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Case study

Alkali-silica reaction (ASR) in concrete structures: Mechanisms, effects and evaluation test methods adopted in the United States

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ABSTRACT

Alkali-silica reaction (ASR) and its associated deformation are major durability problems in concrete structures and was reported as far back as the 1940s by Stanton (2008) [1]. This deleterious reaction causes excessive expansion and cracks that can lead to severe degradation of the concrete structures. Despite the age-long discovery and numerous ASR studies, understanding the ASR mechanism remains challenging due to complex processes and reactions. This paper presents a review of ASR in concrete structures and details the factors associated with ASR, the reaction mechanism and chemistry, and its adverse effect on concrete structures. The alkalis in the pore solution, the reactive amorphous silica present in aggregates, and the presence of moisture (with other external climatic inputs) are the key factors responsible for ASR. The study also provides a critical assessment of the various test methods for ASR evaluation in the United States. A case study correlating the results (from the literature) of three prominent test methods was also carried out. From this review, the new miniature concrete prism test (MCPT) method was concluded to be rapid, reliable, and capable of determining the influence of aggregate reactivity, alkali availability, and exposure conditions as compared to other methods.

1. Introduction

Portland cement concrete (PCC), which consists of 60–75 % aggregates, 10–15 % of Portland cement (with other supplementary cementitious materials or admixtures), and water, has been recognised as the most widely used construction material in the world [2,3]. The presence of reactive amorphous or poorly crystallised structures from some natural aggregates and the hydroxyl ions in Portland cement, aggregate particles, or admixtures produces a deleterious chemical reaction in the presence of concrete pore solution. This chemical reaction is commonly known as the alkali-aggregate reaction (AAR). AAR is a major concrete durability problem, causing severe damages in many civil engineering infrastructures such as buildings, pavements, bridges, dams, and other concrete structures worldwide [4–7]. AAR can be categorised into two forms of reactions; (i) alkali-silica reaction (ASR) that develops due to reactive silica minerals in aggregate materials and (ii) alkali carbonate reaction (ACR) caused by aggregate particles containing carbonate or dolomite [8].

Due to the high percentage of silica present in most aggregates, the most widespread AAR type is the ASR (first recognised by

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Fig. 1. A typical picture of ASR in concrete with Stanton [1]. Adopted from [11].

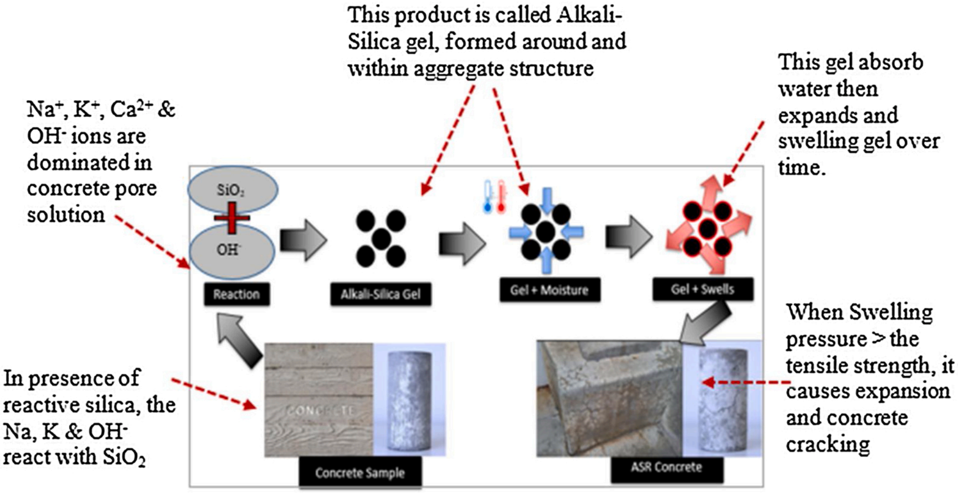


Fig. 2. The schematic of ASR mechanism in concrete structures.

Stanton [1] - Fig. 1). The silica reacts with available alkali from the cement to form a hygroscopic alkali-silica gel. Most concrete structures built in the United States during the 1940s have been affected by ASR and become deficient over time [4]. ASR causes severe damages that manifested as extensive expansion, cracking, aggregates pop-out, gel exudation, and harmful white deposits on the concrete surfaces [9,10].

Numerous researches have been conducted on ASR over the last century, beginning from Stanton's pioneering work in 1940 [1]. The number of articles on ASR has grown extensively, making the subject of ASR in concrete a popular durability problem [10]. Despite ASR being well studied over these years, the United States and Canada have recently identified structural distresses caused by ASR in Seabrook nuclear powers and Mactaquac Dams, respectively [12,13]. Such recent problems call for continuous research and review on recent developments. The deterioration of concrete caused by ASR is continual, expansive, and generally slow [8]. This reaction produces an alkali-silica gel over time and leads to progressive deformation of concrete due to internal forces triggering loss in serviceability and longevity [1,8]. The ASR-induced distress, in turn, results in major damage in concrete structures and eventually results in the demolition of the structure. These phenomenon/mechanism has been highlighted in several research works [10,14–21].

