

EFFECT OF ASR EXPANSION RATE AND CONFINEMENT ON CONCRETE DEGRADATION

Ammar Abd-Elssamd, Zhongguo John Ma, Yann Le Pape, Nolan W. Hayes, Maria
Guimaraes

Biography:

ACI member **Ammar Abd- Elssamd** is a PhD student at the University of Tennessee, Knoxville, Department of Civil and Environmental Engineering. He received his BS from the University of Khartoum in Sudan and his MS from the University of Tennessee, Chattanooga. His research interests include durability of concrete materials and aging management of alkali-silica reaction (ASR)-affected structures.

ACI member **Zhongguo John Ma** is a professor at the University of Tennessee, Knoxville, Tennessee. He is a member of Joint ACI American Society of Civil Engineers (ASCE) Committee 343 for Concrete Bridge Design and 445 for Shear and Torsion. His research interests include reinforced and prestressed concrete, fiber-reinforced polymers, and evaluation of ASR-affected structures.

ACI member **Yann Le Pape** is a senior scientist with Oak Ridge National Laboratory (ORNL). He received his BS, MS, and PhD in civil engineering from the University of Strasbourg, France. His research interests include the assessment of aging effects on the structural integrity and long-term operation of reinforced and prestressed structures for the nuclear and hydropower industries.

Nolan W. Hayes is a PhD student at the University of Tennessee, Knoxville, Department of Civil and Environmental Engineering. He received his BS from the University of Tennessee, Knoxville. His research interests include concrete deterioration mechanisms and durability performance of aging infrastructure.

1 **Maria Guimaraes** is a program manager at the Electric Power Research Institute (EPRI). She
2 received her bachelor's degree in construction engineering from the Universidad Nacional del
3 Nordeste, Argentina. She obtained her master's degree in soil mechanics and foundation
4 engineering from the University of Newcastle in the United Kingdom. She also holds a
5 doctorate degree in civil and environmental engineering from the Georgia Institute of
6 Technology.

7

8

ABSTRACT

9 Alkali-silica reaction (ASR) is a major deterioration mechanism that affects the durability of
10 concrete structures. As the slow rate of ASR development and the restrained expansion in field
11 concrete might affect the development of ASR damage, an experimental program was
12 performed to investigate the effects of the rate of ASR expansion and confinement on the
13 degradation of mechanical properties of concretes. Literature data on the degradation of
14 mechanical properties of concretes with ASR expansion were collected and analyzed to
15 investigate the influence of the rate of ASR expansion and confinement on the degradation
16 trends. Degradation of mechanical properties was found to be significantly influenced by the
17 rate of ASR expansion and slightly affected by confinements. The slow rate of ASR expansion
18 seems to be beneficial in limiting concrete degradation. The effects of confinement seem to be
19 related to the direction of restraint and crack orientations.

20

21 **Keywords:** alkali-silica reaction, confined concrete, mechanical properties degradation, rate
22 of expansion, crack orientation.

23

INTRODUCTION

24 Alkali-silica reaction in concrete causes formation of alkali-silica gel that can, under certain
25 circumstances, lead to abnormal expansion, cracking, and eventual loss of mechanical

1 properties.¹ The formation of ASR gel and the subsequent expansion in affected structures
2 usually develops over several years, if not decades, before damage (e.g., cracks) can be
3 observed.² Evaluating the degree of ASR formation and the subsequent degraded mechanical
4 properties of affected concrete is essential in developing a reliable structural condition
5 assessment considering in-service operation and structural integrity of ASR- affected structures.
6 During the past two decades, extensive studies have been conducted on the effect of ASR on
7 the loss of mechanical properties of free-expanding laboratory specimens under accelerated
8 conditions, namely the reduction of elastic modulus and compressive and tensile strengths.³⁻¹⁷
9 Despite the overall reduction trend of mechanical properties as a function of ASR expansion,
10 it is difficult to predict how much reduction of properties can be expected at a given expansion
11 level. This challenge can be attributed to many factors that can impact the degradation trend:
12 concrete mix,¹⁸ aggregate types and reactivity,³⁻⁵ expansion rate and magnitude,⁴ and restraint
13 condition.^{15,19,20} In addition to these factors, the main question remains as to whether the results
14 from accelerated conditions under free-expansion can represent the behavior of field concrete.
15 The ASR in structures develops over years or even decades under the restraint and confined
16 conditions imposed particularly by structural elements, permanent loading, and reinforcement
17 configurations. ASR concretes under confined conditions tend to expand in the direction of
18 least stress, so the ASR cracks will be mostly oriented perpendicular to that direction.^{6,15,21} On
19 the other hand, the rate of ASR expansion plays a major role in ASR damage progression and
20 subsequent degradation of mechanical properties.³ Two additional time-dependent
21 mechanisms take place concurrently during ASR development: the maturity development
22 caused by cementitious material hydration, and creep. When ASR-induced expansion develops
23 at a relatively slow rate, the ongoing cement hydration can contribute to the offset of ASR
24 damage by allowing the concrete to develop its strength and mature before the effects of ASR
25 manifest.^{3,5} The creep of the cement paste can also influence ASR damage progress as

1 investigated by Giorla et al.² Creep can play a major role in relaxing the slowly developed
2 stresses induced by ASR gel pressure, consequently reducing the extent of ASR damage.
3 However, more damage can be induced when the rate of ASR increases².
4 As there are many factors that can influence the degradation trend of mechanical properties of
5 ASR-affected concrete, this paper focuses on two major factors that are essential in field
6 concretes: ASR expansion rate and confinements. The paper addresses (1) new experimental
7 data on the effect of ASR on the mechanical properties of confined concrete coupled with the
8 effects of the rate of ASR development are presented, and (2) analysis of data from literature
9 to investigate the influence of the rate of ASR expansion and confinement on the degradation
10 trends.

11
12 **RESEARCH SIGNIFICANCE**

13 Most studies on the degradation of mechanical properties of ASR-affected concretes have been
14 conducted in accelerated conditions under free expansion, which might not accurately represent
15 the ASR development and subsequent degradation of field concretes. Thus, for a more realistic
16 assessment of ASR-affected field concretes, the influence of the expansion rates and
17 confinements on the degradation trends of mechanical properties need to be addressed. This
18 paper establishes degradation trends between mechanical properties of ASR-affected concrete
19 and the measured expansion of concrete in order to assess the condition of affected concretes.

20
21 **EXPERIMENTAL INVESTIGATION**

22 A testing program was conducted on 150 cylinders 4 × 8 inch (~100 × 200 mm) in size. The
23 cylinders were cast with two types of reactive aggregates—slowly reactive aggregate and
24 highly reactive (quick) aggregate—and under two conditions—biaxial confinement (confined)
25 and free expanding (unconfined). Two types of aggregate reactivity were selected to assess the

1 influence of relatively slow and quick ASR development on concrete degradation. The lateral
2 confined condition forced the ASR expansion to develop parallel to the casting direction only,
3 while under the unconfined condition, expansion occurs in all directions. Mechanical properties
4 that have been studied include compressive strength (per ASTM C469), elastic modulus (per
5 ASTM C39), and tensile splitting strength (per ASTM C496). The degradation of mechanical
6 properties caused by ASR development was evaluated at low expansion of <0.1%, moderate
7 expansion of 0.1–0.15%, and high expansion of 0.2–0.3%. Nonreactive samples were prepared
8 to serve as control experiment specimens.

9

10 **Materials and testing**

11 The aggregates used to cast the mixtures include a highly reactive limestone coarse aggregate
12 from Clarkesville, Tennessee (HRC), a slowly reactive limestone coarse aggregate from
13 Caryville, Tennessee (SRC), a nonreactive limestone coarse aggregate from Blountville,
14 Tennessee (NRC), and a nonreactive natural sand from North Carolina (NRF). **Table 1** shows
15 the aggregate reactivity based on the results from the ASTM C1260 mortar-bar test and the
16 ASTM C1293 concrete prism test. Type I Portland cement with a relatively high equivalent
17 alkali content (1.04% Na₂O_{eq}) was used. The materials were used to cast three different
18 mixtures: highly reactive (HR), slowly reactive (SR) and, nonreactive (NR). All mixtures were
19 alkali boosted by adding a 50% (weight/weight) sodium hydroxide solution (NaOH) to increase
20 the alkali content of concrete to 10.6 lb/yd³ (6.30 kg/m³). The mixture proportions for the
21 specimens are provided in **Table 2**.

