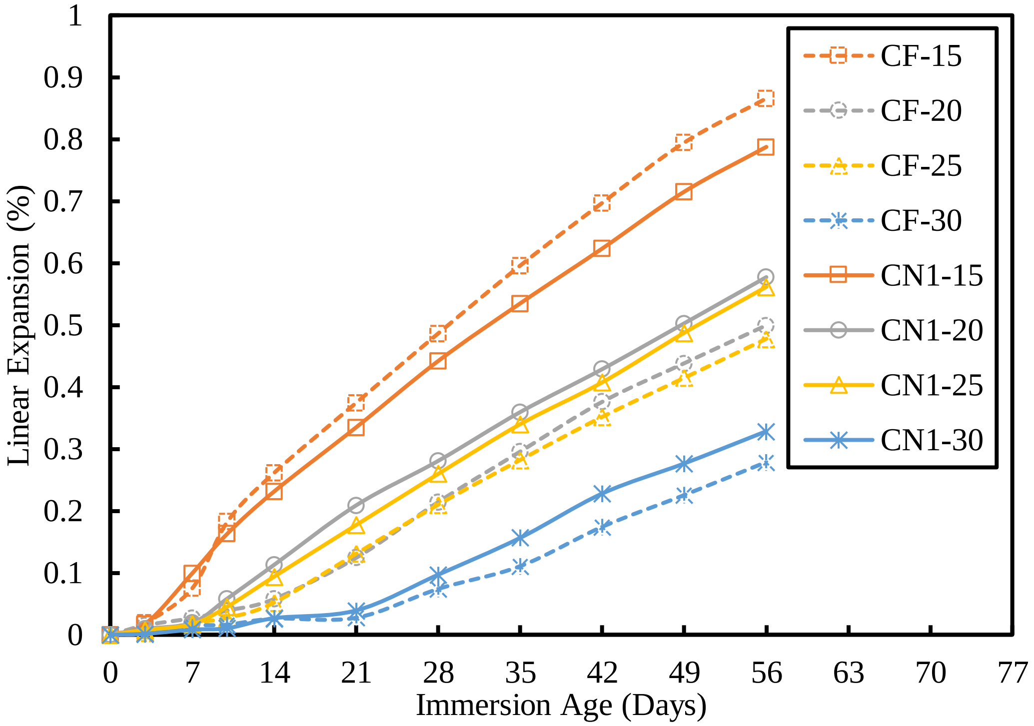


Figure 5.9: Expansion of industrial and N1 natural pozzolan mortars using aggregate source C

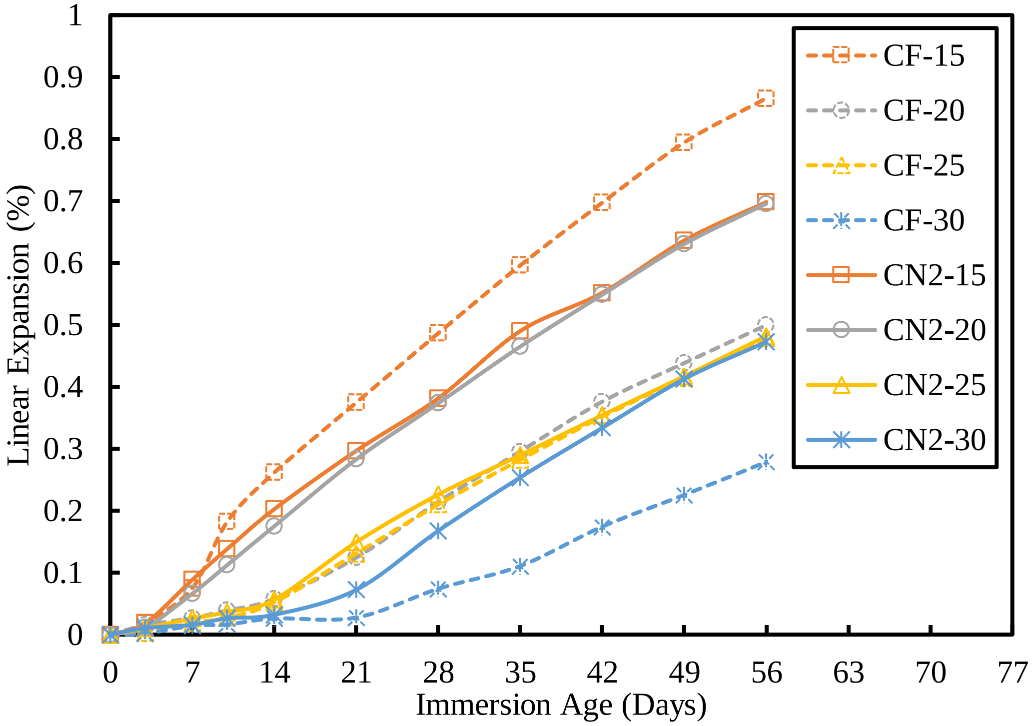


Figure 5.10: Expansion of industrial and N2 natural pozzolan mortars using aggregate source C

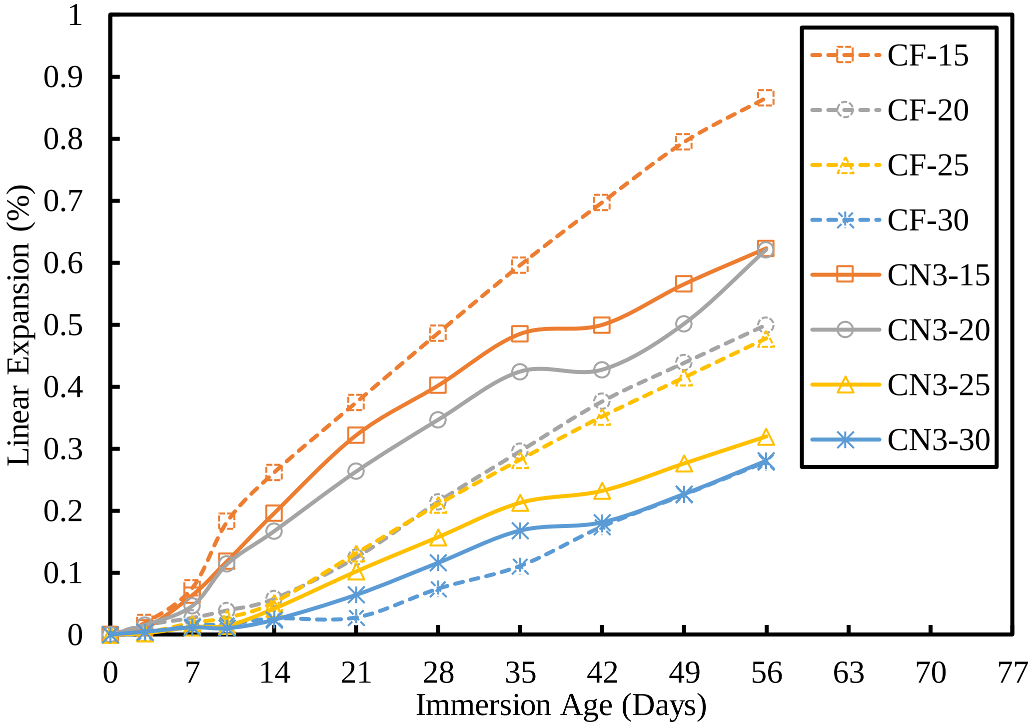


Figure 5.11: Expansion of industrial and N3 natural pozzolan mortars using aggregate source C

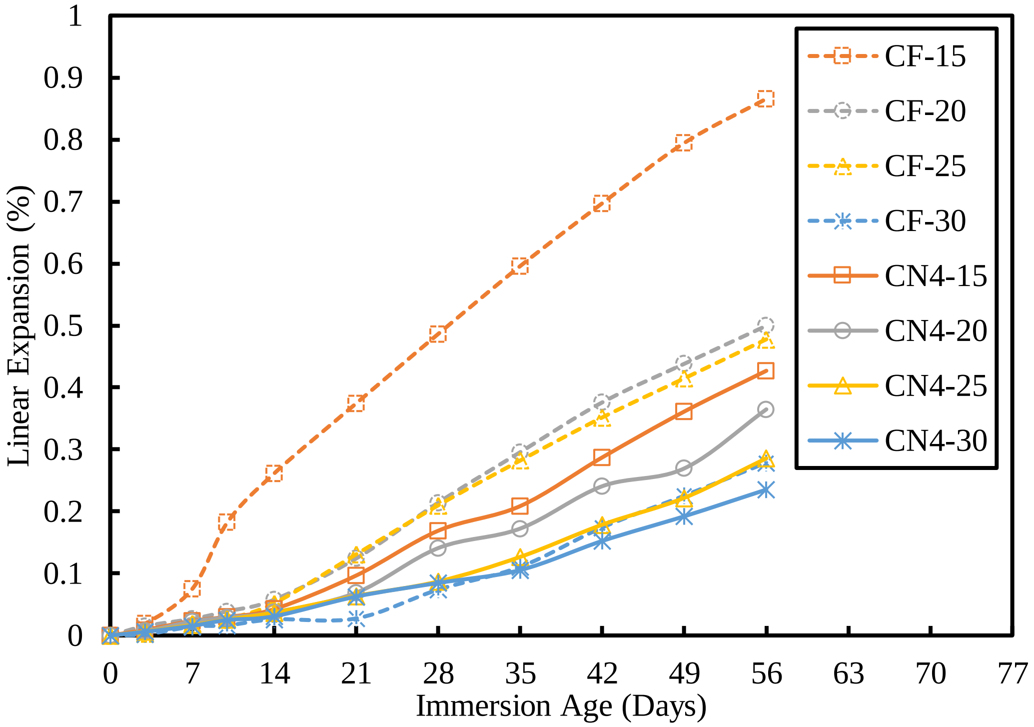


Figure 5.12: Expansion of industrial and N4 natural pozzolan mortars using aggregate source C

5.1.4 Aggregate Source D

The expansions due to alkali-silica reactivity of the aggregate source D mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.13 through 5.16 and Figures 5.13 through 5.16. As can be seen, both Class F fly ash and natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. Overall, the four natural pozzolan sources utilized in this study were more effective in the reduction of alkali-silica reactivity of mortars made with aggregate source D when compared to that of the companion mortars containing Class F fly ash.