Numerous test methods have been developed to evaluate aggregates' detrimental reactivity as ASR. Some of these test methods are the ASTM C 295: Petrographic examination of aggregates, ASTM C 1260: Accelerated mortar bar test (AMBT), and ASTM C 1293: Concrete prism test (CPT) [22–24]. Over time, these evaluation methods have exhibited shortcomings [25,26] that produced false-positive or false-negative results contrary to field performance. These necessitated the need for re-evaluating the methods. Therefore, a new ASR testing method called "AASHTO TP 110 (recently renamed as AASHTO T 380 in 2019 [27]) - Miniature concrete prism test (MCPT)" was developed in 2014 to overcome the shortcomings [26–29]. Also, this method has been adopted for ASR mitigation strategies in concrete [26,30–33].

There is a continuous need to review the state-of-the-art of ASR mechanisms due to the associated complex sequential reactions, severe effects on concrete life span, and the inconsistencies of evaluation techniques [34–36]. Furthermore, recent problems and research continue to abound on ASR, such as the development of the new AASHTO TP 110 [27]. Therefore, this study provides an explicit explanation of the ASR mechanism (thermodynamics and kinetics) and its numerous effects on civil infrastructures (such as

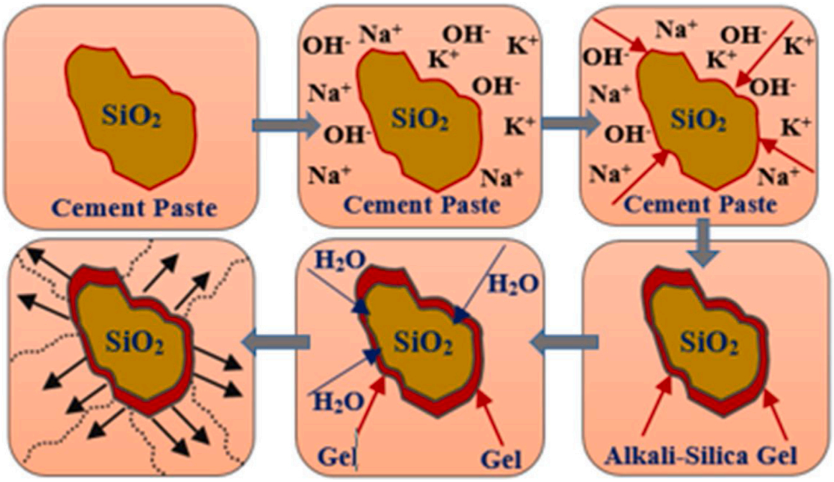


Fig. 3. A schematic diagram of ASR mechanism in concrete. Adopted from [46–48].

highway pavement and bridges). A full description of the test procedures used to determine aggregates susceptibility to ASR is also discussed, including results from recent publications. A case study was also conducted to evaluate the new method's (MCPT) performance, as used by recent researchers, over the previous well-known test methods.

2. Mechanism of ASR

2.1. Background of ASR

ASR is a deleterious chemical reaction with a multi-stage process and sequential reactions [10]. In some aggregate, the active silica constituents react with alkalis in the cementitious materials, producing alkali-silica gel. The reaction product (gel) is hygroscopic, with a remarkable ability to absorb water. In the presence of moisture, the gel expands, aggravatable by varying climatic conditions (such as temperature, relative humidity), and subsequently leading to cracks and other ASR-induced distress [8,37,38]. An insufficient amount of silica in aggregates, alkali concentration, and moisture will not result in an amount of gel capable of causing deleterious effects. The schematic of the ASR mechanism is shown in Fig. 2.

2.2. Chemistry of alkali-silica reaction

The ASR is a chemical reaction between reactive silica in aggregates and hydroxyl ions in concrete pore solution. The state of silica (SiO_2) in the aggregates is chemically passive (in the form of quartz) and mainly structured as siloxane groups (≡Si-O-Si≡). However, the disorderliness of crystalline silica at the surface causes them to have the affinity to attract water and produce amorphous hydrous silica (silanol group [≡Si-OH]) [40]. Thereafter, the silica(s) inclines towards dissolution in the presence of highly concentrated hydroxyl ions by first neutralising the silanol groups (≡Si-OH) and then neutralising the siloxane groups (≡Si-O-Si≡) as illustrated in Eqs. 2.1 and 2.2 [7].

$$\equiv \text{Si-OH} + \text{OH}^- = \text{Si-O}^- + \text{H}_2\text{O} \tag{2.1}$$

$$\equiv \text{Si-O-Si} \equiv + 2\text{OH}^- = 2\text{Si-O-} + \text{H}_2\text{O} \tag{2.2}$$

As the structures (≡Si-OH, ≡Si-O-Si≡) gradually break down, they also attract the soluble alkali hydroxides present abundantly in the concrete pore solution as NaOH or KOH [39]. The calcium hydroxide, $Ca(OH)_2$ produced from cement hydration, also adds to the hydroxyl ions (OH^-) in the pore solution. Alkali-silicate solution and gel (depending on the level of moisture) are the preliminary products of the reaction between these siloxane groups (≡Si-O-Si≡) and hydroxyl ions (Eq. 2.3). Thereafter, the Si-OH reacts with more OH^- and alkali metals forming alkali silicate hydrate and water as presented in Eqs. 2.4 and 2.5 [20,39–41].

$$\equiv \text{Si-O-Si} \equiv + \text{OH}^- + \text{R}^+(\text{Na or K}) = \equiv \text{Si-O-Na} + \text{H-O-Si} \equiv \tag{2.3}$$

$$\equiv \text{Si-OH} + \text{OH}^- + \text{Na+} = \equiv \text{Si-O-Na} + \text{H}_2\text{O} \tag{2.4}$$

$$\equiv \text{Si-O-Na} + \text{nH}_2\text{O} = \equiv \text{Si-O}^- \ (\text{H}_2\text{O})_\text{n} + \text{Na}^+ \tag{2.5}$$

A diffusion process of this hydrated alkali-silicate gel occurs within the aggregates to the cement paste, which then reacts with the paste's calcium ions to form an alkali-calcium-silicate hydrate gel. In the presence of moisture, this final product expands. An excess expansion generates cracks at the interfacial transition zone (ITZ) between the aggregate and cement paste that cumulates into stress

Table 1
Outline of major aggregate tested for ASR.