22 Five groups of cylinders were prepared from concrete batches of the HR, SR, and NR mixtures:
23 nonreactive cylinders to serve as control specimens (control-NR), confined slowly reactive
24 (CON-SR) cylinders, unconfined slowly reactive (UNC-SR) cylinders, confined highly
25 reactive (CON-HR) cylinders, and unconfined highly reactive (UNC-HR) cylinders. The

1 control-NR, UNC-SR, and UNC-HR cylinder specimens were removed from their casting
2 molds 48 hours after casting. The confined specimens, CON-SR and CON-HR, were cast and
3 kept in relatively rigid steel cylinders with a ¼ in (6.4 mm) wall thickness until testing. A
4 release agent (WD-40) was applied to the internal surfaces of steel cylinders to minimize
5 friction between the concrete and steel during ASR expansion. Companion specimens include
6 4 × 8 in (100 × 200 mm) plastic cylinders for the unconfined condition, 4 × 8 in (100 × 200 mm)
7 steel cylinders for the confined condition, and 3 × 3 × 11 in (76.2 × 76.2 × 279.4 mm) prisms
8 which were cast to assess the potential expansion and weight variations during conditioning.
9 After casting, the specimens were covered and conditioned at 65 – 75°F (18 – 24°C) and
10 55–60% relative humidity (RH) for 48 hours prior to being removed from the molds and
11 undergoing an initial length and weight measurement. Specimens were then moved to a
12 chamber maintained at 73 ± 2°F (23±1°C) and 85 ± 5% RH for 28 days to minimize ASR
13 development while allowing the concrete hydration process to advance for 7 and 28 days
14 without ASR expansion. After 28 days, the temperature of the chamber was increased to 100°F
15 (38°C), and the humidity was increased to 95% RH, conditions similar to those specified in
16 ASTM C1293, to allow ASR progression for a period of 15 months. Expansion and weight
17 gain of companion specimens was monitored until target expansions were achieved. The
18 expansion was measured using a length comparator device (with an accuracy of 0.0001 in.) to
19 evaluate the change in length periodically after the initial measurement at 48 hours after casting.
20 The weight of specimens was measured using a scale (with an accuracy of 0.1 g.) immediately
21 after expansion measurement to evaluate the percentage of weight gain periodically after the
22 initial measurement at 48 hours after casting. Target average expansions for slowly reactive
23 cylinders were 0.05%, 0.10%, 0.15% (±0.02%), and greater than 0.15%. Target expansion
24 levels for the highly reactive cylinders were 0.15%, 0.25%, 0.30%, 0.35% (±0.02%), and
25 greater than 0.35%.

1 Once the companion cylinders reached the desired expansion value, five of them were removed
2 from the chamber for concrete properties testing. Of the five cylinders removed, three
3 underwent testing for compressive strength and modulus of elasticity, and two were subjected
4 to testing for splitting tensile strength. The unconfined cylinders containers were placed in a
5 room at 65–75°F and 55–60% RH for 24 hours before testing. The steel confinement around
6 the confined cylinders was removed using a diamond cutting saw 24 hours after the cylinders
7 were removed from the chamber. Then the cylinders were placed in a room at 65–75°F and
8 55–60% RH for another 24 hours to relax the stresses from confinement before testing.

9

10 **EXPERIMENTAL RESULTS AND DISCUSSION**

11 **Weight and expansion measurements on companion specimens**

12 The evolution of weight and ASR expansion for the three concrete mixtures over a 455-day
13 duration was measured for all companion specimens (**Fig 1**). The percentage of weight gain,
14 which was mainly due to moisture uptake by companion specimens, is shown in **Fig. 1a**. A
15 significantly lower weight gain of <0.4% can be observed in the confined specimens as
16 compared to a weight gain of 1.0–1.4% in the unconfined specimens. The sealing effect of the
17 steel molds significantly reduced the exposed surfaces for moisture uptake by confined
18 specimens, with an almost 80% reduction in exposed surface area. At the end of conditioning
19 period, the 1.2–1.4% weight gain for HR unconfined specimens was higher than the 1–1.2%
20 weight gain in the SR unconfined specimens. The NR concrete exhibited the lowest weight
21 gain among the unconfined samples as a result of crack formation during ASR development.
22 **Figure 2** shows more cracks in HR samples, less cracks in SR samples, and no cracks in NR
23 samples.

24 According to Multon et al.⁸ and Gautam et al.,²² volumetric expansion induced by ASR
25 is approximately constant for free expanding and restrained concrete with at least one

1 unrestrained direction, regardless of its stress state or boundary conditions. This conclusion
2 was also confirmed for large concrete specimens in a recent study conducted by Hayes et al.¹⁹
3 However, concrete under a triaxial state of stress exhibits a lower rate of volumetric expansion
4 compared to the rate of volumetric expansion under a uniaxial or biaxial stress condition.^{8,22} In
5 this study, the volumetric expansion (**Fig. 1d**) of the unconfined and confined cylinders can be
6 estimated using the following equation⁸:

$$7 \quad \varepsilon_{\text{vol.}} = \varepsilon_{\text{ax.}} + 2\varepsilon_{\text{lat.}}, \quad (\text{Eq. 1})$$

8 where

9 $\varepsilon_{\text{vol.}}$ = volumetric expansion %;

10 $\varepsilon_{\text{ax.}}$ = longitudinal expansion (axial) %; and

11 $\varepsilon_{\text{lat.}}$ = lateral expansion (radial) %.

12 For the unconfined cylinders, the longitudinal exp.% represents expansion measured on the
13 companion unconfined cylinders along the casting direction, and the lateral exp.% represents
14 expansion measured on the companion prisms perpendicular to the casting direction. While the
15 longitudinal exp.% represents expansion measured on the companion confined cylinders along
16 the casting direction, the lateral expansion was assumed to be zero due to steel mold
17 confinement. This leads to some underestimation, though minor, of the actual volumetric
18 expansion.²³ **Fig. 1 (a) and (d)** illustrate the effect of internal moisture content on the
19 development of volumetric ASR expansion. While significant ASR expansion occurred in
20 confined samples with limited external water supply (0.16% and 0.25% expansion for CON-
21 SR and CON-HR mixtures, respectively), the sealing effect from confinement accounted for
22 60% and 70% reduction in volumetric expansion potential for SR and HR mixtures respectively.
23 The sealing effect and boundary conditions (confinement and stress state) can contribute to the
24 heterogeneity of ASR in field concrete.

25

1 **Material properties**

2 **Figures 3a, b, and c** present the evolution of the compressive strength, tensile strength, and
3 elastic modulus, respectively, for the different concrete mixtures. The measured properties
4 were represented by the mean and standard deviation for three specimens at each time step,
5 except only two specimens were used for the splitting tensile strength. All three properties were
6 showing similar evolution due to the cement hydration process for all specimens until 28 days.
7 The evolution of properties in NRC is used as a reference for the strength gain due to cement
8 hydration in the following discussion (i.e., the slope of the NR line between 28 and 455 days).
9 As shown in **Fig. 3a**, the compressive strength of NRC increased 50% at 455 days when
10 compared with its value at 28 days. The increase in compressive strength due to cement
11 hydration in reactive samples overcomes the loss of strength due to ASR during the early stage
12 of expansion. However, at a later stage, the compressive strength either decreases or stays
13 relatively constant, reflecting the effect of ASR damage on compressive strength. The confined
14 specimen showed a remarkable gain in its 28-day strength when compared to the unconfined
15 specimens, which seemed to be affected by ASR progression. Nevertheless, ASR damage does
16 not seem to decrease the 28-day compressive strength before a linear expansion of
17 approximately 0.35% is achieved. Similar behavior can be observed in the evolution of splitting
18 tensile strength (**Fig. 3b**). The ongoing hydration seemed to overcome the losses due to ASR
19 damage for most of the reactive samples. However, ASR expansion seems to affect the tensile
20 strength by 23% maximum reduction, which is significantly more than the 5% maximum
21 reduction in compressive strength. The highly reactive specimens showed more degradation,
22 reflecting the effect of the high expansion rate. **Figure 3c** shows the evolution of the elastic
23 modulus over time. A quick drop of the elastic modulus was observed in all the reactive
24 samples except for the confined slowly reactive sample, which only showed a 2% reduction.
25 The elastic modulus is a good indicator for the early stage of ASR development. The rapid

1 decrease at a relatively early time could be related to the rate of ASR development. It can also
2 be observed that cement hydration has less contribution on the offset of ASR damage in elastic
3 modulus during early ASR as compared with the compressive strength and tensile strength.

4

5

ANALYSIS OF LITERATURE DATA

6 Experimental data were collected from literature and from data obtained in the present study to
7 investigate the influence of ASR expansion rates and the confinement on the loss of mechanical
8 properties of affected concretes, namely the reduction of elastic modulus, as well as
9 compressive and tensile strengths. The data on free expansion were collected from several
10 studies^{3-17,19,24} to investigate the influence of ASR expansion rates (e.g., % expansion/ year) on
11 the loss of mechanical properties. Limited data on the loss of mechanical properties in
12 specimens under confined expansion were collected, including data from Jones and Clark,⁶
13 Gautam,¹⁵ and Hayes et al.,¹⁹ in addition to the data from the present study. The literature data
14 were classified based on the rate of ASR expansion and confinement, and then a simple
15 regression analysis was conducted.

16

Summary of literature data

17 **Figure 4** presents the literature data collected by the authors relating the averaged linear ASR-
18 induced expansion to the loss of relative modulus of elasticity and compressive strength. The
19 properties from each data set are normalized to the corresponding value at 28 days. The data
20 indicate that the modulus of elasticity is the most sensitive mechanical property regarding ASR
21 progression, while the degradation of the compressive strength seems to be lower than that of
22 the elastic modulus. The reported effects of ASR on the compressive strength were
23 contradictory, as both gain and reduction of the property have been reported in relation to ASR
24 expansion. Despite the overall trend of reduced mechanical properties as a function of linear
25 expansion.