For natural pozzolan N1, the expansions due to alkali-silica reactivity of natural pozzolan contained mortars were lower than that of the fly ash contained mortars at the 15 and 20% of cement substitution levels. At the levels of 25 and 30% cement substitution both pozzolan types produced comparable result as shown in Table 5.13, at 14-day immersion age, natural pozzolan N1 reduced ASR-induced expansion averagely by 45, and 41% for cement substitution levels of 15, and 20%, respectively, when compared to that of the companion fly ash mortars. The superior performance of N1 natural pozzolan mortars, over that of Class F fly ash mortars in mitigating alkali-silica reactivity, was also evident at the immersion age of 28 and 56 days. The reductions of expansion at these two immersion ages were averagely 22, 13%; and 11, 7%; respectively.

Incorporation of the N2 natural pozzolan in the mortars containing aggregate source D resulted in an overall better performance in reducing ASR expansion than when Class F fly ash was used (with the exception of 20% replacement level). On the average, N2 natural pozzolan mortar produced lower ASR-induced expansion of the mortars containing aggregate source D by nearly -11, -29, 17, and 60%; 13, -16, 9, and, 26%; and 25, -6, 11, and 3% at the immersion ages of 14, 28 and 56 days, respectively.

Once N3 natural pozzolan used, both of these two pozzolan types displayed mixed but comparably similar results in mitigating the ASR expansions of the studied mortars made with aggregate source D at the immersion age of 14 days and lower cement substitution level. When immersion age was extended to 28 and 56 days, the expansions of N3 natural pozzolan mortars were lower than that of the equivalent Class F fly ash mortars by approximately 9, -10, 36, and 49%; and 33, 5, 41, and 43%; respectively; for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

When N4 natural pozzolan was used to prepare mortars containing aggregate source D, the resulting ASR- induced expansions were well below that of Class F fly ash mortars at the three critical immersion ages. At the 14 days, N4 natural pozzolan mitigated the alkali silica reactivity of the reactive aggregate source D better than the Class F fly ash by averagely 76, 70, 46, and 62% for the Portland cement replacement of 15, 20, 25, and 30%, respectively. For immersion ages of 28 and 56 days, these reductions were 62, 55, 65, and 63%; and 54, 44, 47, and 52%; respectively.

Table 5.13: Expansion of industrial and N1 natural pozzolan mortars using aggregate source D

Imm. Ages (Days)	Expansion (%)								
	D-0	DF-15	DF-20	DF-25	DF-30	DN1-15	DN1-20	DN1-25	DN1-30
14	0.7178	0.1803	0.1235	0.0680	0.0808	0.0997	0.0723	0.0708	0.0593
28	1.0210	0.4405	0.3123	0.2470	0.2268	0.3435	0.2705	0.2495	0.2295
56	1.2150	0.9280	0.6550	0.5418	0.4893	0.8250	0.6093	0.5995	0.5843

Table 5.14: Expansion of industrial and N2 natural pozzolan mortars using aggregate source D

Imm. Ages (Days)	Expansion (%)								
	D-0	DF-15	DF-20	DF-25	DF-30	DN2-15	DN2-20	DN2-25	DN2-30
14	0.7178	0.1803	0.1235	0.0680	0.0808	0.2025	0.1750	0.0563	0.0320
28	1.0210	0.4405	0.3123	0.2470	0.2268	0.3815	0.3735	0.2260	0.1675
56	1.2150	0.9280	0.6550	0.5418	0.4893	0.6983	0.6958	0.4818	0.4725

Table 5.15: Expansion of industrial and N3 natural pozzolan mortars using aggregate source D

Imm. Ages (Days)	Expansion (%)								
	D-0	DF-15	DF-20	DF-25	DF-30	DN3-15	DN3-20	DN3-25	DN3-30
14	0.7178	0.1803	0.1235	0.0680	0.0808	0.1958	0.1668	0.0418	0.0238
28	1.0210	0.4405	0.3123	0.2470	0.2268	0.4018	0.3465	0.1573	0.1158
56	1.2150	0.9280	0.6550	0.5418	0.4893	0.6230	0.6210	0.3195	0.2803

Table 5.16: Expansion of industrial and N4 natural pozzolan mortars using aggregate source D

Imm. Ages (Days)	Expansion (%)								
	D-0	DF-15	DF-20	DF-25	DF-30	DN4-15	DN4-20	DN4-25	DN4-30
14	0.7178	0.1803	0.1235	0.0680	0.0808	0.0425	0.0375	0.0370	0.0310
28	1.0210	0.4405	0.3123	0.2470	0.2268	0.1690	0.1410	0.0870	0.0847
56	1.2150	0.9280	0.6550	0.5418	0.4893	0.4270	0.3648	0.2858	0.2353

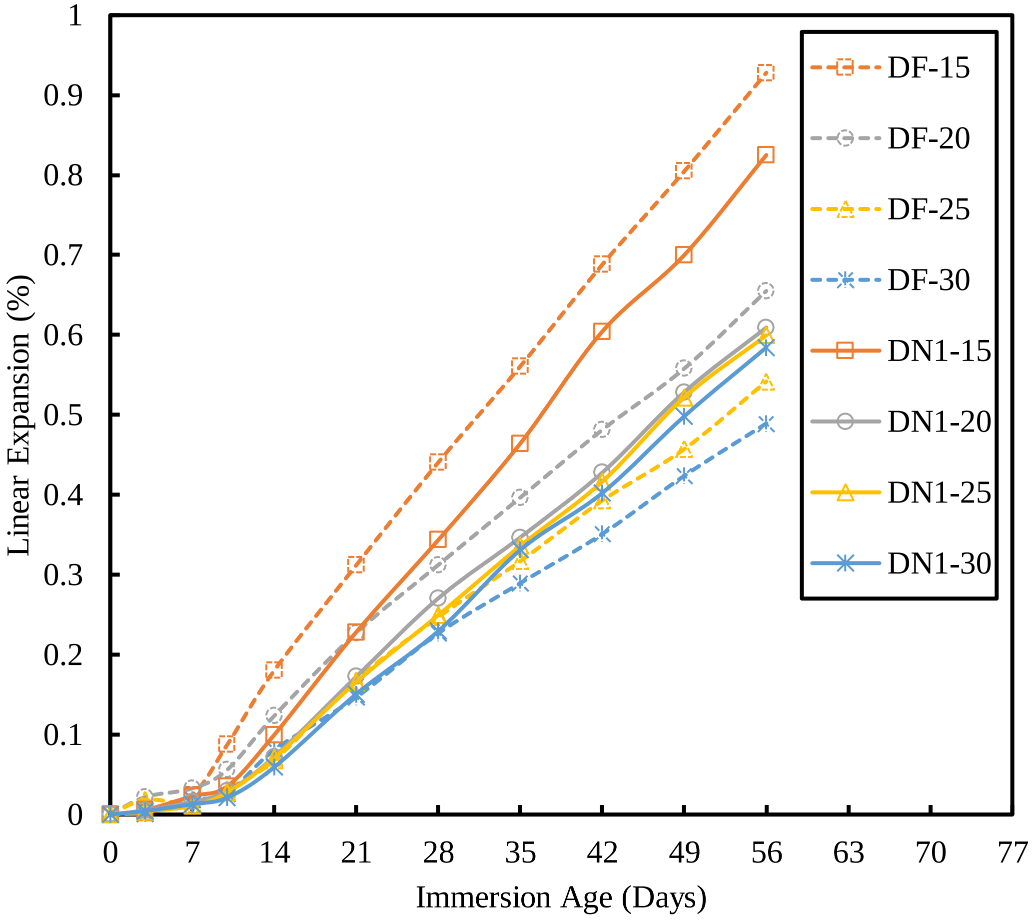


Figure 5.13: Expansion of industrial and N1 natural pozzolan mortars using aggregate source D

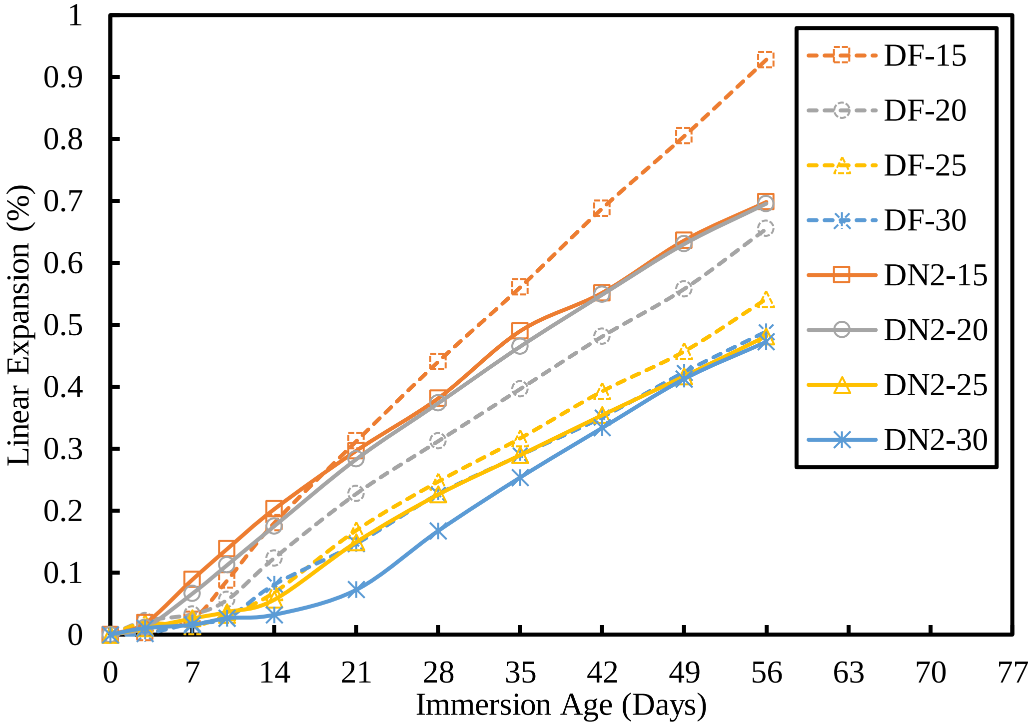


Figure 5.14: Expansion of industrial and N2 natural pozzolan mortars using aggregate source D