Aggregate Type	ASR classification	Source	Reference
Basalt	Reactive	USA	Adam [54] Lane [55]
Opal	Reactive	USA	Berube, and Frenette [51]
Dolomitic Limestone	Reactive	USA	Lane [55] Grattan-Bellew et al. [56]
Chert	Reactive	USA	Moser et al. [57]
Spratt	Reactive	CA	Thomas et al. [58] Lane [55]
Glass aggregate	Reactive	Canada	Shafaatian et al. [59]
Limestone	Non-Reactive	USA	Stark et al. [60] Touma et al. [61]
Andesite	Reactive	USA	Adam (2004) [54] Thomas et al. [62] Touma et al. [61]
Dolomite	Non-Reactive	USA	Stark et al. [60]
Dacite	Reactive	Canada & USA	Thomas et al. [62] Touma et al. [61] Hooton [63]
Quartz sand	Non-Reactive	USA	Stark et al. [60] Touma et al. [61]
Rhyolite	Reactive	USA	Touma et al. [61] Adam [54]

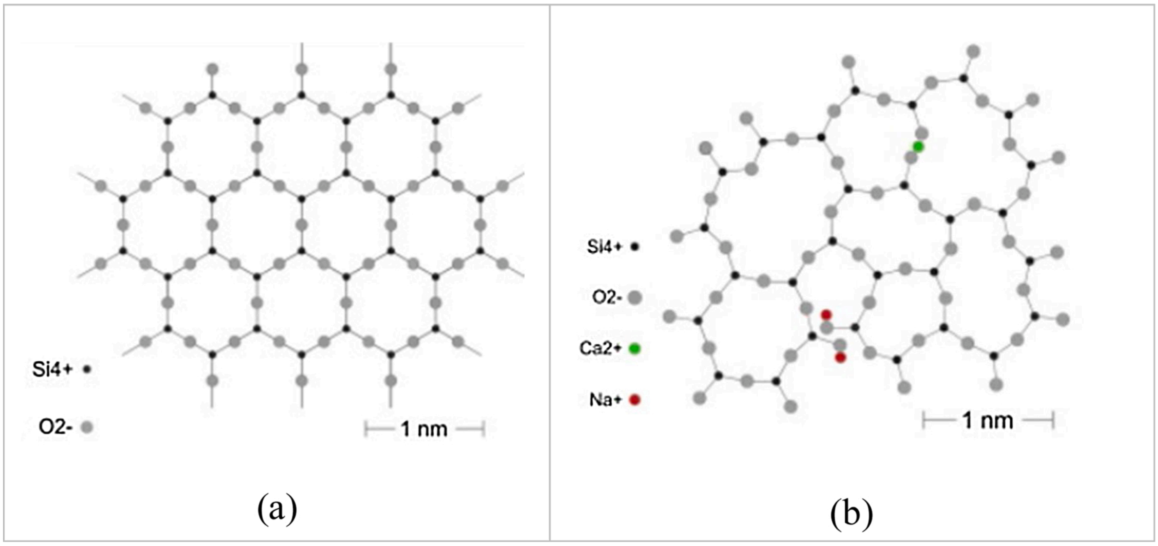


Fig. 4. A common representation of (a) quartz: a form of crystalline lattice structure SiO_2 (b) opal: a form of amorphous structure SiO_2. Adopted from [34].

and cracks in concrete structures [42–45]. Fig. 3 illustrates the schematic picture of ASR chemistry in concrete structures as adopted from [46–48].

2.3. Factors affecting alkali-silica reaction (ASR)

The ASR gel does not directly cause concrete's distress but absorbs moisture in the surrounding to expand and induce internal stresses. Such stresses can exceed the tensile strength of concrete, causing progressive cracking and associated deterioration. The three main components widely regarded as essential for ASR in concrete materials are:

- Presence of reactive siliceous components in aggregates (both coarse and fine fractions)
- Adequate alkali content from cementitious materials, and
- Presence of moisture along with other factors, such as temperature and additives.

Table 2
Reported aggregates and their size fraction that are highly prone to ASR.

Aggregates evaluated for ASR	aggregates size prone to ASR	Reference
Siliceous magnesium limestone containing opal & chalcedony	0.17 – 0.6mm	Stanton [1]
opal aggregates	0.02– 0.125 mm	Diamond and Thaulow [74]
Opaline aggregate particles	0.07−0.85mm	Wood (1968) [75]
Various siliceous aggregates	0.15mm	Zhang [76]
Reactive siliceous aggregates	0.15–0.30 mm	Kuroda et al. [69]
Siliceous limestone	1.25–3.25 mm	Multon et al. [66]
Alpine chloritic schist aggregate	2 to 4 mm	Dunant and Scrivener [77]
Soda lime glass aggregates	1.18−2.36 mm	Rajabipour et al. [34]
Spherical glass particles using the mortar bar specimens	2–3 mm	Bažant and Steffens [41]