1 ASR expansion, it is difficult to predict how much properties will be reduced at a given
2 expansion level due to the influence of factors such as concrete mix, aggregate types and
3 reactivity, expansion rate and magnitude, and restraint condition. Hence, further analysis is
4 needed.

5 **Table 3** and **Table 4** summarize the experimental studies and conditioning regimes related to
6 data analyzed in this paper. The concretes are classified solely on the basis of the rate of ASR
7 expansion, regardless of their mix design, as discussed in the following section. The majority
8 of the studies included a pretreatment conditioning for specimens at 68–73°F (20–23°C) in
9 humid conditions for several days before the initiation of the accelerated ASR condition. The
10 studies conducted by Swamy and Al-Asali,³ Giaccio et al.,⁴ Ben Haha,⁹ and Jones and Clark⁶
11 did not include pretreatment conditioning. The ASR conditioning was mostly conducted at
12 100°F (38°C) and >95% RH, with the exception of Na et al.,¹⁴ Fan and Hanson,¹⁰ and Hafic,¹¹
13 who placed the specimens in NaOH solutions. Experimental studies and conditioning regimes
14 for confined specimens are summarized in **Table 5**.

15

16 **Estimation of volumetric expansion**

17 The experimental data on the loss of mechanical properties were mainly reported as a function
18 of linear expansion measured on companion specimens such as prisms (expansion
19 perpendicular to casting direction) and/or cylinders (expansion parallel to casting direction)
20 (Table 3). Expansion data from Gautam¹⁵ and Hafic¹¹ were collected on cube specimens, and
21 Hayes et al.¹⁹ collected expansion data from large blocks.

22 Samples under free expansion tend to expand in the direction parallel to the casting direction
23 (expansion anisotropy).²⁵ **Figure 5** shows that expansion along the casting direction measured
24 in the cylinders is about 1.52 times that measured in prisms perpendicular to the casting
25 direction. This value is consistent with the coefficients of anisotropy reported by Smaoui et al.,

1 ²⁶ which range between 1.45–1.98. While the shape of the specimen (i.e., prism vs. cylinder)
 2 might have an influence on ASR expansion, results from Smaoui et al.²⁶ indicate that the
 3 average three-dimensional expansion for cylinders and prisms with comparable size are quite
 4 similar. Moreover, concretes under confined conditions tend to expand in the direction of least
 5 stress. However, the volumetric expansion induced by ASR is approximately constant for free
 6 expanding and restrained concrete with at least one unrestrained direction, regardless of stress
 7 state or boundary conditions.^{8,19,22} Therefore, for a realistic assessment of ASR development,
 8 ASR expansion for a given concrete under free or restrained expansion should be presented in
 9 terms of volumetric expansion rather than linear expansion. Volumetric expansions for the data
 10 were estimated based on the linear relationship between casting directions (**Fig. 5**) using the
 11 equation below:⁸

$$\epsilon_{\text{vol.}} = \epsilon_{\text{Par.}} + 2\epsilon_{\text{Perp.}}, \quad (\text{Eq. 2})$$

12 where

13 $\epsilon_{\text{vol.}}$ = volumetric expansion %;

14 $\epsilon_{\text{Par.}}$ = expansion parallel to casting direction %; and

15 $\epsilon_{\text{Perp.}}$ = expansion perpendicular to casting direction %.

16 If the ASR expansion were measured in longitudinal prisms, then the volumetric expansion
 17 was estimated as

$$\epsilon_{\text{vol.}} = 1.52 * \epsilon_{\text{Perp.}} + 2 * \epsilon_{\text{Perp.}} = 3.52 * \epsilon_{\text{Perp.}}, \quad (\text{Eq. 3})$$

18 where

$$\epsilon_{\text{Par.}} = 1.52 * \epsilon_{\text{Perp.}}$$

19 Similarly, if the ASR expansion were measured in vertical cylinders, then the volumetric
 20 expansion was estimated as

$$\epsilon_{\text{vol.}} = \epsilon_{\text{Par.}} + 2 * (0.66) * \epsilon_{\text{Par.}} = 2.32 * \epsilon_{\text{Par.}}, \quad (\text{Eq. 4})$$

21 where

$$\epsilon_{\text{Perp.}} = 0.66 * \epsilon_{\text{Par.}}$$

1 For the data collected on cube specimens (Gautam¹⁵ and Hafic¹¹) or blocks (Hayes et al.¹⁹), the
2 volumetric expansion is the summation of the expansions along x, y, and z directions.

3

4 **Concrete classification**

5 Concretes are classified solely on the basis of their rate of volumetric ASR expansion
6 (i.e., % expansion/year), regardless of their mix design and conditioning regimes. Following
7 the classification proposed in ASTM C1778-16, Standard Guide for Reducing the Risk of
8 Deleterious Alkali-Aggregate Reaction [AAR] in Concrete, the concretes were classified into
9 three categories based on the rate of ASR expansion in the concrete prism test (ASTM C1293).

10 The three categories are as follows:

- 11 1. moderately or slowly reactive (SR) at $0.04 (0.14) \leq \text{exp. \% / year} < 0.12 (0.42)$,
- 12 2. highly reactive (HR) at $0.12 (0.42) \leq \text{exp. \% / year} < 0.24 (0.84)$, and
- 13 3. very highly reactive (VHR) at $\text{exp. \% / year} \geq 0.24 (0.84)$

14 Note that the values in brackets are the estimated volumetric expansion using **Eq. 3**.

15

16 **The effects of ASR expansion rates on the loss of mechanical properties**

17 **Figure 6** shows the degradation of compressive strength and elastic modulus for unconfined
18 concretes as a function of the volumetric expansion under different ASR expansion rates. The
19 compressive strength and elastic modulus were normalized to the values of these properties at
20 28 days after casting or at the value when ASR linear expansion is less than 0.04% (ASTM
21 C1293 limit for nonreactive concrete). The data demonstrate that the effect of ASR expansion
22 on compressive strength and elastic modulus is significantly influenced by the rate of ASR
23 development: as the rate of ASR expansion increases, the reduction of properties increases at
24 the same expansion level. At a 0.5% volumetric expansion, while up to 50% reduction of elastic
25 modulus can occur at a very high rate of ASR expansion, the reduction was limited to 20–25%

1 for the slow rate of ASR expansion. Similarly, while no significant reduction of compressive
2 strength below the 28-day value was observed for the high and slow rates of expansion,
3 significant reduction at a very high rate of ASR expansion was observed.

4 Good logarithmic correlation with the coefficient of determination $R^2 = 0.9$ is observed
5 between elastic modulus and volumetric expansion at the very high rate of expansion, and
6 lower values for R^2 are obtained as the rate of ASR expansion reduces (0.62 for HR and 0.6
7 for SR). This could be mainly attributed to the ongoing cement hydration and creep, which
8 might affect the degradation trend for different concrete mixtures with slower expansion rates.

9 At the very high rate of expansion, the effects of ASR expansion are dominant, so a strong
10 correlation is observed. This observation is more pronounced in the evolution of compressive
11 strength at different expansion rates. At slow rates of ASR expansion, the compressive strength
12 continued to increase due to the ongoing cement hydration without reduction. The contribution
13 of cement hydration appears to be encountered by ASR damage as the rate of ASR expansion
14 increases.

15 Relatively good correlations ($R^2 = 0.74$) are observed between degradation of compressive
16 strength and volumetric expansion at very high expansion rates when ASR effects are dominant.

17 In contrast, at low rates of expansion, the effects of cement hydration seem to dominate, and a
18 continuous gain of compressive strength with ASR expansion is noted. At high rates of
19 expansion, the correlation was poor ($R^2 = 0.30$) due to the effects of competing mechanisms,
20 ASR expansion, cement hydration, and creep. Although many studies concluded that
21 compressive strength is not a good indicator for ASR progress,^{3,4} the data suggest that
22 compressive strength can be a good indicator for the rate of ASR expansion.

23 The degradation of tensile splitting strength of unconfined concretes with volumetric expansion
24 for different ASR expansion rates is shown in **Fig. 7**. The tensile data presented were limited
25 for up to the volumetric expansion of 1.0%, as there was significant scatter in data above this

1 limit. Jones and Clark⁶ observed that the scatter of tensile splitting data increases with ASR
2 expansion. This was attributed to the sensitivity of the testing setups to crack orientations on
3 the surfaces of specimens. The tensile splitting strength of unconfined concretes appears to be
4 affected by the rate of ASR expansion to some extent. Similar behavior for the high and slow
5 rates of expansion was observed at up to 0.5% volumetric expansion with a maximum of 1–
6 20% reduction. The very high rate of expansion showed rapid reduction, with up to 40%
7 reduction at 0.5% volumetric expansion—twice the reduction of the slow and high rates of
8 expansion. Relatively good correlation is observed for the very high rate of expansion ($R^2 =$
9 0.78) compared to those at high and low rates of expansion ($R^2 = 0.60 - 0.61$).

10 It is clear from the data presented in this section that the degradation trends of mechanical
11 properties of ASR-affected concretes are significantly influenced by the rate of ASR expansion
12 and damage progression. At the same expansion level, concrete with a high rate of expansion
13 can experience more degradation than that with a slower rate of ASR expansion.