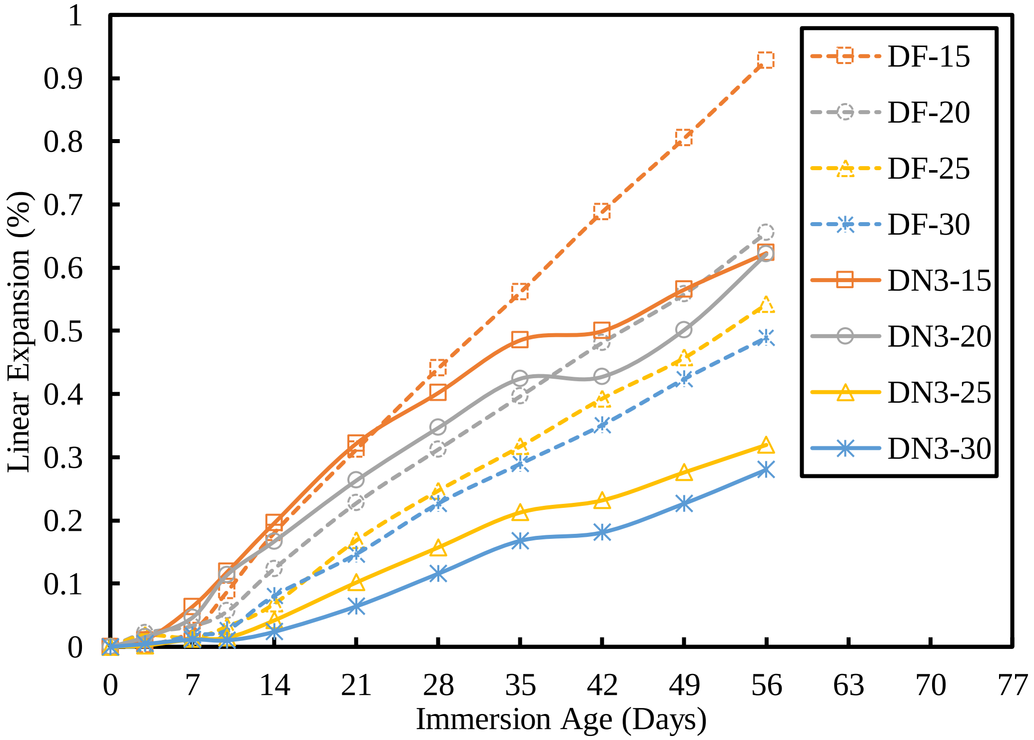


Figure 5.15: Expansion of industrial and N3 natural pozzolan mortars using aggregate source D

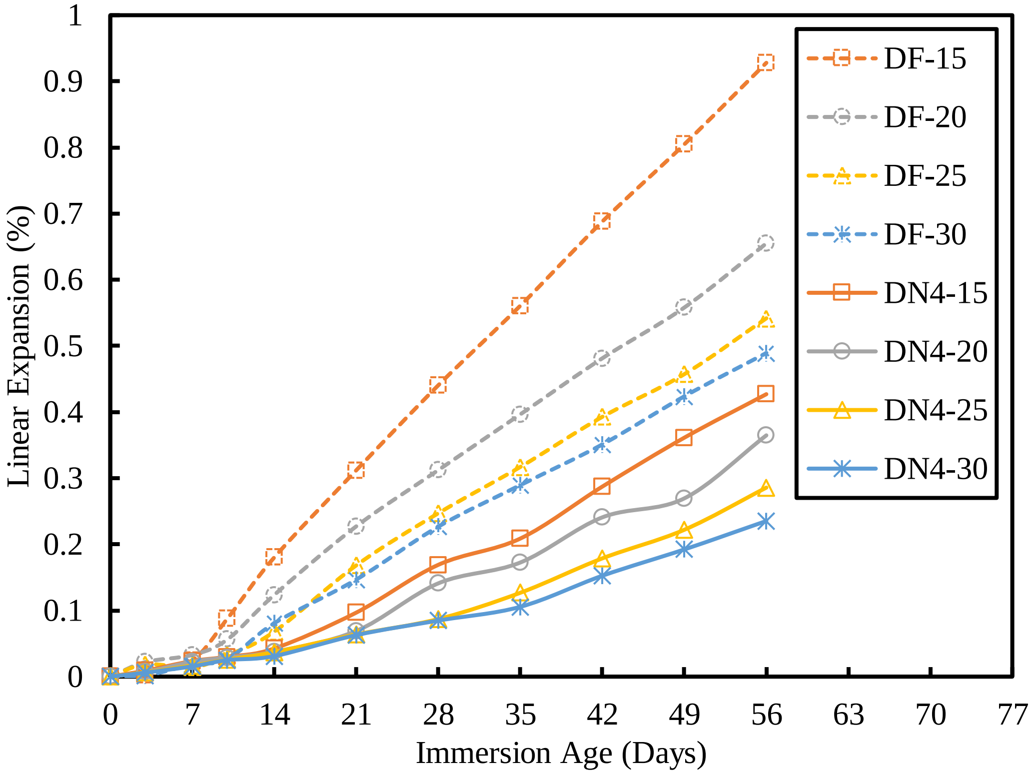


Figure 5.16: Expansion of industrial and N4 natural pozzolan mortars using aggregate source D

5.1.5 Aggregate source E

The expansions due to alkali-silica reactivity of the aggregate source E mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.17 through 5.20 and Figures 5.17 through 5.20. As can be seen, both Class F fly ash and natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. Overall, the four natural pozzolan sources utilized in this study were less effective in the reduction of alkali-silica reactivity of mortars made with aggregate source E when compared to that of the companion mortars containing Class F fly ash. However, at some Portland cement substitution levels, natural pozzolan mortars had lower expansion when compared to that of the Class F fly ash mortars.

For of natural pozzolan N1, the expansions due to alkali-silica reactivity of natural pozzolan contained mortars were higher than that of the fly ash contained mortars at all four cement substitution levels. As shown in Table 5.17, at 14-day immersion age, Class F fly ash mortars had lower expansions averagely by 17, 35, 47, and 10% for cement substitution levels of 15, 20, 25, and 30%, respectively, when compared to that of the companion N1 natural pozzolan mortars. The inferior performance of N1 natural pozzolan mortars, over that of Class F fly ash mortars, in mitigating alkali-silica reactivity was also evident at the immersion ages of 28 and 56 days. The reduction of expansion at these two immersion ages were averagely 16, 6, 42, and 33%; and 1, -8, 19, and 25%; respectively.

Incorporation of the N2 natural pozzolan in the mortars containing aggregate source E resulted in an overall better performance in reducing ASR expansion than when Class F fly ash was used. At 14-day immersion age, both fly ash and N2 natural pozzolan displayed relatively similar results. However as days of immersion increased to 28 and 56 days, the expansions of N2 natural pozzolan mortars were below that of the Class F fly ash mortars at all Portland cement substitution levels. On the average, N2 natural pozzolan had lower ASR-Induced expansions than that of Class F fly ash mortars by nearly 20, 59, 29, and, 29%; and 5, 30, 3, and 10% at the immersion age of 28 and 56 days, respectively.

Once N3 natural pozzolan was used, Class F fly ash showed lower expansion results in mitigating the ASR of the studied mortars made with aggregate source E at all three immersion ages and for all cement substitution levels. For immersion age 14, 28 and 56 days, the expansions of Class F fly ash mortars were lower than the equivalent N3 natural pozzolan mortars by approximately 53, 68, 23, and 36%; 31, 35, 49, and 43%; and 0, -1, 24, and 13%; respectively; for Portland cement replacement levels of 15, 20, 25, and 30% by weight.

When N4 natural pozzolan was used to prepare mortars containing aggregate source E, the resulting ASR- induced expansions were well below that of Class F fly ash mortars at the 28 and 56 days immersion ages. At 14 days immersion, both pozzolans showed similar performance in mitigating alkali silica reactivity of the reactive aggregate source E. On the average, N4 natural pozzolan mortars had lower ASR-induced expansions than that of the Class F fly ash mortars by nearly 21, -3, 1, and -9%; 55, 56, 36, and 56%; and 37, 36, 23, and 47% at the immersion ages of 14, 28 and 56 days, respectively.

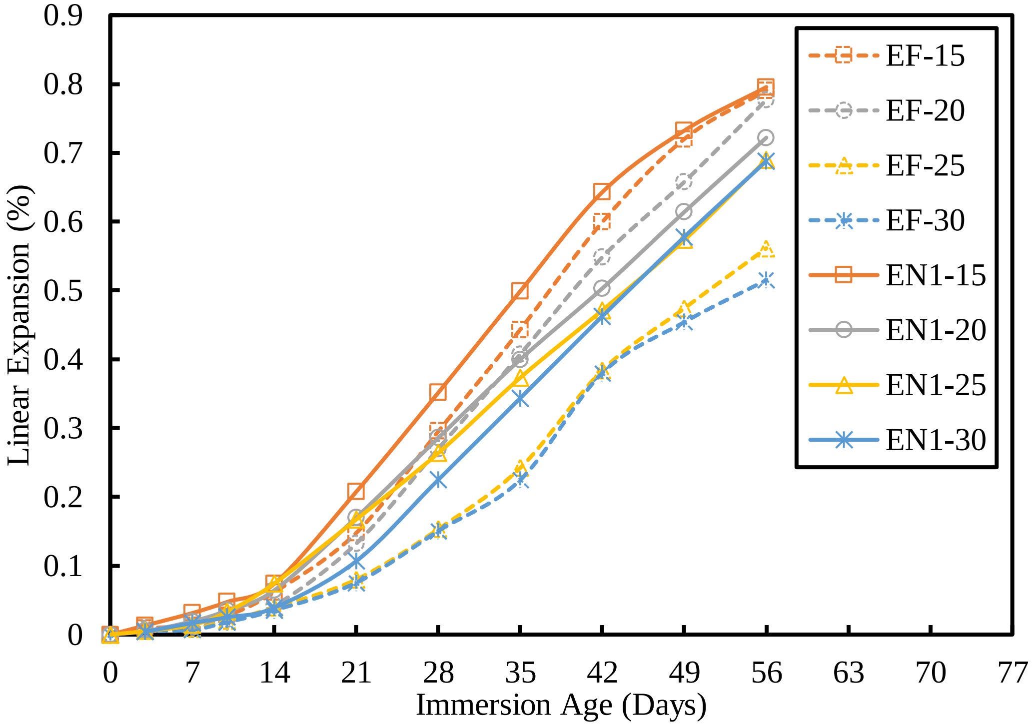


Figure 5.17: Expansion of industrial and N1 natural pozzolan mortars using aggregate source E