2.3.1. *Reactive aggregates*

The durability and chemical stability of a concrete structure is determined by the quality of aggregates used in such a structure. About 65–75 % of the concrete volume is made up of aggregates [49,50]. As a result, aggregate (coarse and fine) significantly influences the development of ASR and the concrete properties affected by ASR. According to the Federal Highway Administration (FHWA) report, many aggregate sources have been reported reactive (containing highly reactive silica content) and exhibited high ASR potential when exposed to a solution of high alkalinity [46]. The chemical composition, crystallinity, amorphous structure of aggregates, and the degree of solubility of the amorphous silicate in alkaline pore solution all affect the aggregate susceptibility to ASR [10,17]. According to the literature, many of the well-known aggregates used for concrete production have been reported to be susceptible to ASR; this is summarised in Table 1. As shown by Berube [51], some reactive aggregates are andesite, chert, opal, tridymite, cristobalite, acid volcanic glass, siliceous rocks, basalt glass, and dacite. In contrast, dolomite, limestone, chalcedony, cryptocrystalline quartz, and strained quartz rocks were found not to be prone to ASR expansion but to ACR expansion [51].

There are mainly two groups of rocks, as the parent of aggregates, with crystalline structure differences. One is the "extreme reactive rocks" containing amorphous silica and lack minerals with crystalline structures (e.g. opal, tridymite, cristobalite, acid volcanic glass, and basalt glass etc.). These reactive aggregates contain microcrystalline silica or metastable crystals. This structure is found to be in disorder, containing micro-cracks internally, with many lattice defects that generate channels for easy penetration of alkalis from the pore solution [52]. As a result, the reactive silica can easily transfer in a larger surface area causing more ASR to occur. The second group of rocks is "mild or non-reactive rocks", which are made of minerals with crystalline structures (*e.g.* chalcedony, cryptocrystalline quartz, and strained quartz, etc.) [51,53]. For instance, Thomas et al. compared the structure of quartz (a non-reactive aggregate type) with the structure of opal (a reactive aggregate type) [11]. The quartz structure has the silica to be completely crystalline, with each silicon tetrahedron linked by oxygen ions. Each oxygen ion is connected with two silicon to achieve electrical neutrality (Fig. 4a). While the Opal structure has a crypto-crystalline and amorphous silica with each silicon not tetrahedron linked and oxygen ions untied, making them unstable (Fig. 4b) [34]. In the presence of ASR, the hydroxyl ions from pore solutions penetrate the siliceous particles, and the lattice structure is loosened. Thus, in a crypto-crystalline or amorphous silica (such as opal), this lattice structure is easily broken down by the ingress of hydroxyl ions, leading to ASR susceptibility of the aggregates. On the contrary, well-crystallised silica is not susceptible to ASR attack due to ordered lattice structure and tied oxygen ions with each silicon which cannot be penetrated by the alkali ions [7,10,11].

The porosity degree of aggregate particles also plays a vital role in the rate of ASR expansion. A higher porosity increases the ASR susceptibility and rate [10,37,62]. Typically, highly porous aggregate and concrete allow easy ingress of moisture from the environment to activate ASR. According to the study by Haha et al., it was reported that highly porous aggregates suffered more ASR expansion as compared to the aggregates with lower porosity. It was found that the alkali ions are easily diffused in the porous aggregate particles than less porous aggregates, which then initiates aggregates dissolution leading to ASR [64].

The relationship between aggregates size or gradation and ASR expansion has been reported as a major factor. Table 2 showed some reported aggregates and their size fraction that are highly susceptible to ASR. In general, finer aggregates fractions have been reported to be more susceptible to ASR than coarser aggregate fractions [37,65,66]. This is because, during milling into smaller particles, the finer materials possess a lower degree of structural order and unstable silica minerals than large aggregates [37,67]. Furthermore, smaller aggregate internal grain size's inverse relationship to its surface area causes a greater chance for alkali to attack [37,68]. Therefore, ASR expansion increases with reducing particle size because of the increased specific surface area of reactive aggregates [1,64,69].

Contrarily, some researchers have reported that finer aggregates sizes could reduce ASR [66,70–73]. For instance, Poyet et al. found an ASR mitigation effect with small size aggregates than larger coarse aggregates [70]. Similarly, Wigum and Lindgård stated that coarse aggregate fractions are more susceptible to ASR than fine aggregates [73]. This is because very fine reactive aggregate particles may take part in the pozzolanic reaction at early stages. Therefore, the alkali-silicate gel is quickly converted to calcium-silicate-hydrate, reducing the pore solution's alkalinity [47]. These suggest opposing effects and balance between alkali-silica and the pozzolanic reactions of very fine aggregates.