14

15 **The effects of confinements on the loss of mechanical properties**

16 To investigate the effects of confinement on the degradation of mechanical properties,
17 experimental data on confined and unconfined ASR concretes with similar expansion rates
18 were analyzed. **Figure 8** shows the degradation of elastic modulus, compressive strength, and
19 tensile splitting strength for confined and unconfined concretes under very high rates of ASR
20 expansion. Experimental data on confined specimens with very high rates of ASR expansion
21 were limited to the data collected from Jones and Clark.⁶ **Figures 8a** and **8b** show almost
22 similar degradation trends between confined and unconfined concretes in elastic modulus and
23 compressive strength. Samples that were restrained parallel to the loading direction exhibited
24 lower degradation than unconfined specimens. The reduction of compressive strength and
25 elastic modulus are higher in samples with ASR cracks that are mostly oriented perpendicular

1 to the direction of loading during mechanical testing, which can be attributed to the cracks'
2 closing mechanism.^{15,21} Limited data on confined tensile splitting strength suggest that the
3 confinement direction might similarly impact the tensile strength, as shown in **Fig. 8c**.
4 The experimental data on confined specimens with slow rate of ASR expansion were collected
5 from Gautam,¹⁵ Hayes et al.,¹⁹ and the present study, as shown in **Fig. 9**. The degradation trends
6 of concrete with slow rates of ASR expansion are significantly influenced by the competing
7 mechanisms: ASR expansion, cement hydration, and creep. Nevertheless, the degradation of
8 elastic modulus and splitting tensile strength are affected by the direction of confinement
9 relative to loading direction. Specimens restrained perpendicular to loading direction (cracks
10 are likely to be horizontal) exhibit higher stiffness degradation than that of free expansion and
11 restrained expansion (parallel to loading) specimens. Compressive strength of slowly reactive
12 specimens (confined and unconfined) seems to be mainly controlled by cement hydration. The
13 data presented in this section suggest that the confinement has less impact on the degradation
14 of the mechanical properties of ASR concrete. However, the direction of confinement and
15 subsequent crack orientation might significantly impact the degradation trend of modulus of
16 elasticity.

17

18 **SUMMARY AND CONCLUSIONS**

19 Testing was performed and literature data were collected to investigate the effects of the rate
20 of ASR expansion and confinement on the degradation trends of mechanical properties of ASR-
21 affected concretes, namely the elastic modulus, compressive strength, and tensile splitting
22 strength. The main findings are summarized below.

- 23 1. The degradation trend of mechanical properties of ASR-affected concrete is significantly
24 influenced by the rate of ASR expansion and slightly affected by confinements. At the same
25 expansion level, concrete with a higher rate of ASR expansion can experience more

1 degradation than one with a slower rate of ASR expansion. The direction of confinement
2 and subsequent crack orientation might impact the degradation trend of elastic modulus.
3 The reduction of elastic modulus is higher when ASR cracks mostly orient perpendicular
4 to the direction of loading.

5 2. The behavior of field concrete is most likely represented by experimental studies
6 conducted at slow ASR expansion rates rather than those conducted at high or very high
7 rates. The effect of ASR damage on field concrete is most likely offset or minimized by
8 continuing hydration of concrete and creep of the cement paste.

9 3. ASR expansion rate is sensitive to confinement and stress conditions. Interior concrete
10 within a structure might exhibit a lower volumetric expansion than exposed external
11 concrete surfaces due to the coupled effects of water supply reduction and triaxial state of
12 stresses.

13 4. A logarithmic correlation with the coefficient of determination of $R^2 = 0.9$ is observed
14 between elastic modulus and volumetric expansion at a very high rate of expansion.
15 However, lower values of R^2 are obtained as the rate of ASR expansion reduces (0.62 for
16 high rate and 0.6 for slow rate) due to the potential effects of cement hydration and creep
17 of the cement paste. Similar observation is noted in the degradation trends of tensile
18 splitting strength.

19 5. The effects of ASR expansion are not just on the reduction of compressive strength below
20 its 28-day value, but also on the reduction of strength gain with time after 28 days.
21 Therefore, the gain of concrete strength with time must be considered when evaluating the
22 effects of ASR on concrete strength. Relatively good correlation ($R^2 = 0.74$) is observed
23 between degradation of compressive strength and volumetric expansion at very high
24 expansion rates when ASR effects are dominant. In contrast, at low rates of ASR

1 expansion, the effects of cement hydration seem to dominate, and thus a continuous gain
2 of compressive strength with ASR expansion is noted.

4 ACKNOWLEDGMENTS

5 This work is part of a research project entitled “Aging Management of ASR affected structures.”
6 The authors would like to express their gratitude and sincere appreciation to the Electric Power
7 Research Institute (EPRI) for funding this project.

9 REFERENCES

- 10 1. Thomas, M. D., Fournier, B., Folliard, K. J., “Alkali- Aggregate Reactivity (AAR) Facts
11 Book,” Technical Report No. FHWA-HIF-13-019, United States, Federal Highway
12 Administration, Office of Pavement Technology, 2013.
- 13 2. Giorla, A. B., Scrivener, K. L., and Dunant, C. F., “Influence of Visco-elasticity on the Stress
14 Development Induced by Alkali–Silica Reaction,” *Cement and Concrete Research*, V. 70,
15 April 2015, pp. 1–8.
- 16 3. Swamy, R., and Al-Asali, M., “Expansion of Concrete Due to Alkali- Silica Reaction,” *ACI*
17 *Materials Journal*, V. 85, No. 1, January–February 1988, pp. 33–40.
- 18 4. Giaccio, G., Zerbino, R., Ponce, J., and Batic, O., “Mechanical Behavior of Concretes
19 Damaged by Alkali-Silica Reaction,” *Cement and Concrete Research*, V. 38, No.7, 2008, pp.
20 993–1004.
- 21 5. Ahmed, T., Burley, E., Rigden, S., and Abu-Tair, A. I., “The Effect of Alkali Reactivity on
22 the Mechanical Properties of Concrete,” *Construction and Building Materials*, V. 17, No. 2,
23 2003, pp.123–144.
- 24 6. Jones, A., and Clark, L., “The Effects of Restraint on ASR Expansion of Reinforced
25 Concrete,” *Magazine of Concrete Research*, V. 48, No. 174, 1996, pp. 1–13.

- 1 7. Batic, O., Giaccio, G., and Zerbino, R., “On the Effect of ASR Cracking on the Mechanical
2 Behavior of Concrete in Tension and Compression,” *In Proceedings of the 12th International*
3 *Conference on Alkali-Aggregate Reaction in Concrete*, 2004, pp. 1136–1141.
- 4 8. Multon, S., Seignol, J.-F., and Toutlemonde, F., “Structural Behavior of Concrete Beams
5 Affected by Alkali-Silica Reaction,” *ACI Materials Journal*, V. 102, No. 2, 2005, pp. 67–76.
- 6 9. Ben Haha, M., “Mechanical Effects of Alkali-Silica Reaction in Concrete Studied by SEM-
7 Image Analysis,” *PhD thesis Ecole Polytechnique Fédérale de Lausanne (EPFL)*, 2006.
- 8 10. Fan, S., and Hanson, J., “Effect of Alkali Silica Reaction Expansion and Cracking on
9 Structural Behavior of Reinforced Concrete Beams,” *ACI Structural Journal*, V. 95, No. 5
10 September–October 1998, pp. 488–495.
- 11 11. Hafçı, A., “Effect of Alkali–Silica Reaction Expansion on Mechanical Properties of
12 Concrete,” Dissertation master’s Thesis, *Middle East Technical University*, 2013.
- 13 12. Sanchez, L., Fournier, B., Jolin, M., Bastien, J., Mitchell, D., and Noel, M., “Thorough
14 Characterization of Concrete Damage Caused by AAR through the Use of a Multi-level
15 Approach,” *In Proceedings of the 15th International Conference on Alkali-Aggregate*
16 *Reaction in Concrete*, São Paulo, SP, Brazil, 2016.
- 17 13. Sanchez, L., “Contribution to the Assessment of Damage in Aging Concrete Infrastructures
18 Affected by Alkali-Aggregate Reaction,” PhD thesis, *Université Laval*, 2014.
- 19 14. Na, O., Xi, Y., Ou, E., and Saouma, V. E., “The Effects of Alkali- Silica Reaction on the
20 Mechanical Properties of Concretes with Three Different Types of Reactive Aggregate,”
21 *Structural Concrete*, V. 17, No. 1, 2016, pp. 74–83.
- 22 15. Gautam, B. P., “Multiaxially Loaded Concrete Undergoing Alkali-Silica Reaction (ASR),”
23 PhD thesis, *University of Toronto*, Canada, 2016.
- 24 16. Esposito, R., Anac, C., Hendriks, M. A., and Copuroglu. O., “Influence of the Alkali-Silica
25 Reaction on the Mechanical Degradation of Concrete,” *Journal of Materials in Civil*