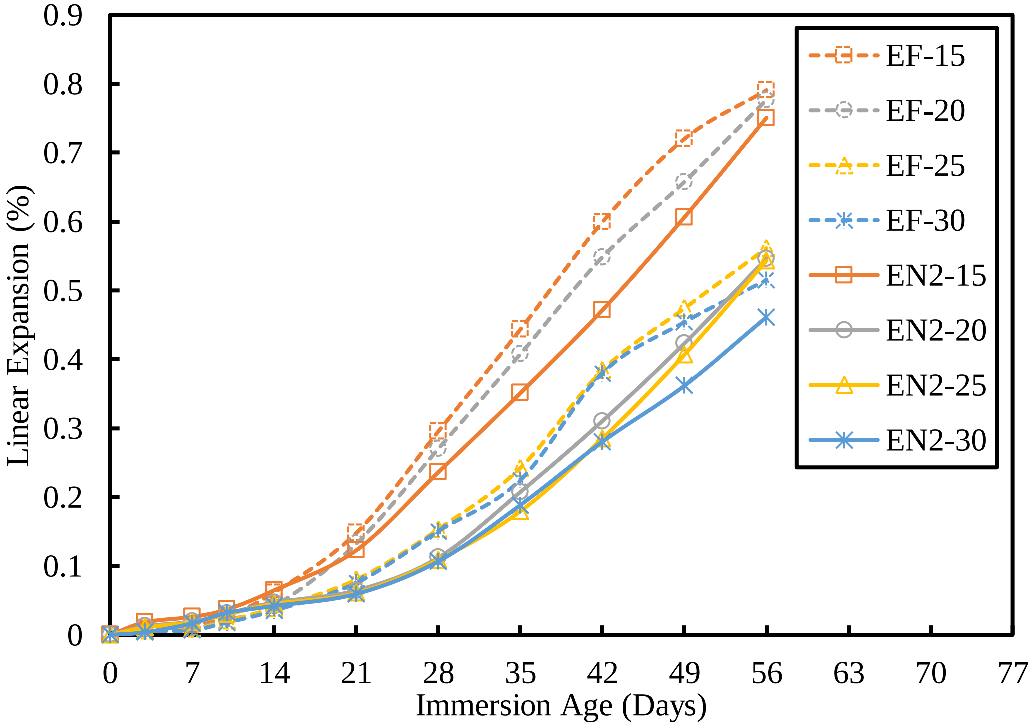


Figure 5.18: Expansion of industrial and N2 natural pozzolan mortars using aggregate source E

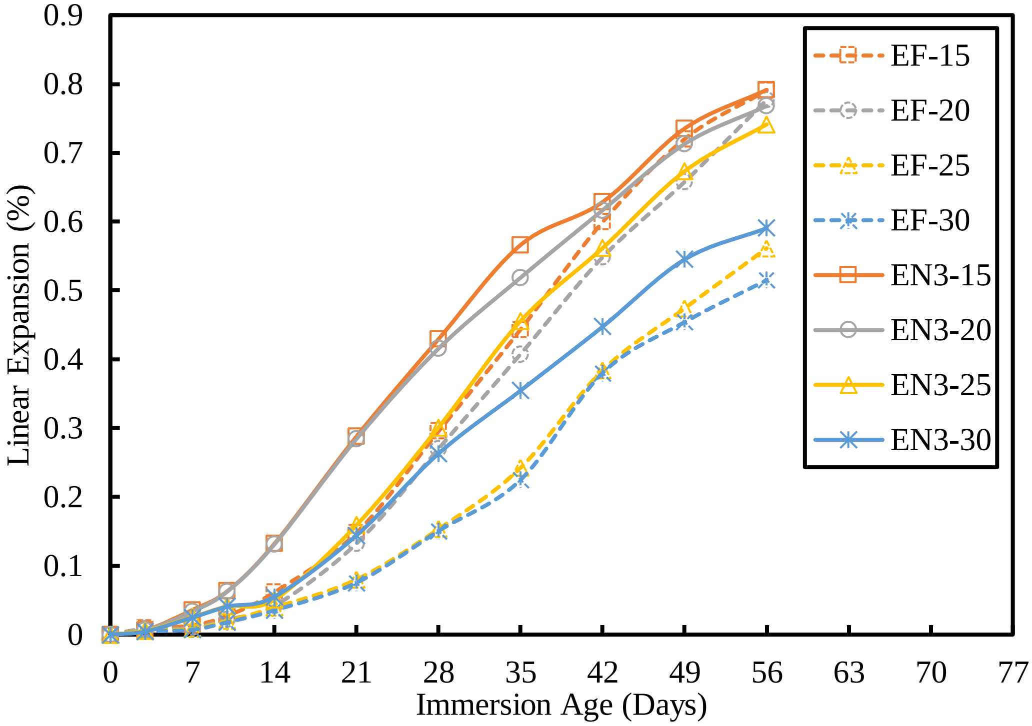


Figure 5.19: Expansion of industrial and N3 natural pozzolan mortars using aggregate source E

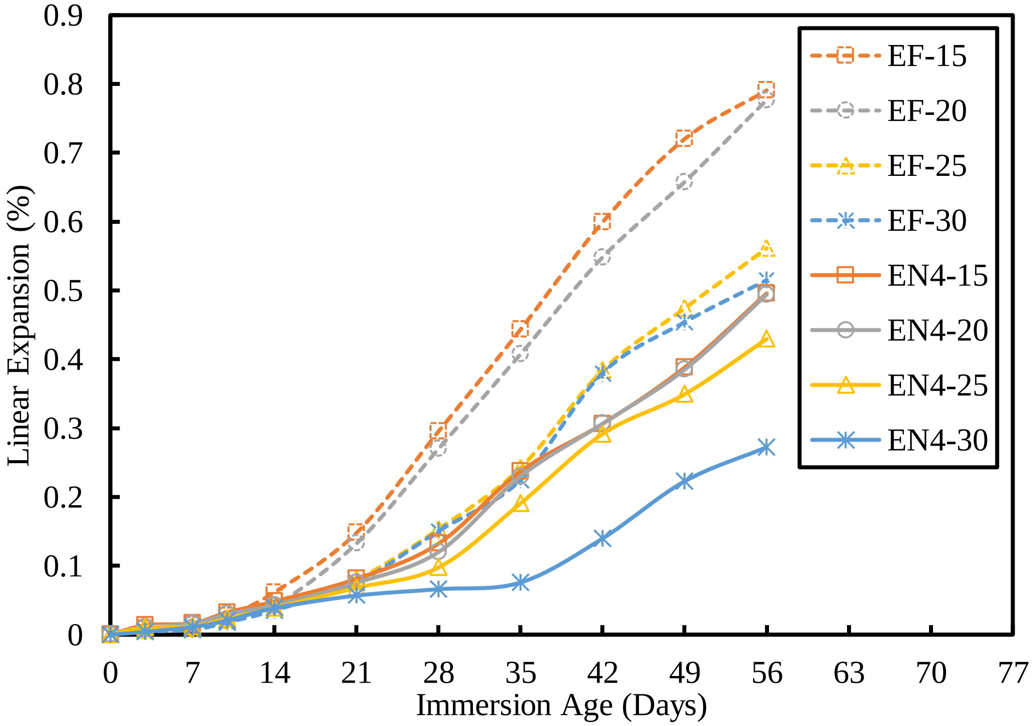


Figure 5.20: Expansion of industrial and N4 natural pozzolan mortars using aggregate source E

Table 5.17: Expansion of industrial and N1 natural pozzolan mortars using aggregate source E

Imm. Ages (Days)	Expansion (%)								
	E-0	EF-15	EF-20	EF-25	EF-30	EN1-15	EN1-20	EN1-25	EN1-30
14	0.3575	0.0615	0.0418	0.0392	0.0352	0.0738	0.0643	0.0742	0.0390
28	0.5275	0.2953	0.2700	0.1533	0.1505	0.3515	0.2858	0.2638	0.2250
56	0.8050	0.7908	0.7768	0.5613	0.5150	0.7955	0.7220	0.6898	0.6880

Table 5.18: Expansion of industrial and N2 natural pozzolan mortars using aggregate source E

Imm. Ages (Days)	Expansion (%)								
	E-0	EF-15	EF-20	EF-25	EF-30	EN2-15	EN2-20	EN2-25	EN2-30
14	0.3575	0.0615	0.0418	0.0392	0.0352	0.0647	0.0470	0.0450	0.0420
28	0.5275	0.2953	0.2700	0.1533	0.1505	0.2360	0.1120	0.1090	0.1067
56	0.8050	0.7908	0.7768	0.5613	0.5150	0.7507	0.5463	0.5433	0.4613

Table 5.19: Expansion of industrial and N3 natural pozzolan mortars using aggregate source E

Imm. Ages (Days)	Expansion (%)								
	E-0	EF-15	EF-20	EF-25	EF-30	EN3-15	EN3-20	EN3-25	EN3-30
14	0.3575	0.0615	0.0418	0.0392	0.0352	0.1320	0.1310	0.0508	0.0550
28	0.5275	0.2953	0.2700	0.1533	0.1505	0.4293	0.4155	0.3010	0.2630
56	0.8050	0.7908	0.7768	0.5613	0.5150	0.7915	0.7680	0.7413	0.5905

Table 5.20: Expansion of industrial and N4 natural pozzolan mortars using aggregate source E

Imm. Ages (Days)	Expansion (%)								
	E-0	EF-15	EF-20	EF-25	EF-30	EN4-15	EN4-20	EN4-25	EN4-30
14	0.3575	0.0615	0.0418	0.0392	0.0352	0.0483	0.0430	0.0390	0.0385
28	0.5275	0.2953	0.2700	0.1533	0.1505	0.1323	0.1200	0.0975	0.0660
56	0.8050	0.7908	0.7768	0.5613	0.5150	0.4958	0.4940	0.4295	0.2723

5.1.6 Aggregate Source F

The expansions due to alkali-silica reactivity of the aggregate source F mortars containing Class F fly ash or natural pozzolans (N1 to N4) are documented in Tables 5.21 through 5.24 and Figures 5.21 through 5.24. As can be seen, both Class F fly ash and natural pozzolans reduced the ASR-induced expansion significantly as compared to that of the control mortar. At 15, 20, and 25% cement replacement level, natural pozzolan seems to be more effective in reducing the ASR-induced expansion. However, at 30% cement replacement level, class F fly ash performed better in reducing the ASR-induced expansion. Overall, both industrial and natural pozzolan utilized in this study were similarly effective in the reduction of alkali-silica reactivity of mortars made with aggregate source F.

In the case of natural pozzolan N1, the expansion due to alkali-silica reactivity of natural pozzolan contained mortars were lower than that of the fly ash contained mortars at the three levels of Portland cement substitution (15, 20, and 25% by weight). However, at 30% replacement level, mixed results were observed. As shown in Table 5.21, at 14-day immersion age, natural pozzolan N1 had lower ASR-induced expansion averagely by 42, 66, and 63% for cement substitution of 15, 20, and 25%, respectively, when compared to that of the companion Class F fly ash mortars. The superior performance of N1 natural pozzolan mortars, over that of Class F fly ash mortars, in mitigating alkali-silica reactivity was also evident at the immersion age of 28 and 56 days. The reductions of expansion at these two immersion ages were averagely 27, 72, and 69%; and 15, 16, and 2%; respectively, for Portland cement replacement of 15, 20, and 25% by weight.