Experimental work and field observation have reported that the greatest observed expansion varies non-monotonically with aggregate size and proportion. This highest expansion occurs at a certain (range of) size and proportion; above or below this range, the expansion decreases. Recent articles have focused on this *pessimum* effect on ASR, which describes the balance between alkali hydroxide concentration of a pore solution and the aggregate's reactivity [1,71,78–80]. According to Stanton's work, a certain

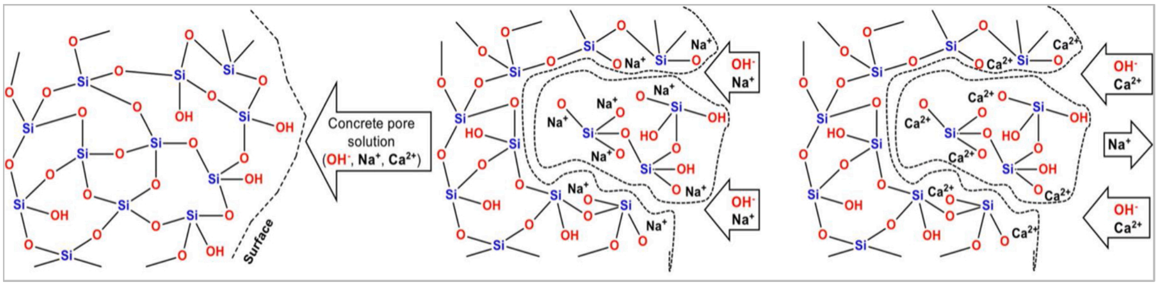


Fig. 5. Schematic of the model proposed by Poole [97], with the formation of alkali-silica gel due to attack of calcium (Ca^{2+}), sodium (Na^{+}), or potassium (K^{+}) ions. Only the Na^{+} ions are represented. Adapted from [95].

proportion of reactive aggregates induced higher ASR expansion; however, as the content of the reactive aggregates in concrete increased or decreased, the expansion decreased [1]. Similarly, it was found that concrete expansion decreased when the grain size is increased or decreased. French also observed this pessimum effect in the field and noted that aggregates with grains size fractions ranging from 4 to 10 mm are prone to ASR expansion [81]. Other researchers have shown a *pessimum* effect for various aggregates, with pessimum values occurring in a wide interval of particle sizes [65,66,77,82,83]. This difference in reactivity of different particle sizes is due to the time needed to diffuse OH– to the reactive sites, which may be in the aggregates' interior [66]. Thus, based on numerous factors associated with the effect of aggregate size on ASR, it is difficult to conclude a particular size fraction that is susceptible to ASR.

Besides the *pessimum* effect, the alkaline content of various aggregates is another theory that affects ASR expansion in concrete. Aggregates can also supply alkali to the binder matrix in concrete which amplifies ASR. According to Grattan-Bellew, reducing alkali hydroxides for individual aggregate particles reduced expansion due to ASR [84]. The amount of alkali released from aggregate particles depends on its mineral structure. The alkali dissolution from aggregate into concrete was attributed to the cation exchange with the pore solution's calcium hydroxide [47,56,84]. According to Goquel, the alkali content released from an aggregate that can initiate ASR expansion varies from 0.1 to 1% Na_2O for well- crystalline and amorphous aggregates, respectively [85]. Overall, the following conclusion can be drawn based on the effect of aggregate on ASR, (1) aggregates susceptibility to ASR depends on the size and the tendency of this dependence may not be predictable, (2) the size dependence of reactivity could be because of different reasons for different aggregate such as *pessimum* effect and alkali threshold limit (i.e., the level of alkali content of the pore solution) [11, 86–88], and (3) based on the size dependency, aggregates need to be tested at the same size that will ultimately be used for the intended concrete production.

2.3.2. *Alkalinity of cementitious materials*

One of the major ingredients in ASR is the pore solution alkalinity, where Portland cement is the main primary source of alkalis in concrete structures. Aggregates, supplementary cementitious materials (SCMs such as silica fume, natural pozzolans, slag cement, fly ash, and others), an external source (such as seawater and deicing salts), and chemical admixtures also contribute to the additional alkali leading to ASR in the concrete [8,51,89]. The hydration of cement contributes to the pore solution's huge alkalinity, and effort to minimise this could lead to low alkalinity and carbonation, resulting in corrosion for reinforced concrete infrastructure. The portland cement hydration produces interstitial concrete pore solution, which is mainly comprised of calcium hydroxide ($Ca(OH)_2$), potassium hydroxide (KOH), and sodium hydroxide (NaOH) [90]. Aside from the alkalis produced from portland cement, reactive aggregates have also been found to release a certain percentage of alkali to the solution [84,85,91]. The release and exchange of cations from aggregates with the calcium hydroxide present in the pore solution is the chemistry behind the alkalis' dissolution to cause ASR gel. Though cement, aggregates, and other cementitious materials contain numerous alkali metals but sodium, Na^{+}, and potassium, K^{+} ions contribute significantly to ASR concrete damage [89]. The quantity of alkalis in concrete in the form of Na and K is expressed in Eq. 2.1 below.

$$Na_2O_{eq} = Na_2O + 0.658\ K_2O \text{ (in percentage)} \tag{2.6}$$

The conventional North American Portland cement contains 0.2–1.2% $Na_2O_{eq,}$ while an alkali content as high as 1.65 % of Na_2O or more is found worldwide [92]. Despite the low percentage of alkalis compared to other oxide contents of Portland cement, the high solubility of these alkaline makes them dominate the concrete pore solution. The sulfate (SO_4^{2-}) and the hydroxide (OH-) ions dissolved into the solution to maintain balance with the Na^{+} and K^{+} ions, playing an important role in ASR-induced damage [46,60]. The total alkali content formed in the concrete mix can also increase as a result of external sources (such as seawater, deicing water, water from the industries using sodium and potassium solution, the groundwater) and admixtures (such as retarders, water reducers, and air-entraining) which may contain Na^{+} and K^{+} ions [40,79,93,94]. This leads to the high alkalinity of the concrete interstitial solution, which potentially increases ASR expansion [89].