- 1 *Engineering*, V. 28, No. 6, 2016, pp. 04016007.
- 2 17. Giannini, E., and Folliard, K., “Stiffness Damage and Mechanical Testing of Core
3 Specimens for the Evaluation of Structures Affected by ASR,” *In Proceedings of the 14th*
4 *International Conference on Alkali–Aggregate Reaction in Concrete*, Austin, Texas, USA,
5 May 2012.
- 6 18. Marzouk, H., and Langdon, S., “The Effect of Alkali-Aggregate Reactivity on the
7 Mechanical Properties of High and Normal Strength Concrete,” *Cement and Concrete*
8 *Composites*, V. 25, No. 4-5, 2003, pp. 549–556.
- 9 19. Hayes, N. W., Gui, Q., Abd-Elssamd, A., Le Pape, Y., Giorla, A. B., Le Pape, S., Giannini,
10 E. R., and Ma, Z. J., “Monitoring Alkali-Silica Reaction Significance in Nuclear Concrete
11 Structural Members,” *Journal of Advanced Concrete Technology*, V. 16, No. 4 2018, pp.
12 179–190.
- 13 20. Clark, L., and Ng, K., “Prediction of the Punching Shear-strength of Reinforced-concrete
14 Slabs with ASR,” *In The 9th International Concrete on Alkali-Aggregate Reaction in*
15 *Concrete*, London, England, July 27–31, 1992, V. 1 and 2, pp. 167–174.
- 16 21. Barbosa, R. A., Hansen, S. G., Hansen, K. K., Hoang, L. C., Grek, B., and Maag, I.,
17 “Assessment of Severely ASR Damaged Bridges: From Diagnosis to Structural Effects,” *In*
18 *Proceedings of the 15th International Conference on Alkali-aggregate Reaction in Concrete*,
19 São Paulo, SP, Brazil, 2016.
- 20 22. Gautam, B., Panesar, D., Sheikh, S., and Vecchio, F., “Effect of Multiaxial Stresses on
21 Alkali-Silica Reaction Damage of Concrete,” *ACI Materials Journal*, V. 114, No. 4, 2017,
22 pp. 595–604.
- 23 23. Multon, S., and Toutlemonde, F., “Effect of Applied Stresses on Alkali–Silica Reaction-
24 Induced Expansions,” *Cement and Concrete Research*, V. 36, No. 5, 2006, pp. 912–920.
- 25 24. Sargolzahi, M., Kodjo, S., Rivard, P., and Rhazi, J., “Effectiveness of Nondestructive

1 Testing for the Evaluation of Alkali-Silica Reaction in Concrete”, *Construction and Building*
2 *Materials*, V.24, No.8, 2010, pp.1398-1403.

3 25. Larive, C., Joly, M., and Coussy, O., “Heterogeneity and Anisotropy in ASR-affected
4 Concrete – Consequences for Structural Assessment,” *In Proceedings of the 11th*
5 *International Conference on Alkali-aggregate Reaction in Concrete*, Quebec, Canada 2000,
6 pp. 969– 978.

7 26. Smaoui, N., Be´rube´, M., Fournier, B., and Bissonette, B., “Influence of Specimen
8 Geometry, Orientation of Casting Plane, and Mode of Concrete Consolidation on Expansion
9 Due to ASR,” *Cement, Concrete and Aggregates*, V. 26, No. 2, 2006, pp. 1–13.

10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

TABLES AND FIGURES

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

List of Tables:

Table 1 – Aggregate reactivity

Table 2 – Design proportions of concrete mixtures

Table 3 – Summary of experimental studies on unconfined concretes

Table 4 – Summary of experimental studies conditioning regimes

Table 5 – Summary of experimental studies on confined concretes

List of Figures:

Fig. 1 – Weight gain and expansion: NR=nonreactive cylinders, UNC/CON - SR=unconfined/confined slowly reactive cylinders, UNC/CON- HR=unconfined/confined highly reactive cylinders, Prisms-SR = slowly reactive prisms, Prisms-HR = highly reactive prisms. The measured expansion is represented by the mean and standard deviation for three measurements at each time step.

Fig. 2 – Cracks formation on unconfined specimens.

Fig. 3 – Change in concrete properties with time: Dashed line = unconfined specimens; Solid line = confined specimens; Red = highly reactive specimens; Blue = slowly reactive specimens; Black = nonreactive specimens.

Fig. 4 – Effect of ASR expansion on relative mechanical properties for unconfined concrete. The gray area represents an envelope of the literature data.³⁻¹⁷

Fig. 5 – The effects of casting direction on ASR expansion.

Fig. 6 – Impact of ASR expansion rates on the loss of elastic modulus and compressive strength of unconfined concretes. Data on VHR were collected from eight references^{3-6, 10,11,13,17}. Data on HR were collected from four references^{13,15,16,19} and from the present study. Data on SR were collected from nine references^{4,8,9,13-17,28} and from the present study.

1 **Fig. 7** – Impact of ASR expansion rates on the loss of tensile splitting strength of unconfined
2 concretes. Data on VHR collected from five references ^{3,5,6,10,11}. Data on HR collected from
3 two references ^{16,19} and from the present study. Data on SR collected from four references
4 ^{8,9,15,16} and from the present study.

5 **Fig. 8** – Impact of confinement on the loss of mechanical properties of highly reactive concretes.
6 Unconfined data on VHR elastic modulus and compressive strength were collected from eight
7 references ^{3-5,10,11,13,15,17}. Unconfined data on VHR -splitting tensile strength were collected
8 from five references ^{3,5,6,10,11}. Confined data on VHR elastic modulus, compressive strength,
9 and splitting tensile strength were collected from Jones and Clark⁶ only.

10 **Fig. 9** – Impact of confinement on the loss of mechanical properties of slowly reactive
11 concretes. Unconfined data on SR elastic modulus and compressive strength were collected
12 from nine references ^{4,8,9,13-17,28} and from the present study. Unconfined data on SR tensile
13 splitting strength were collected from four references ^{8,9,15,16} and from the present study.
14 Confined SR data with a restraint perpendicular to loading were collected from Gautam.¹⁵
15 Confined SR data with a restraint parallel to loading were collected from Hayes et al.¹⁹ and
16 from the present study.

17

18

19

20

21

22

23

24

25

1

Table 1–Aggregate reactivity

Aggregate	Type	ASTM C1260	ASTM C1293	Reactivity (per ASTM C1778)
		Expansion (14 days) %	Expansion (1 year) %	
HRC	Coarse	0.35	0.26	Highly reactive
SRC	Coarse	0.18	0.14	Slowly/Moderately reactive
NRC	Coarse	0.06	0.03	Nonreactive
NRF	Fine	0.04	0.03	Nonreactive

2

3

4

Table 2–Design proportions of concrete mixtures

Materials	Quantity, lb/yd ³ (kg/m ³)		
	HR	SR	NR
Cement	708 (420)	708 (420)	708 (420)
Water	354 (210)	354 (210)	354 (210)
50% NaOH solution	8.4 (4.98)	8.4 (4.98)	8.4 (4.98)
HRC (oven dry)	1769 (1049)	-	-
SRC (oven dry)	-	1823 (1081)	-
NRC (oven dry)	-	-	1836 (1089)
NRF (oven dry)	1054 (625)	1054 (625)	1054 (625)
W/C	0.5	0.5	0.5

5 Note: Aggregate quantities are given for oven-dry materials. Water quantities assume aggregates in saturated-

6 surface dry (SSD) condition. The W/C ratio is selected as 0.5 to be consistent with literature data as most tests

7 were conducted at this ratio.

8

9

Table 3–Summary of experimental studies on unconfined concretes

Author	Mix ID	Reactive aggregate		Expansion		Classification
		Description	Type	Specimen	Rate (%/year) Linear (volumetric)	
Swamy	A	4.5% Beltane opal	F	Long prisms	1.64 (5.8)	VHR
	B	15% fused silica	F		0.62 (2.2)	VHR
Ahmed	A	Thames valley (50% chert)	F	Long + Lat prisms	0.43 (1.51)	VHR
	B	15% fused silica	F		1.68 (5.91)	VHR
Giaccio	R2	Highly reactive sand	F	Long prisms	0.26 (0.92)	VHR
	R3	10% highly reactive orthoquartzite	C		0.30 (1.02)	VHR
	R4	Slowly reactive granitic migmatite	C		0.11 (0.39)	SR
Ben Haha	A	Chlorite schist	C	Long prisms	0.11 (0.39)	SR
	C	Biotite schist	C		0.11 (0.39)	SR
Na	-	Highly reactive aggregate	C	Long cylinders	0.17 (0.39)	SR