Incorporation of the N2 natural pozzolan in the mortars containing aggregate source F resulted better performance in reducing ASR expansion than when Class F fly ash was used (15 and 25% Portland cement replacement levels). At 20% Portland cement replacement level, similar ASR-induced expansion was observed for both natural and companion fly ash used. However, at 30% replacement level, mixed results were observed. On the average, N2 natural pozzolan reduced ASR-induced expansion of the mortars containing aggregate source F by nearly 24, -1, and 53%; 28, -4, and 72%; and 27, 4, and 60% at the immersion ages of 14, 28 and 56 days; respectively, for Portland cement replacement levels of 15, 20, and 25% by weight.

Similar to N2, N3 natural pozzolan resulted in an overall better performance in reducing ASR expansion than when Class F fly ash was used at 15, 20, and 25% cement replacement level. At 14 days immersion, the expansions of N3 natural pozzolan mortars were lower than the equivalent Class F fly ash mortar by approximately 70, 26, and 57% for Portland cement replacement of 15, 20, and 25% by weight. When immersion age was extended to 28 and 56 days, N3 natural pozzolan mortars showed 50, 15, and 75%; and 46, 20, and 60% lower expansions compared to the companion fly ash for Portland cement replacement of 15, 20, and 25% by weight.

When N4 natural pozzolan was used to prepare mortars containing aggregate source F, the resulting ASR- induced expansions were well below that of Class F fly ash mortars at the three critical immersion ages (15, 20, and 25% cement replacement level). At the 14 days, N4 natural pozzolan mitigated the alkali silica reactivity of the reactive aggregate source F better than the Class F fly ash by averagely 80, 58, and 54% for the Portland cement replacement of 15, 20, and 25%, respectively. For immersion ages of 28 and 56 days, these reductions were 87, 79, and 73%; and 69, 60, and 61%; respectively.

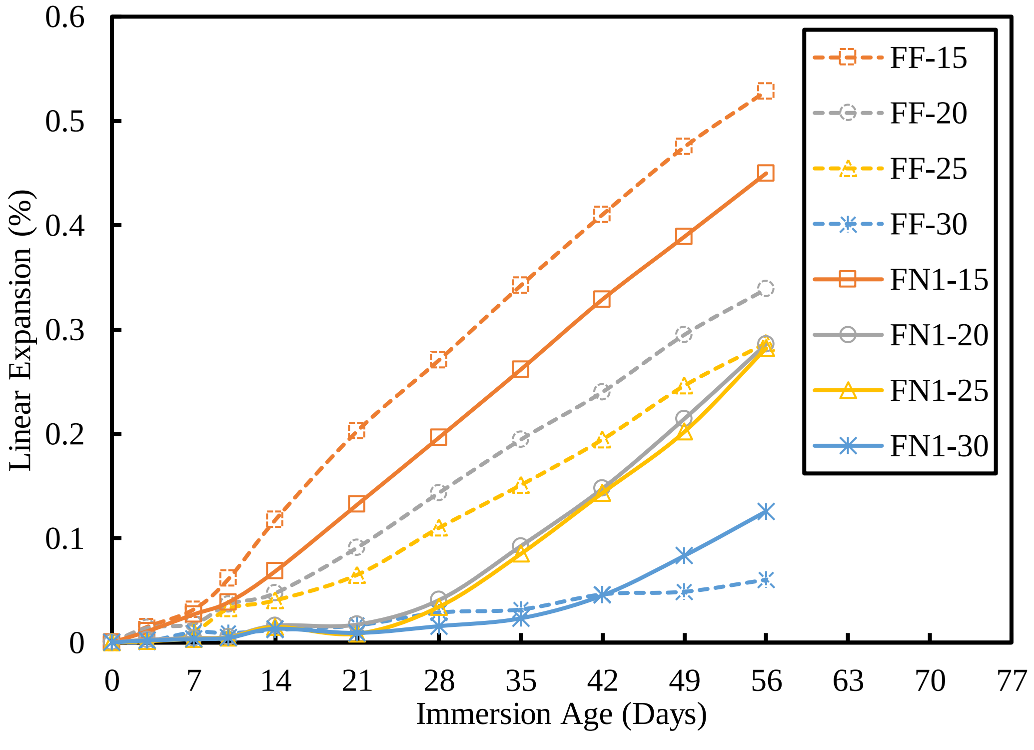


Figure 5.21: Expansion of industrial and N1 natural pozzolan mortars using aggregate source F

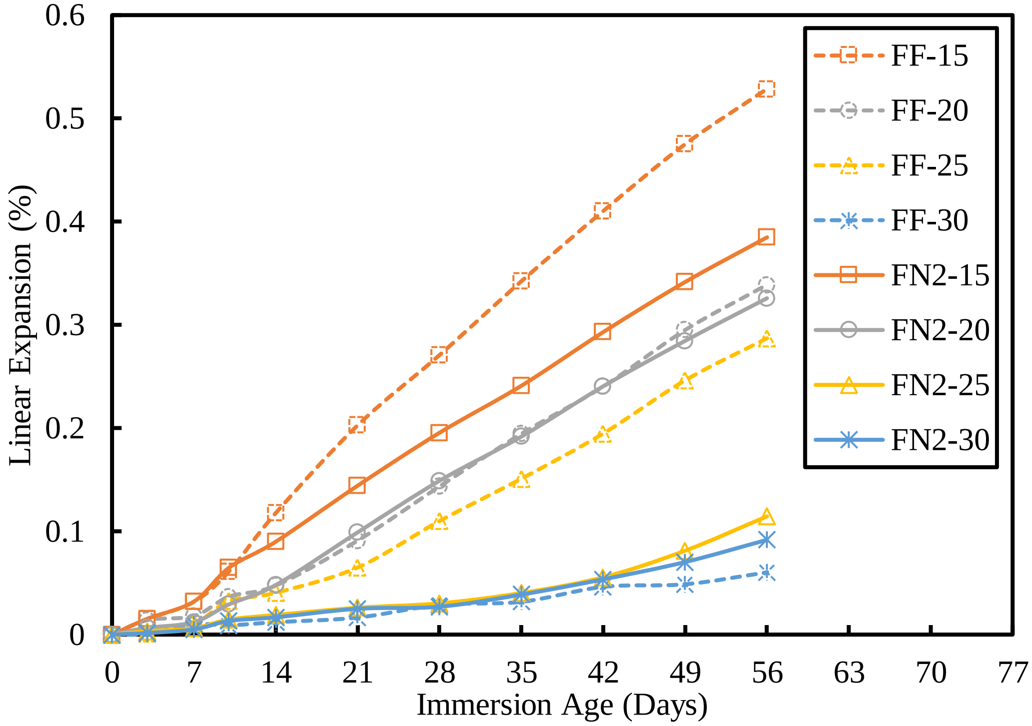


Figure 5.22: Expansion of industrial and N2 natural pozzolan mortars using aggregate source F

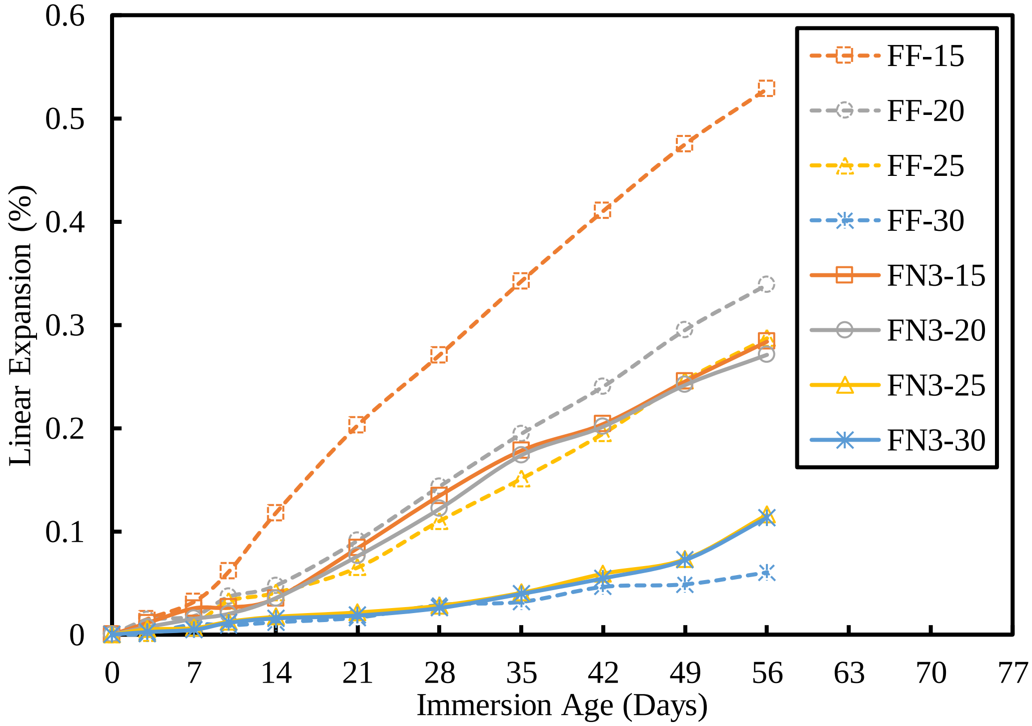


Figure 5.23: Expansion of industrial and N3 natural pozzolan mortars using aggregate source F