Lastly, it has been recently reported that $Ca(OH)_2$also plays an important role in ASR as the source of calcium ions (Ca^{2+}), which react with dissolved silica forming the deleterious calcium-rich ASR gel rim around aggregate particle surface [95,96]. Ca^{2+}, whose main source is from $Ca(OH)_2$ (formed during cement hydration) leads to the formation of calcium-alkali-silicate gels of variable composition around the aggregates. The alkalis are Na^{+} and K^{+} ions. These gels absorb water molecules and expand over time. The

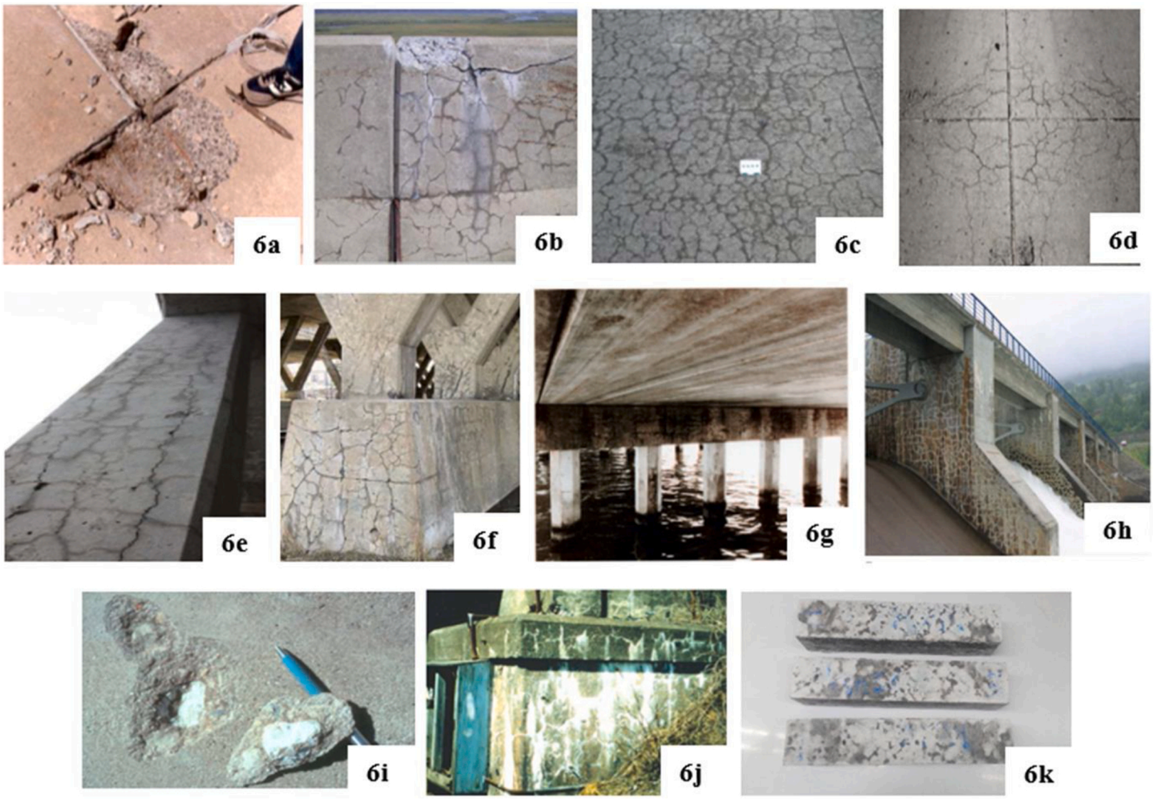


Fig. 6. Various effects of ASR: (6a) concrete spalling joint induced by ASR; (6b) parapet wall o bridges movement; (6c) a well-developed cracks associated with ASR; (6d) D-cracking associated with ASR; (6e) longitudinal cracking related to ASR in column bridges; (6f) verticals cracks shown in parapet walls; (6 g) horizontal cracking on pier cap of the bridge; (6 h) map cracking in bridge wing walls cause by ASR; (6i) pop-outs distress; (6 j) surface discolouration and exudation; (6k) expansion & cracks seen in the testing specimen. Adapted from Thomas [11].

swelling caused by this absorption will then induce expansive forces and tensile stress, causing ASR-induce microcracking around the concrete surface [95]. For instance, Wang developed a model that illustrated the exchange of Ca^{2+} for alkali ions on silica gel. It was concluded that in this exchange, a partial releasing of alkali ions in a mechanism known as "alkali recycling" occurred, regenerating these ions for further production of swelling alkali-silica complex [95]. This conclusion was further explained in the work of Poole [97]. He proposed a model that suggested breaking the siloxane bonds by distorting the silica structure and reducing the lattice structure's local stability. The siloxane bonds break, forming new bonds as water and Ca^{2+}, Na^{+} and K^{+} ions penetrate the structure (see Fig. 5 from stage 1 to 3)) [97].

2.3.3. Sufficient moisture and climatic factors

The effects of environmental conditions on concrete also increase their susceptibility to ASR. The main environmental factors affecting ASR are moisture content and the associated concrete alkali redistribution due to seasonal climatic variations (temperature, humidity, and wetting/drying cycles). So also is the penetration of alkalis from external sources (seawater and deicers). The optimum combination of silica from aggregates and alkalis from Portland cement will initiate ASR, whereas the environmental factors are essential to making ASR expansive (deleterious in concrete structures). Water is a critical ingredient for propagating ASR in concrete, acting as a transporter of the alkali ions in the cement paste matrix [98–101]. The water appears to have a double effect on ASR; as a reactive agent (it influences the expansion rate at the time of formation of the reaction products) and as a transport agent of different reactive species [101]. Aside from the mixing water, water can also be externally absorbed into the concrete. The pressure causing ASR-induced cracks may also start when the gel absorbs water from the surroundings, leading to greater expansion and cracking in the aggregates interfacial transition zone over a long time [65,102]. Thus, reducing the exposure to water may constrain or halt the reaction and ASR expansion.