Fan	-	Gold hill	C	Long cylinders	0.42 (0.97)	VHR
Giannini	R1	Reactive sand (El Paso, TX)	F	Long cylinders	0.42 (0.97)	VHR
	R2	Reactive mixed gravel (Bernalillo, NM)	C		0.14 (0.32)	SR
Hafic	Cube	Reactive natural sand	F	C	0.1 (0.30) @3M	VHR
	Cylinder	Reactive natural sand	F	Long cylinders	0.1 (0.23) @3M	VHR
Jones	-	Thames valley (50% chert)	F	Long cylinders	0.63(1.46)	VHR
Multon	-	Reactive coarse	C	Long cylinders + Long prisms	(0.24)	SR
Sanchez	TX + HP (25)	Polymictic sand	F	Long cylinders	0.3 (0.70) @3M	VHR
	TX + dia (25)	Polymictic sand	F		0.3 (0.70) @3M	VHR
	NM + Lav (25)	Polymictic gravel	C		0.18 (0.41) @6M	HR
	QC + Lav (25)	Siliceous & argillaceous limestone	C		0.18 (0.41) @6M	HR
	TX + HP (35)	Polymictic sand	F		0.3 (0.70) @3M	VHR
	TX + dia (35)	Polymictic sand	F		0.3 (0.70) @3M	VHR
	TX + NM (35)	Polymictic sand	F+C		0 (0.70) @3M	VHR
	King + Lav (35)	Dolomitic argillaceous limestone	C		0.3 (0.70) @3M	VHR
	WT + HP (35)	Polymictic sand	F		0.18 (0.41) @6M	HR
	NM + Lav (35)	Polymictic gravel	C		0.18 (0.41) @6M	HR
	QC + LAV (35)	Siliceous & argillaceous limestone	C		0.18 (0.41) @6M	HR
	Conr + Lav (35)	Metagreywacke, shale, siltstone	C		0.16 (0.37) @1Y	SR
	Pots + Lav (35)	Siliceous sandstone	C		0.16 (0.37) @1Y	SR
	Rec + Lav (35)	Granite, gneiss, mylonite	C		0.13 (0.30) @1Y	SR
	Wyo + lav (35)	Granite, amphibolite	C		0.10 (0.23) @1Y	SR
	Virg + lav (35)	Metagranite	C		0.06 (0.14) @1Y	SR
	TX + HP (45)	Polymictic sand	F		0.3 (0.70) @3M	VHR
	TX + dia (45)	Polymictic sand	F		0.3 (0.70) @3M	VHR
	NM + Lav (45)	Polymictic gravel	C		0.18 (0.41) @6M	HR
	QC + Lav (45)	Siliceous and argillaceous limestone			0.18 (0.41) @6M	HR
Gautam	Cubes	Crushed siliceous limestone	C	(x, y, z)	(0.44) @1.2Y	SR
	Mix F	Crushed siliceous limestone	C	Long prisms	0.23 (0.80)	HR
	Mix C	Crushed siliceous limestone	C	Long prisms	0.25 (0.88)	VHR
Esposito	RR1	Natural Dutch aggregates	F+C	Long prisms	0.11 (0.39)	SR
	RR2	Crushed Norwegian aggregates	F+C	Long prisms	0.18 (0.63)	HR
Sargolzahi		Spratt limestone	C	Long prisms	0.075 (0.26)	SR
Hayes		Crushed siliceous rock (argillite)	C	Large block 11.5×9.8×3.3 ft	(0.42)	HR
This study	HR	Crushed limestone	C	Long cylinders + long prisms	(0.8)	HR
	SR	Crushed limestone	C		(0.36)	SR

1 Long: expansion measured on prisms or cylinders longitudinally; Lat: expansion measured on prisms or cylinders laterally; M: duration in
 2 months; Y: duration in years; VHR: very high rate of expansion; HR: high rate of expansion, SR: slow rate of expansion; F: fine; C: coarse
 3

4 **Table 4–Summary of experimental studies conditioning regimes**

5

Author	Pretreatment			ASR conditioning		
	Temperature (C)	Humidity condition	Duration (days)	Temperature (C)	Humidity condition	Duration (days)
Swamy	None			20	96% RH	365
Ahmed	20	In water	28	38	In water	365
Giaccio	None			38	Wrapped with cotton with 5 ml of water	250/120/745
Ben Haha	None			40	In water	365
Na	23	100% RH	28	80	1 N NaOH	180
Fan	23	100% RH	14	38	0.5 N NaOH	360
Giannini	None			38	95% RH	365
Hafic	20	In water	1	60	100%RH + NaOH	102
Jones	None			38	In water	-
Multon	20	In aluminum foil	28	38	Sealed in aluminum foil	365
Sanchez	23	Moist cured	1	38	100% RH	365
Gautam	23	Wet burlap	180	50	95% RH	545
Esposito	20	95% RH	1	38	>96% RH	365
Sargolzahi	-	Moist room	7	38	95% RH	690
Hayes	23	In plastic sheet	28	38	>95% RH	365
This study	23	85% RH	28	38	>95% RH	455

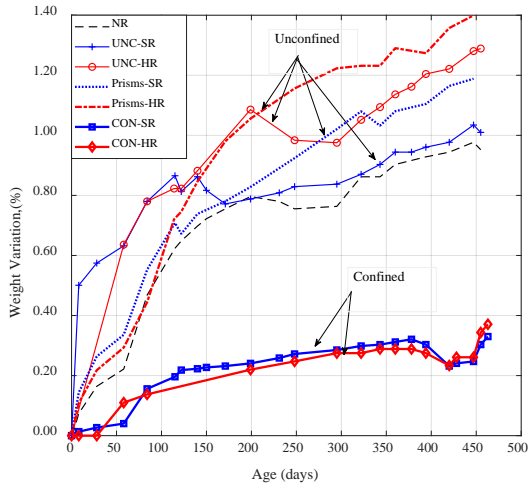
6
7 **Table 5–Summary of experimental studies on confined concretes**

8

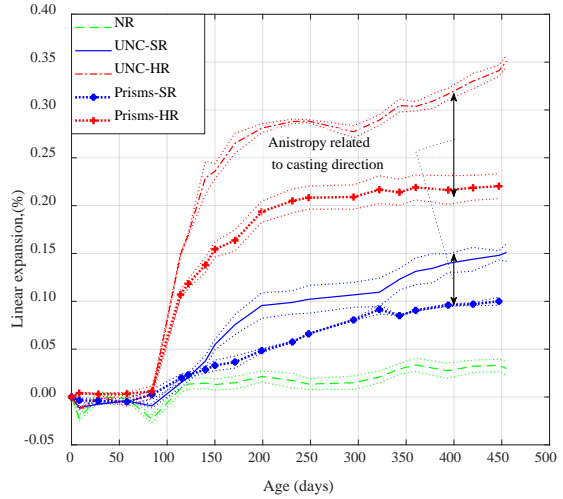
Author	Mix ID	Expansion			Confinement	
		Specimen	Expansion Rate (%/year) Linear (Volumetric)	Classification	Condition	Description
Jones	-	Long cylinders	0.63 (1.26)	HR	Uniaxial	Cylinders (4 × 8 in.) expanded under different stresses applied parallel to their axes

Gautam	u (3.9, 0, 0)	Cubes (x,y, z)	(0.50) @1.2Y	SR	Uniaxial	10-inch cube specimens expanded under different stresses applied along x, y, and z directions; core specimens were extracted along the x direction for mechanical properties testing
	U (9.6, 0, 0)		(0.42) @1.2Y		Uniaxial	
	b (3.9, 3.9, 0)		(0.41) @1.2Y		Biaxial	
	B (9.6, 3.9, 0)		(0.43) @1.2Y		Biaxial	
	t (3.9, 3.9, 3.9)		(0.23) @1.2Y		Triaxial	
	T (9.6, 3.9, 3.9)		(0.16) @1.2Y		Triaxial	
Hayes	Confined	Large block 11.5 × 9.8 × 3.3 ft.	(0.41)	SR	Biaxial	Cylinders (6 × 12 in.) were cast in a steel mold to force the ASR expansion to develop parallel to the casting direction only
	Unconfined					
This study	HR	Long cylinders + Long prisms	(0.25)	SR	Biaxial	Cylinders (4 × 8 in.) were cast in a steel mold to force the ASR expansion to develop parallel to the casting direction only
	SR		(0.16)	SR		

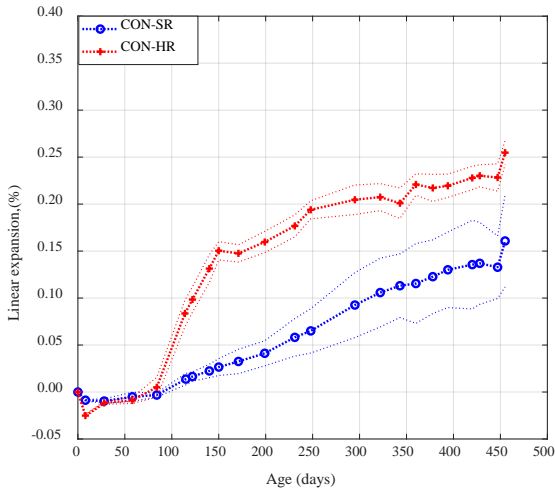
1
2
3
4
5
6
7
8
9
10
11
12
13
14



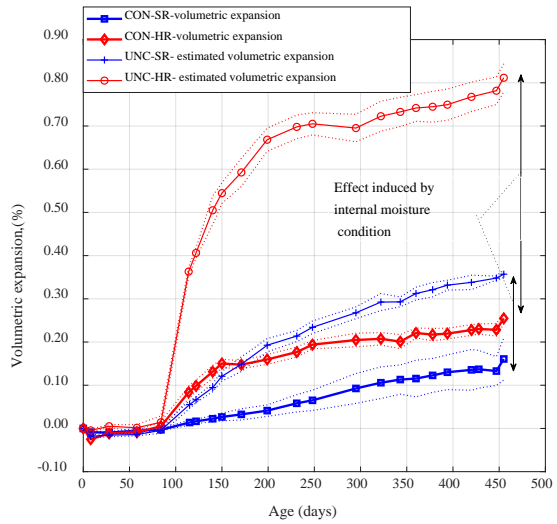
(a) Weight gain



(b) Linear expansion, unconfined



(c) Linear expansion –confined



(d) volumetric expansion

Fig. 1–Weight gain and expansion: NR=nonreactive cylinders, UNC/CON - SR=unconfined/confined slowly reactive cylinders, UNC/CON- HR=unconfined/confined highly reactive cylinders, Prisms-SR = slowly reactive prisms, Prisms-HR = highly reactive prisms. The measured expansion is represented by the mean and standard deviation for three measurements at each time step.