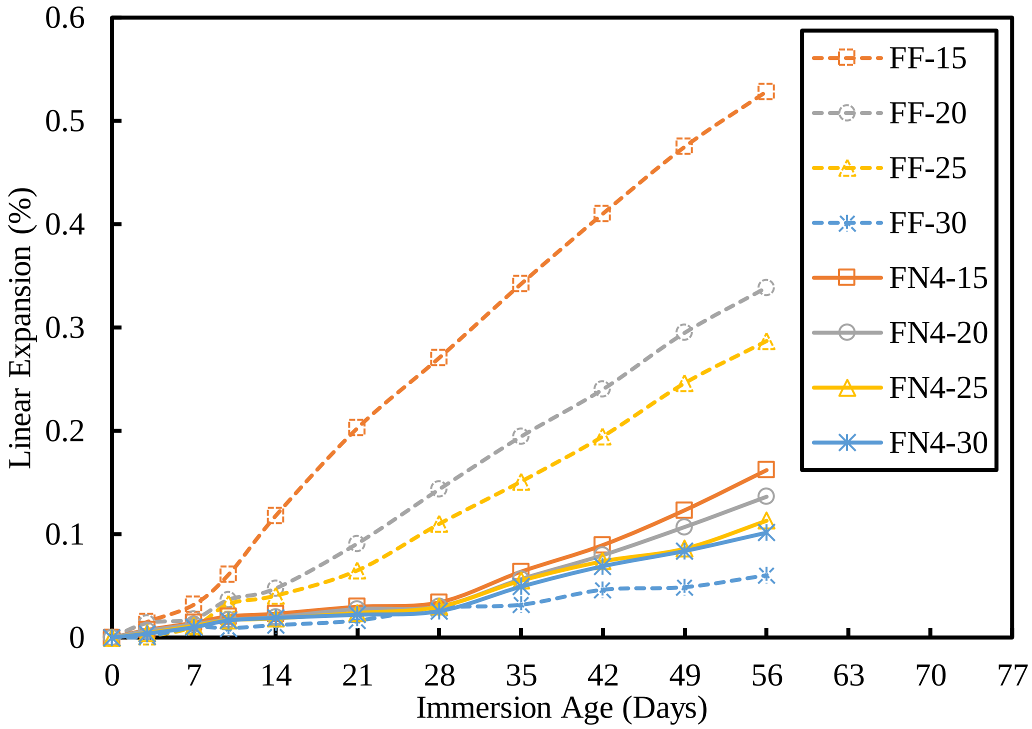


Figure 5.24: Expansion of industrial and N4 natural pozzolan mortars using aggregate source F

Table 5.21: Expansion of industrial and N1 natural pozzolan mortars using aggregate source F

Imm. Ages (Days)	Expansion (%)								
	F-0	FF-15	FF-20	FF-25	FF-30	FN1-15	FN1-20	FN1-25	FN1-30
14	0.3143	0.1178	0.0475	0.0405	0.0120	0.0685	0.0162	0.0150	0.0133
28	0.5655	0.2708	0.1435	0.1100	0.0288	0.1965	0.0408	0.0343	0.0158
56	0.8670	0.5285	0.3388	0.2870	0.0603	0.4498	0.2860	0.2820	0.1258

Table 5.22: Expansion of industrial and N2 natural pozzolan mortars using aggregate source F

Imm. Ages (Days)	Expansion (%)								
	F-0	FF-15	FF-20	FF-25	FF-30	FN2-15	FN2-20	FN2-25	FN2-30
14	0.3143	0.1178	0.0475	0.0405	0.0120	0.0900	0.0480	0.0190	0.0168
28	0.5655	0.2708	0.1435	0.1100	0.0288	0.1955	0.1490	0.0303	0.0270
56	0.8670	0.5285	0.3388	0.2870	0.0603	0.3848	0.3258	0.1145	0.0918

Table 5.23: Expansion of industrial and N3 natural pozzolan mortars using aggregate source F

Imm. Ages (Days)	Expansion (%)								
	F-0	FF-15	FF-20	FF-25	FF-30	FN3-15	FN3-20	FN3-25	FN3-30
14	0.3143	0.1178	0.0475	0.0405	0.0120	0.0353	0.0353	0.0173	0.0158
28	0.5655	0.2708	0.1435	0.1100	0.0288	0.1345	0.1218	0.0280	0.0258
56	0.8670	0.5285	0.3388	0.2870	0.0603	0.2838	0.2710	0.1160	0.1133

Table 5.24: Expansion of industrial and N4 natural pozzolan mortars using aggregate source F

Imm. Ages (Days)	Expansion (%)								
	F-0	FF-15	FF-20	FF-25	FF-30	FN4-15	FN4-20	FN4-25	FN4-30
14	0.3143	0.1178	0.0475	0.0405	0.0120	0.0230	0.0198	0.0185	0.0190
28	0.5655	0.2708	0.1435	0.1100	0.0288	0.0340	0.0300	0.0298	0.0255
56	0.8670	0.5285	0.3388	0.2870	0.0603	0.1620	0.1363	0.1130	0.1015

5.2 Comparison of Loss in Strength (LIS)

5.2.1 Aggregate Source A

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation of 15, 20, 25, and 30% by weight are depicted in Figure 5.25. The actual loss in strength are shown in Table 5.25.

As can be seen, the loses in strength of two-type pozzolan mortars were all below that of the control mortar for the four Portland cement substitution levels. The loss in strength of Class F and natural pozzolan N1, N2, and N3 mortars were similar, whereas the N4 natural pozzolan mortar generated the least loss in strength.

Table 5.25: Loss in strength (LIS) of mortars using aggregate source A

Cement Replacement Level (%)	LIS (%)					
	0	F	N1	N2	N3	N4
15	20.03	16.38	18.91	19.27	18.52	13.23
20	20.03	14.96	15.86	18.14	15.38	10.10
25	20.03	10.76	11.58	15.06	10.48	9.25
30	20.03	8.67	7.80	13.75	6.48	7.11

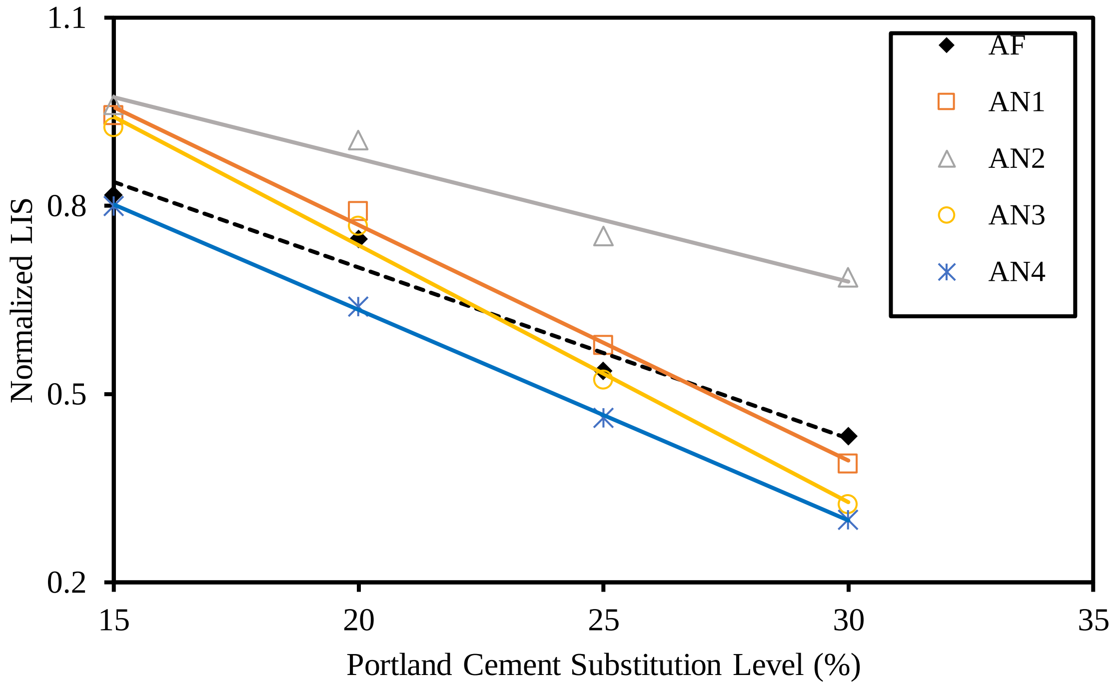


Figure 5.25: Loss in strength of mortars using aggregate source A

5.2.2 Aggregate Source B

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation of 15, 20, 25, and 30% by weight are depicted in Figure 5.26. The actual loss in strength are shown in Table 5.26.

As can be seen, Class F fly ash and N2 and N4 natural pozzolan mortars produced nearly similar losses in strength which were at par with that of the control mortar at the levels of 15 and 20% Portland cement substitution. Once Portland cement replacement level increased to 25 and 30%, both pozzolan type mortars produced a similar loss in strength well exceeding that of the control mortar. Both N1 and N3 natural pozzolan contained mortars were able to produce loss in strength above that of the control mortar at all four Portland cement substitution levels.

Table 5.26: Loss in strength (LIS) of mortars using aggregate source B

Cement Replacement Level (%)	LIS (%)					
	0	F	N1	N2	N3	N4
15	19.75	21.54	35.15	18.08	36.64	23.26
20	19.75	20.58	27.61	17.29	29.82	19.22
25	19.75	16.56	22.87	14.11	26.74	17.34
30	19.75	12.74	19.42	12.19	21.74	14.27

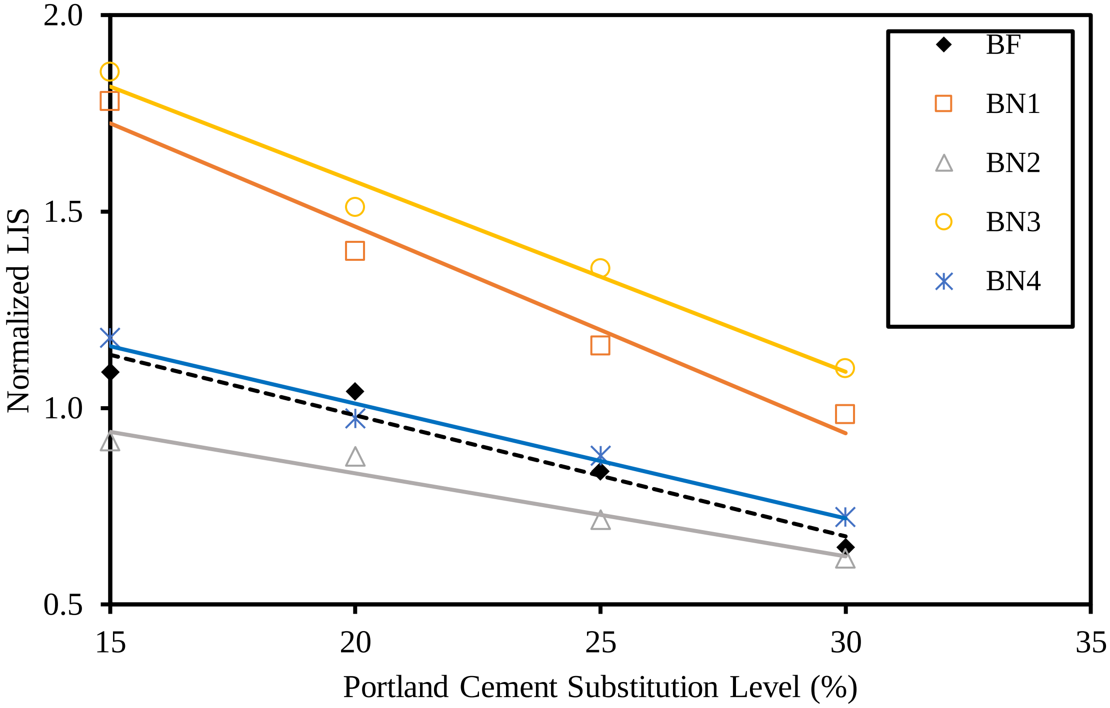


Figure 5.26: Loss in strength of mortars using aggregate source B

5.2.3 Aggregate Source C

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation of 15, 20, 25, and 30% by weight are depicted in Figure 5.27. The actual loss in strength are shown in Table 5.27.