In this regard, high ASR expansion is developed due to the synergic integration of reactive aggregates, alkali cement content, and exposure to a substantial amount of moisture. The presence of reactive aggregates with high alkali cement content without sufficient water presence will only result in no or little expansion [92]. Similarly, an increase in relative humidity (RH) of concrete can also cause a greater effect on the ASR expansion. The expansion re-develops at a rapid pace when the concrete structure has retained the necessary RH. For instance, Tomosawa et al. carried out a correlation between the RH level and the alkali content necessary to develop ASR [103]. It was found that the alkali content is increased at low RH, which triggered ASR expansion. Recently, Deschenes Jr. et al.

also investigated RH's influence on ASR development [99,104]. The authors conclude that ASR swelling gel rose at low RH and that enough drying may prevent ASR deterioration in non-air-entrained concrete [99,104]. Thus, there could be a sign of swelling gel in concrete at a very low relative humidity, but a relative humidity of 80 % or more has been reported to be more suitable for swelling gels, especially for concrete exposed to freezing and thawing, and wetting and drying cycle [20,105,106].

3. Effect of ASR on civil infrastructures

The effects of ASR are not immediate but continual over time as silica and alkali's reaction persists in a moist environment. This harmful reaction then causes expansion over time, resulting in severe distresses and deterioration of civil infrastructures. In the end, ASR affects the engineering properties of concrete, such as compressive strength, tensile strength, flexural strength, or modulus elasticity over time. It also results in deflection, relative movement, permanent deformation, cracking, surface pop-outs, joints materials (sealant) extrusion, surface deposits (gel exudation and efflorescence), discolourations and so on. ASR effects are to a large extent characteristic of every concrete structure; however, in this review, the effects of ASR is only discussed on major highway infrastructure (concrete pavements and bridges), as shown in Fig. 6.

3.1. *Concrete expansion in pavement and bridges*

Concrete expansion is one of the major effects caused by this deleterious reaction. The expansion of the pavement is generally increased as a result of the swelling gel form during ASR. Though the deterioration expansion on concrete is fairly slow due to the swelling gel formation, it is very progressive over its service life [92]. Over time, this leads to a loss in durability, serviceability, and ultimate demolition of concrete structures, reducing the life span. This expansion results in randomly formed map cracking, longitudinal cracks in subtle cases, and joint spalling of concrete pavement in worst cases (see Fig. 6a) [1].

In bridges, the expansion varies from one member to another; this causes distresses such as joint closure, deflections with the associated squeezing of sealing materials, and eventually leading to concrete spalling joints. Also, it can lead to an adjacent concrete structure movement, as shown in Fig. 6b [7].

3.2. *Cracking in pavement and bridges*

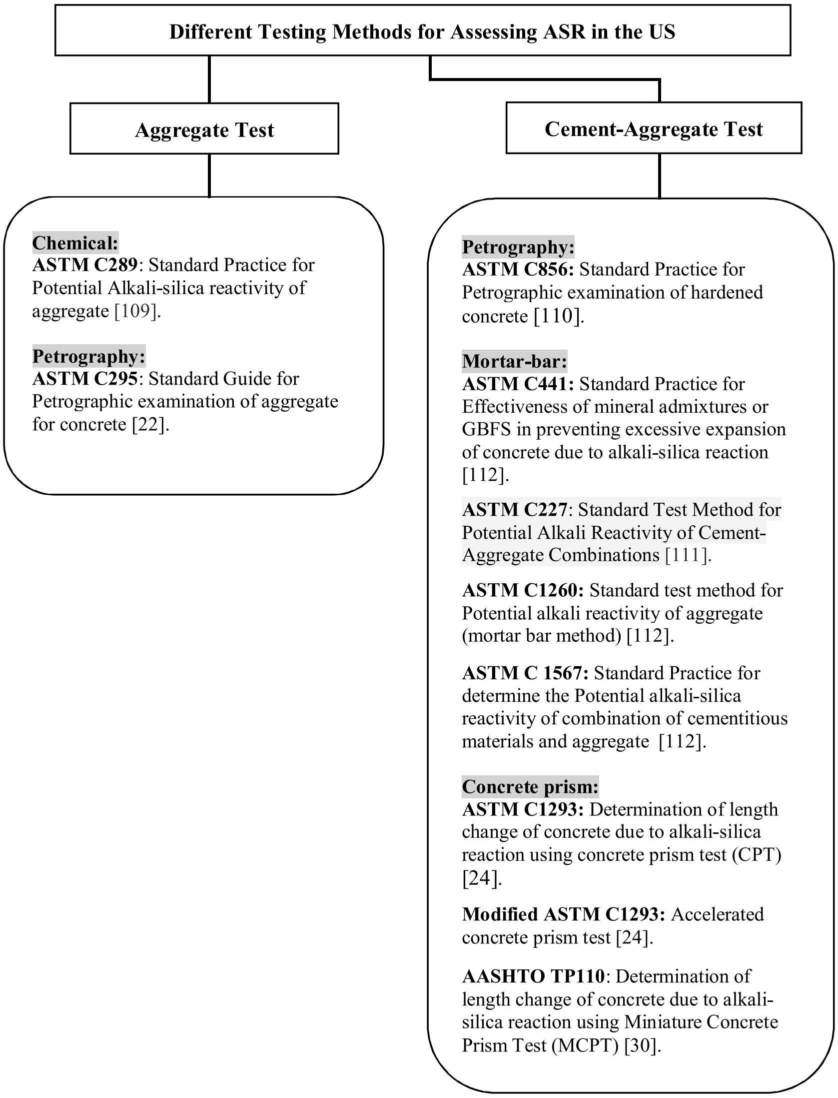
Concrete cracking is also a major ASR-induced distress observed on concrete structures. These cracks can be in the form of longitudinal, transverse, and/or fatigue, which can vary in length, depth, and width. That is, it can go around or through the aggregates or in respect of location, affecting the entire life span of the structure, as shown in Fig. 6c-h [46,60]. The ASR-induced cracking characterised by cracks networks is due to the excessive gel expansion either in or on reactive aggregates particles within the concrete, becoming internally restrained, which then causes internal stress on the concrete [37,107].