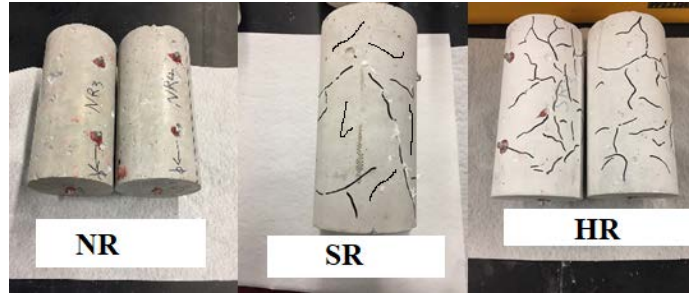
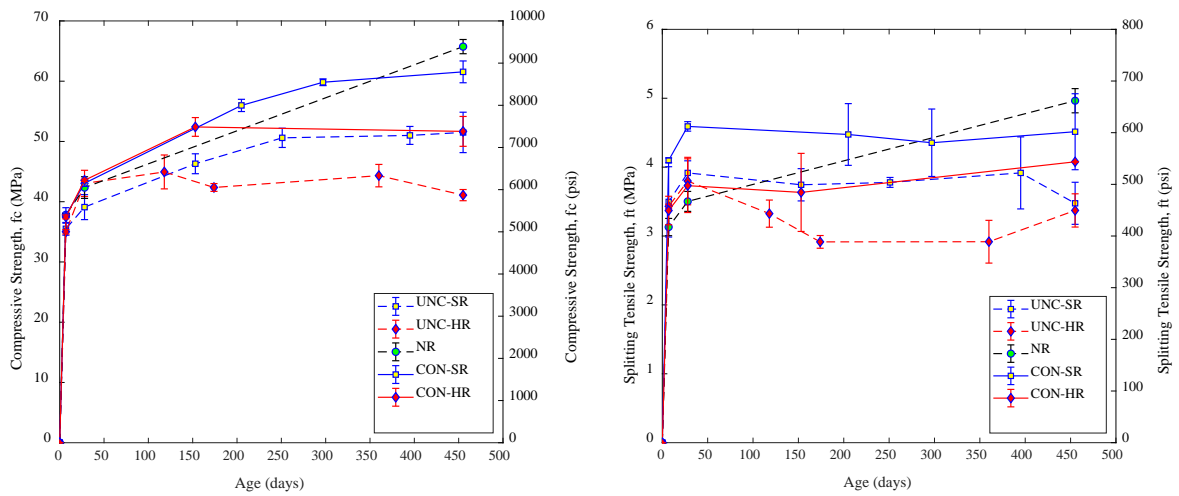
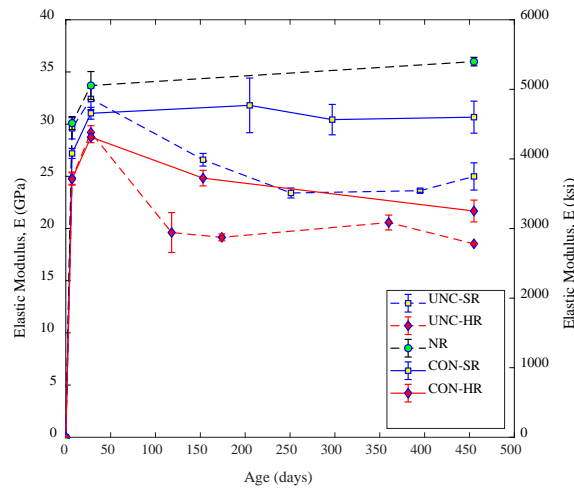


Fig. 2—Cracks formation on unconfined specimens.



(a) Compressive strength

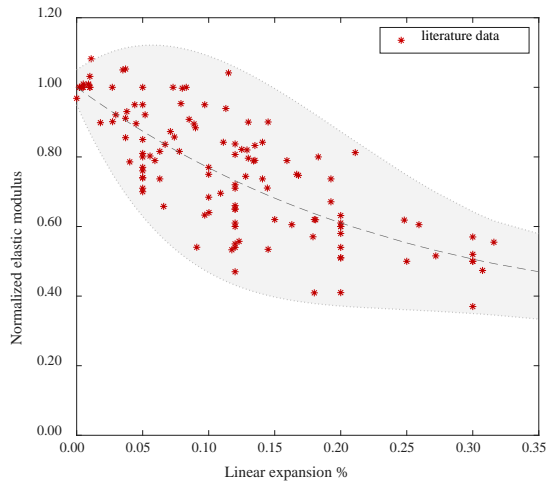
(b) Splitting tensile strength



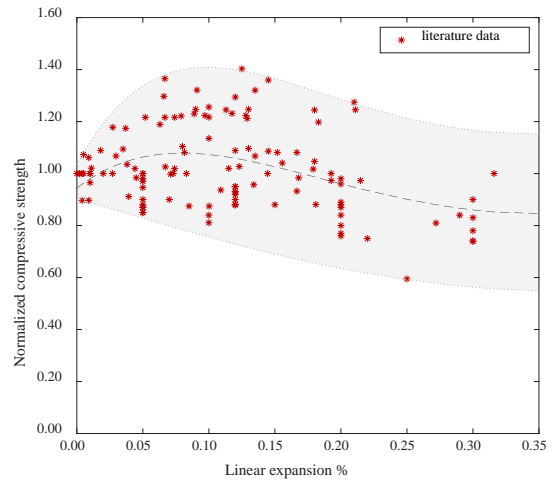
(c) Elastic modulus

Fig. 3—Change in concrete properties with time: Dashed line: unconfined specimens, Solid line: confined specimens, Red: highly reactive specimens, Blue: slowly reactive specimens, Black: nonreactive specimens.

1



2



3

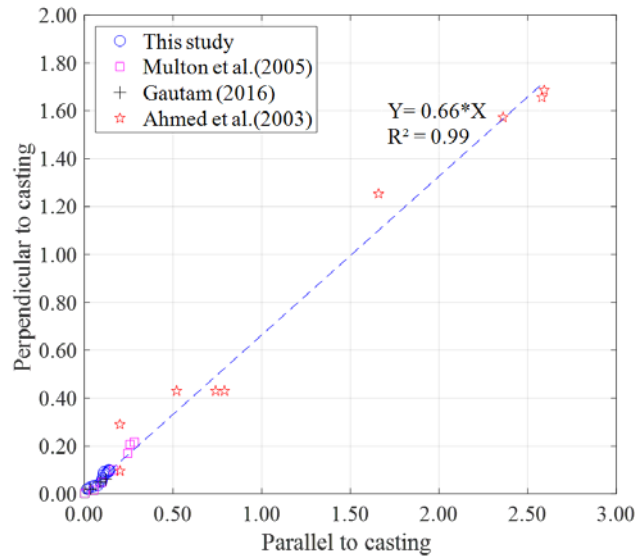
(a) Elastic modulus

(b) Compressive strength

4 **Fig. 4—Effect of ASR expansion on relative mechanical properties for unconfined concrete.**