For the aggregate source C, N3 natural pozzolan mortars produced loss in strength below that of fly ash and control mortars. Both N1 and N3 natural pozzolan mortars generated losses in strength well below that of the Class F fly ash mortar. The losses in strength of the N4 natural pozzolan mortars were highest, well above those of the Class F fly ash and control mortars.

Table 5.27: Loss in strength (LIS) of mortars using aggregate source C

Cement Replacement Level (%)	LIS (%)					
	0	F	N1	N2	N3	N4
15	28.00	34.10	40.66	32.31	23.94	40.49
20	28.00	24.27	34.07	29.67	21.76	38.68
25	28.00	20.02	31.61	26.64	17.66	35.05
30	28.00	12.69	21.40	23.73	12.99	34.61

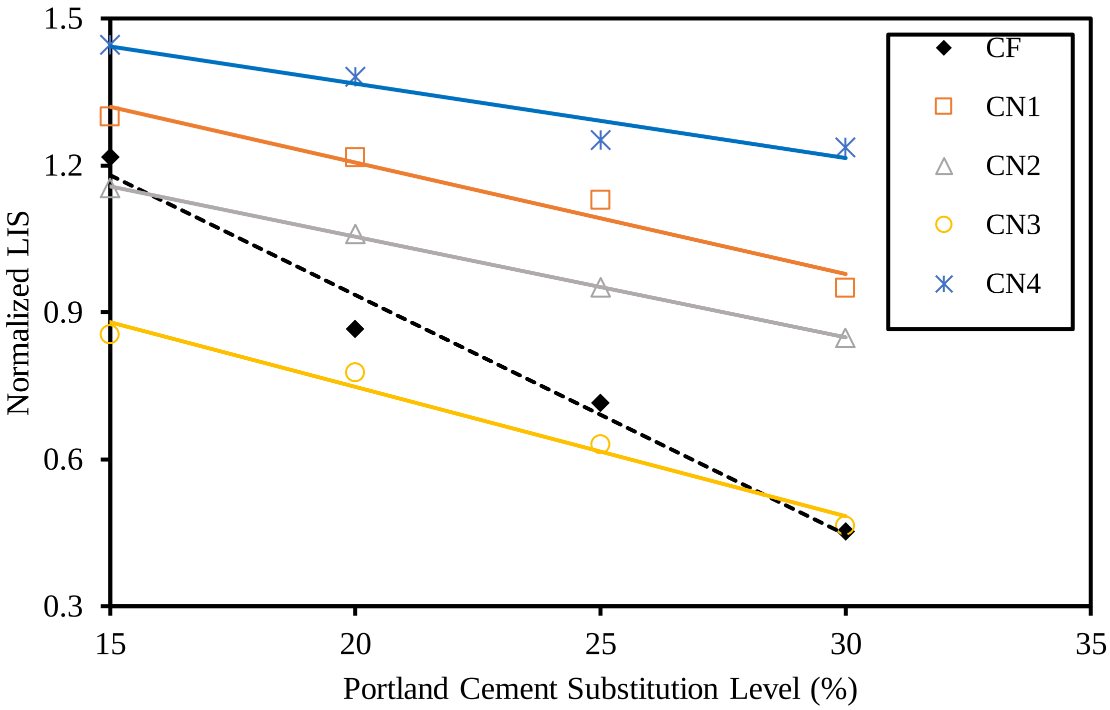


Figure 5.27: Loss in strength of mortars using aggregate source C

5.2.4 Aggregate Source D

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation levels of 15, 20, 25, and 30% by weight are depicted in Figure 5.28. The actual loss in strength are shown in Table 5.28.

When aggregate source D was used for the preparation of the studied mortars, the N1 natural pozzolan contained mortars generated the least losses in strength, well below that of the Class F fly ash and control mortars. The N2, N3 and N4 natural pozzolan mortars, as well as Class F fly ash mortar, produced comparable losses in strength, below that of the control mortar.

Table 5.28: Loss in strength (LIS) of mortars using aggregate source D

Cement Replacement Level (%)	LIS (%)					
	0	F	N1	N2	N3	N4
15	33.23	30.76	21.48	31.74	32.98	34.76
20	33.23	25.57	20.51	30.77	29.52	27.69
25	33.23	23.50	18.74	27.91	20.02	25.07
30	33.23	21.42	13.97	24.30	14.85	20.66

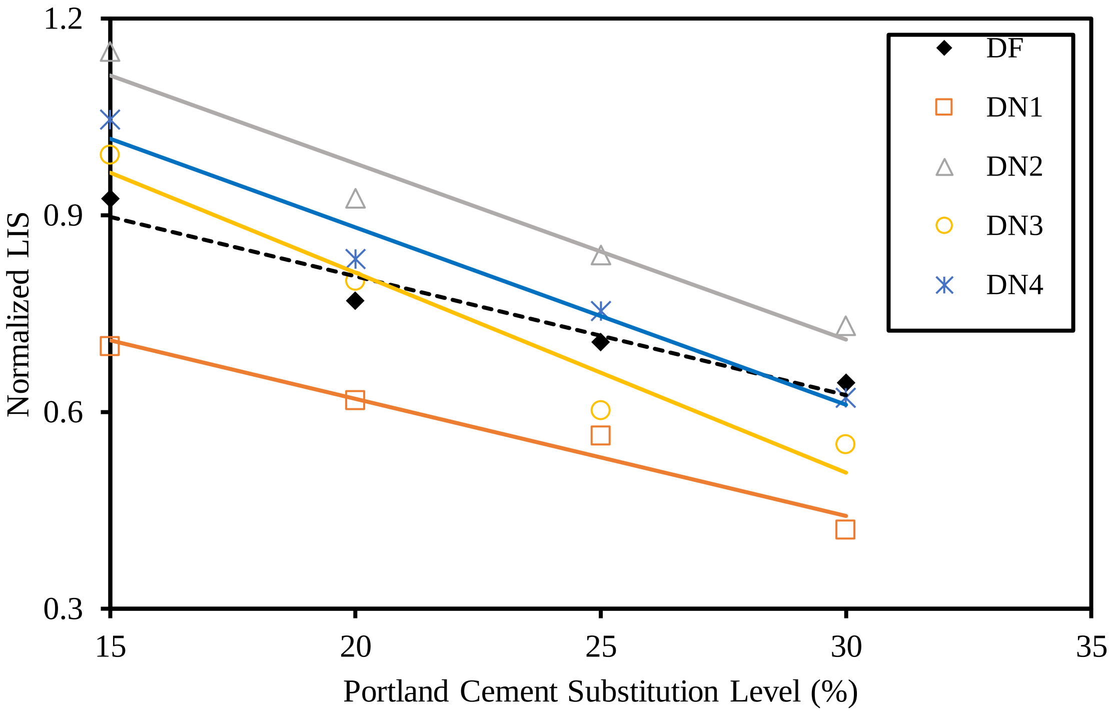


Figure 5.28: Loss in strength of mortars using aggregate source D

5.2.5 Aggregate Source E

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation levels of 15, 20, 25, and 30% by weight are depicted in Figure 5.29. The actual losses in strength are shown in Table 5.29.

As can be seen, while both the pozzolan types produced losses in strength below that of control mortar, their results were mixed and remained relatively comparable at different Portland cement replacement levels.

Table 5.29: Loss in strength (LIS) of mortars using aggregate source E

Cement Replacement Level (%)	LIS (%)					
	0	F	N1	N2	N3	N4
15	58.40	56.05	61.42	57.46	61.78	46.18
20	58.40	52.96	60.63	55.27	53.08	49.95
25	58.40	38.83	51.77	54.56	38.05	45.53
30	58.40	34.83	35.27	48.53	32.68	43.50

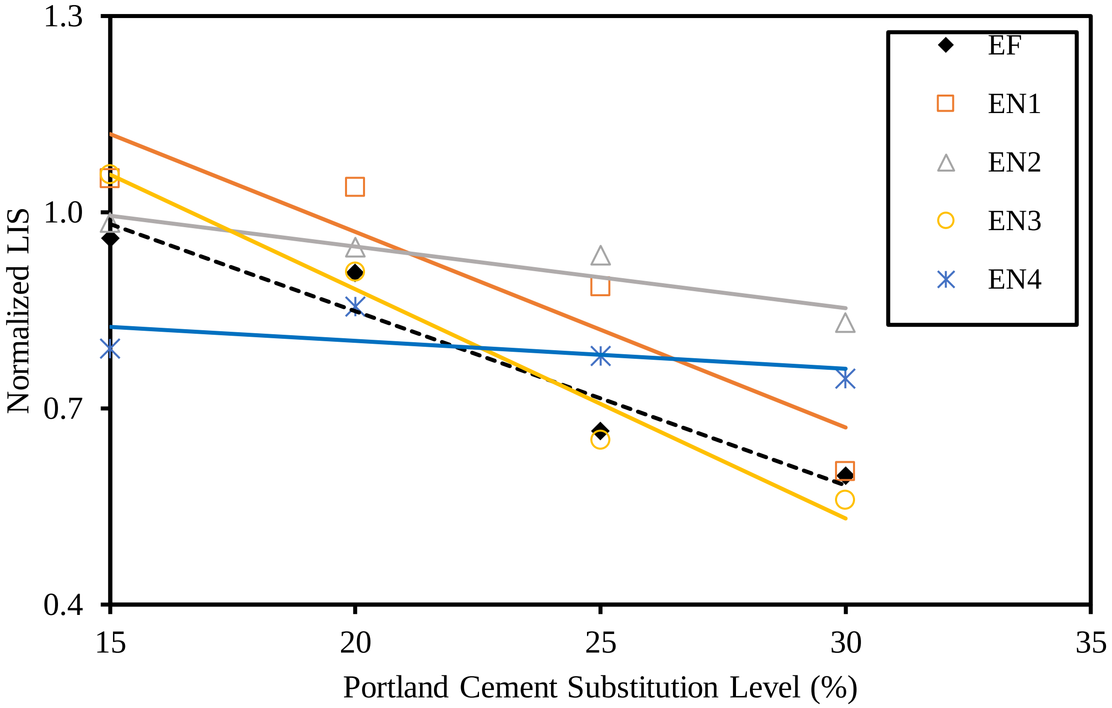


Figure 5.29: Loss in strength of mortars using aggregate source E

5.2.6 Aggregate Source F

The normalized losses in strength of the four natural pozzolan sources and Class F fly ash mortars, in comparison to the loss in strength of the control mortar, for Portland cement substation levels of 15, 20, 25, and 30% by weight are depicted in Figure 5.30. The actual losses in strength are shown in Table 5.30.