5 **The gray area represents an envelope of the literature data.³⁻¹⁷**

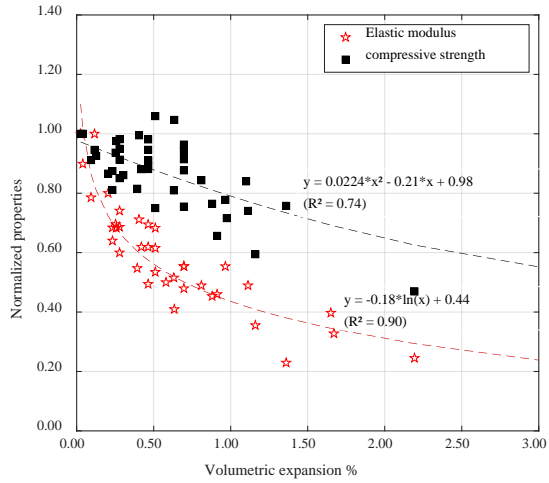
6



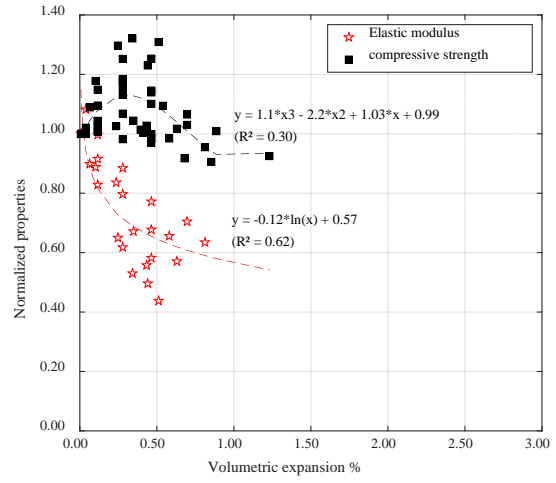
7

8

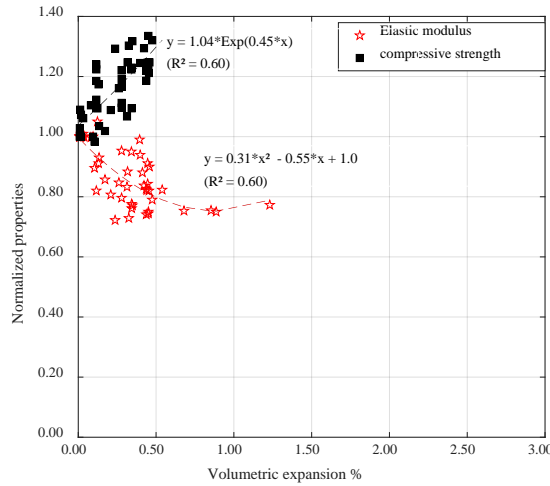
Fig. 5—The effects of casting direction on ASR expansion.



(a) Very high rate (VHR)



(b) High rate (HR)



(c) Slow rate (SR)

1
2

3
4

5 **Fig. 6–Impact of ASR expansion rates on the loss of elastic modulus and compressive**
 6 **strength of unconfined concretes. Data on VHR were collected from eight references** ^{3-6,}
 7 **10,11,13,17. Data on HR were collected from four references** ^{13,15,16,19} **and from the present**
 8 **study. Data on SR were collected from nine references** ^{4,8,9,13-17,24} **and from the present**
 9 **study.**

10

11



1

2 **Fig. 7–Impact of ASR expansion rates on the loss of tensile splitting strength of**
 3 **unconfined concretes. Data on VHR collected from five references ^{3,5,6,10,11}. Data on HR**
 4 **collected from two references ^{16,19} and from the present study. Data on SR collected from**
 5 **four references ^{8,9,15,16} and from the present study.**

6

7

8

9

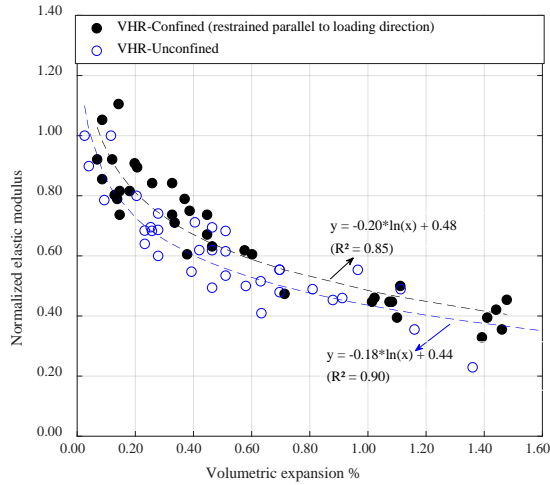
10

11

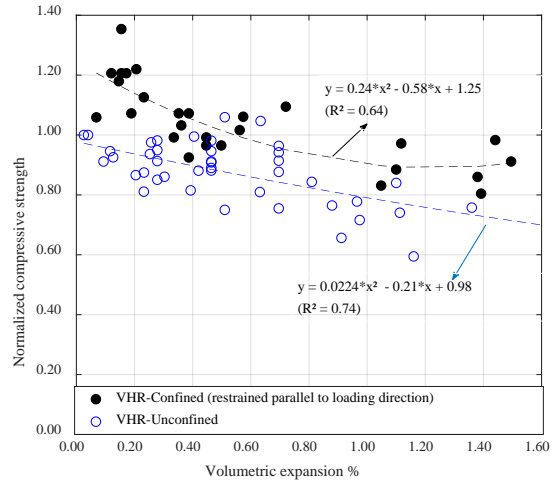
12

13

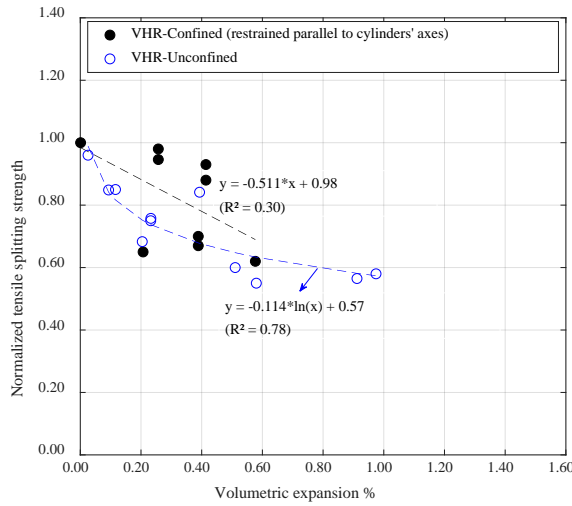
14



(a) Elastic modulus

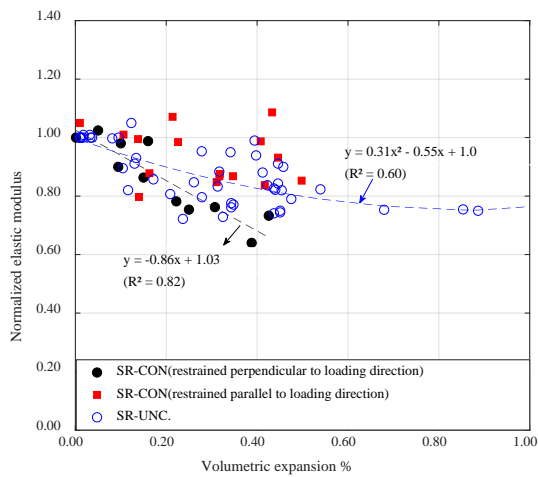


(b) Compressive strength

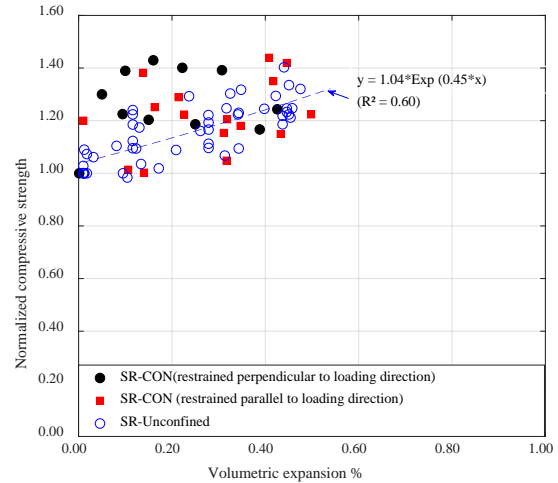


(c) Splitting tensile strength

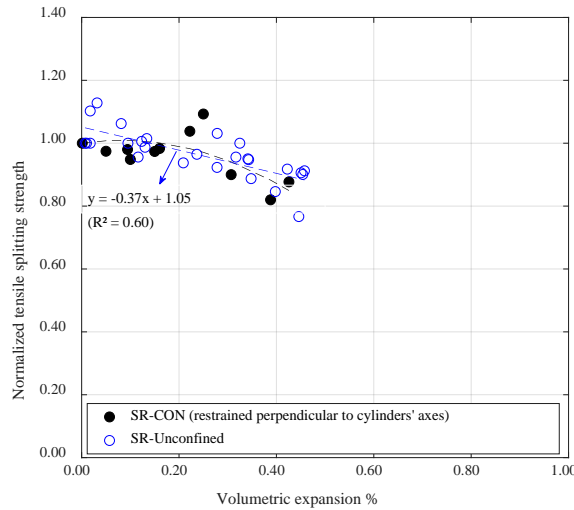
Fig. 8—Impact of confinement on the loss of mechanical properties of highly reactive concretes. Unconfined data on VHR elastic modulus and compressive strength were collected from eight references ^{3-5,10,11,13,15,17}. Unconfined data on VHR -splitting tensile strength were collected from five references ^{3,5,6,10,11}. Confined data on VHR elastic modulus, compressive strength, and splitting tensile strength were collected from Jones and Clark⁶ only.



(a) Elastic modulus



(b) Compressive strength



(c) Splitting tensile strength

Fig. 9–Impact of confinement on the loss of mechanical properties of slowly reactive concretes. Unconfined data on SR elastic modulus and compressive strength were collected from nine references ^{4,8,9,13-17,24} and from the present study. Unconfined data on SR tensile splitting strength were collected from four references ^{8,9,15,16} and from the present study. Confined SR data with a restraint perpendicular to loading were collected from Gautam.¹⁵ Confined SR data with a restraint parallel to loading were collected from Hayes et al.¹⁹ and from the present study.