As can be seen, both pozzolan types mortars produced losses in strength well below that of the control mortar. Both N1 and N3 natural pozzolan contained mortars had losses in strength below that of the Class F fly ash mortar. The losses in strength of the N2 and N4 natural pozzolan and Class F fly ash mortars were similar.

Table 5.30: Loss in strength (LIS) of mortars using aggregate source F

Cement Replacement	LIS (%)					
Level (%)	0	F	N1	N2	N3	N4
15	30.07	33.95	21.81	37.11	17.94	29.54
20	30.07	29.70	19.62	31.78	16.67	27.68
25	30.07	22.19	13.12	28.54	11.93	26.47
30	30.07	21.39	8.39	20.43	9.51	20.10

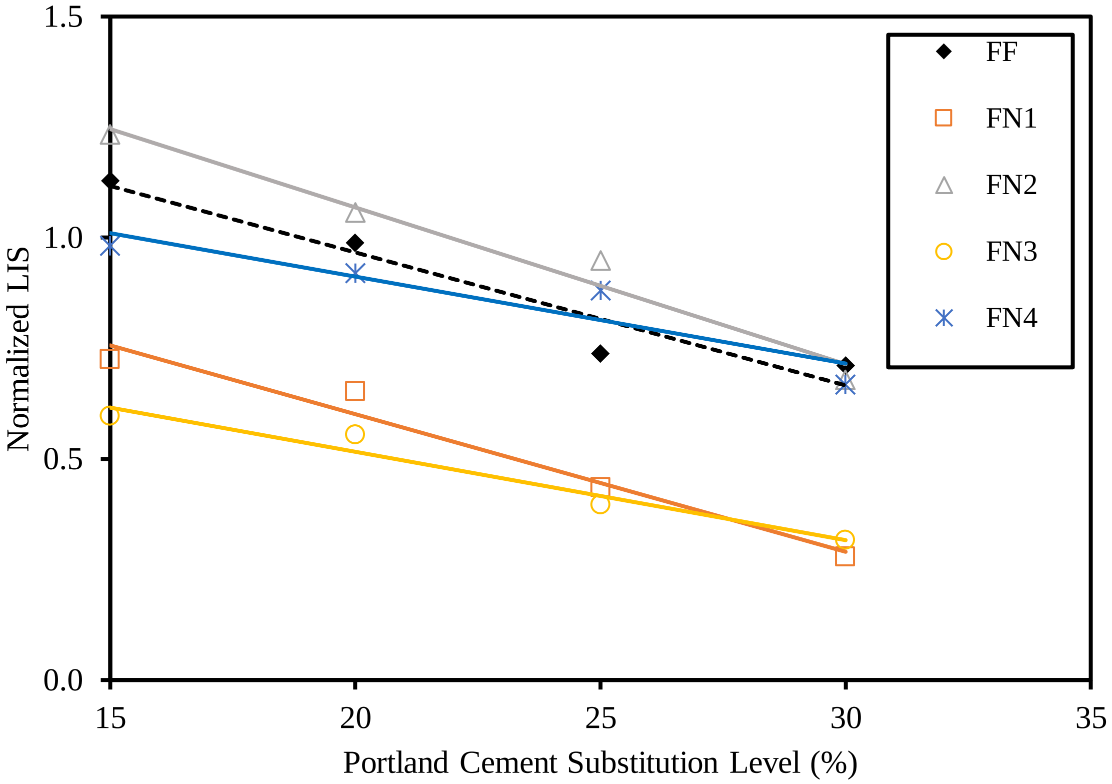


Figure 5.30: Loss in strength of mortars using aggregate source F

Chapter 6
Conclusion

This chapter reports the conclusions of this research study based on the testing performed on mortars prepared using seven aggregate sources, one source of Class F fly ash, four sources of natural pozzolans, and four Portland cement substitution levels. It is highly recommended that any aggregate suspected of alkali-silica reactivity be tested and assessed before it is used in Portland cement concrete. The findings of this study are given in the following three categories.

6.1 Identification of Reactive Aggregate and ASR-Induced Expansions of Control and Natural Pozzolan Contained Mortars

a) From the seven aggregate sources used in this study, only one source (G) was identified as innocuous, whereas the remainders were classified as highly reactive based on the failure limit of 14 days and failure criteria of the extended ages of 28 and 56 days.

b) Based on the failure criteria at the extended ages of 14, 28, and 56 days; the ASR-induced expansions of the studied mortars depended on the aggregate source, natural pozzolan content and source, and immersion age.

c) Based on the failure limit of ASTM C1260, the ASR mitigation of reactive sources A and B required only 15% by weight of Portland cement replacement using any of the four natural pozzolan sources.

d) The ASR mitigation of the mortars containing reactive aggregate source C required 25% by weight substitution of Portland cement by any of the N1, N2, and N3 natural pozzolans. When N4 natural pozzolan was used, 15% by weight replacement of Portland cement was sufficient in suppressing ASR-induced expansion below that of the failure limit of ASTM C1260. Amongst the four natural pozzolan sources, the N4 natural pozzolan mortar exhibited the lowest average ASR-induced expansion.

e) The ASR mitigation of the mortars containing reactive aggregate source D necessitated N1 or N4 natural pozzolan to replace 15% by weight of Portland cement, whereas N2 and N3 natural pozzolans demanded 25% Portland cement replacement to meet the failure criteria of ASTM C1260. N4 natural pozzolan performed best amongst the four natural pozzolan sources to negate ASR-induced expansions of the mortars using aggregate source D.

f) To mitigate the alkali-silica reactivity of mortars containing reactive aggregate E, it was required 15% by weight of Portland cement be replaced by any of the N1, N2, and N4 natural pozzolans. The use of N3 natural pozzolan demanded 25% by weight substitution of Portland cement to meet the failure limit of ASTM C1260. Overall, N4 natural pozzolan showed lowest ASR-induced expansion amongst the four natural pozzolan sources of the mortars using aggregate source E.

g) For the mortars containing reactive aggregate source F, 15% by weight of Portland cement replacement by each of the four natural pozzolan sources was sufficient to mitigate the ASR. Overall, N4 natural pozzolan exhibited the lowest average expansion when compared to other three natural pozzolan sources used in this study.

6.2 Loss in Strength Due to Alkali Silica Reactivity

a) The loss in strength of the studied mortars depended on aggregate and natural pozzolan sources.

b) Irrespective of the aggregate and natural pozzolan sources, the loss in strength of the studied mortars decreased with increases in Portland cement substitution level.

c) For the reactive aggregate source A, all mortars containing natural pozzolan had lower loss in strength than that of the control mortar. N4 natural pozzolan was most effective in minimizing loss in strength followed by N3, N1 and N2 natural pozzolan sources.

d) When reactive aggregate source B was used, the loss in strength of N2 and N4 natural pozzolan mortars were below that of the control mortar which was lower than those of the N1 and N3 natural pozzolan mortars.

e) When reactive aggregate source C was used, only N3 natural pozzolan, and to some extent N1 natural pozzolan, mortars had the loss in strength below that of the control mortar.

f) Substitution of Portland cement by any of the four natural pozzolan sources resulted in the losses in strength well below that of the control mortars containing reactive aggregate source D. The least loss of strength was exhibited by the N1 natural pozzolan followed by the N3, N4, and N2 natural pozzolans in descending order.

g) All natural pozzolan mortars containing reactive aggregate source E displayed loss in strength well below that of the control mortar. The N1 natural pozzolan produced the most loss in strength, whereas N3, N4 and N2 natural pozzolan sources, in descending order, generated the least amount of loss in strength.

h) The loss in strength of nearly all studied natural pozzolan mortars containing reactive aggregate source F were below that of the control mortar. The least loss in strength was obtained by the use of N3 natural pozzolan, followed in descending order by the N1, N4, and N2 natural pozzolans.

6.3 Comparison of Industrial and Natural Pozzolans

a) For the mortars containing reactive aggregate source A, and per failure limit of ASTM C1260, both natural pozzolan and Class F fly ash were successful to mitigate alkali silica reactivity at the rate of 15% by weight of Portland cement replacement. All four natural pozzolan sources were more effective than the Class F fly ash to suppress ASR-induced expansions.

b) For the mortars containing reactive aggregate source B and with 15% Portland cement substitution, both natural pozzolan and Class F fly ash mortars displayed ASR-induced expansions well below the failure limit of ASTM C1260. Overall, the four natural pozzolan sources were from as effective to slightly less effective than the Class F fly ash to mitigate alkali-silica reactivity.

c) For the mortars containing reactive aggregate source C, both industrial and natural pozzolans mitigated the reactivity of the aggregate at the level of 15% by weight of cement replacement per ASTM C 1260 failure limit. Overall, Class F fly ash was more effective than the natural pozzolan to suppress the ASR of the mortars using aggregate source C.

d) The ASR-induced expansions of the mortars containing aggregate source D were successfully reduced to well below the failure criteria of ASTM C1260 using both industrial and natural pozzolans. Class F fly ash mortar required 25% cement substitution to mitigate ASR, whereas N1, N2, N3, N4 natural pozzolans needed

15,25,25 and 15% by weight of Portland cement replacement in order to suppress the reactivity of the aggregate source D.

e) Per ASTM C 1260 failure limit, both industrial and natural pozzolans successfully mitigated alkali-silica reactivity of the mortars containing aggregate source E at the level of 15% by weight of cement replacement. Overall, Class F fly ash mortars produced lower ASR-induced expansions than their companion pozzolan contained mortars for the four cement replacement levels used in this study.

f) Once 15% by weight of Portland cement was used in the mortars containing reactive aggregate F, the ASR-induced expansions of the industrial and natural pozzolan contained mortars decreased well below the failure limit as required by ASTM C1260. Overall, the four natural pozzolan sources and class F fly ash used in this study were similarly effective to mitigate the alkali-silica reactivity of the mortars containing aggregate source F.

g) For all six reactive aggregates used in this investigation, inclusion of the natural and industrial pozzolans in the studied mortars reduced loss in strength well below that of the control mortars. However, both pozzolan types minimized the loss in strength in varying degrees depending on the source of reactive aggregate.

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