At the initial development, cracking is shown on concrete pavement surface as randomly oriented cracks (showing no or little indication of substantial cracks). These cracks can be seen early on a smooth surface than on a grooved or texture surface, with more pronouncement in the wetted surfaces [60]. In addition to this, well-defined longitudinal cracks in the form of map or pattern crackings (developed across the pavement width) can also be experienced due to ASR growth. These cracks increase as a result of traffic wears, especially with the jointed and continuously reinforced pavement. ASR in the jointed pavement can develop severe cracking, especially left to right longitudinal cracking and interconnected cracks (fatigue cracking) [37,107,108]. The cracks are open without being filled with secondary deposits at the surface and increase as moisture content and temperature increases. ASR in continuous reinforced concrete pavement (CRCP) can be observed as a rectilinear crack pattern (when random or transverse cracks interconnect longitudinal cracks) in smooth rather than texture pavement [46]. Additionally, durability cracking, also known as the D-cracking around the joints in the concrete pavement, can also be caused by the ASR mechanism when the cracks are simultaneously parallel to the adjacent joint. This distress cracking progress normally away from the transverse joints and pavement slab edge (see Fig. 6d) [37,46,60,67,107,108].

In bridges, ASR associated cracks in the deck's mid-span and bridge columns are observed as longitudinal cracks from top to bottom, interconnected by tight short mini-cracks that expand transversely between these longitudinal cracks, and also leaving behind the presence of white deposits on these columns. Most vertical cracks observed in bridge parapet walls are caused by ASR deformation because of the white deposit at the base, showing the ASR swelling gel [2,60]. Another collaborative crack associated with ASR is the horizontal cracks in the pier cap over water. Likewise, in the wing wall of bridge structures, a lower level of sub-horizontal cracks can be associated with ASR (especially in the area of free frost action). The curb section can also show distresses due to ASR in the form of longitudinal and fine random cracks. These cracks tend to increase in the presence of moisture or frost areas [37,46].

3.3. *Pop-outs in pavement and bridges*

Concrete pop-outs occur as a result of weak or poor bonding between the cement paste and aggregate particles. Pop-outs can also occur when a fragment of the concrete breaks out of its surface. Pop-outs distress related to ASR occurs when the surface reactive aggregates undergo damage expansion, inducing a detachment and separation from the bottom aggregates. This effect is more pronounced during frost action when the concrete aggregate surface is susceptible to frost actions [8]. The gel formed beneath the pop-out aggregate usually indicates that the concrete hole's distress is caused by ASR (see Fig. 6i) [37,60,108]. Likewise, the concrete pop out associated with ASR is also dependent on the floor finishes and covering and slab sub-grade such as wet cohesive soils (common with pavements). The durability and serviceability of concrete are not generally affected by this kind of distress; however, it can lead to a



Different Testing Methods for Assessing ASR in the US

Aggregate Test

Chemical:
ASTM C289: Standard Practice for Potential Alkali-silica reactivity of aggregate [109].

Petrography:
ASTM C295: Standard Guide for Petrographic examination of aggregate for concrete [22].

Cement-Aggregate Test

Petrography:
ASTM C856: Standard Practice for Petrographic examination of hardened concrete [110].

Mortar-bar:
ASTM C441: Standard Practice for Effectiveness of mineral admixtures or GBFS in preventing excessive expansion of concrete due to alkali-silica reaction [112].

ASTM C227: Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations [111].

ASTM C1260: Standard test method for Potential alkali reactivity of aggregate (mortar bar method) [112].

ASTM C 1567: Standard Practice for determine the Potential alkali-silica reactivity of combination of cementitious materials and aggregate [112].

Concrete prism:
ASTM C1293: Determination of length change of concrete due to alkali-silica reaction using concrete prism test (CPT) [24].

Modified ASTM C1293: Accelerated concrete prism test [24].

AASHTO TP110: Determination of length change of concrete due to alkali-silica reaction using Miniature Concrete Prism Test (MCPT) [30].

Fig. 7. Various test methods use for assessing ASR.

rough concrete surface due to constant traffic [46,97].

3.4. *Surface deposits and colour changes*

Surface deposits in terms of gel exudation and efflorescence can greatly occur along the concrete cracks, ranging from white to dark grey. The ASR gel exuding from the concrete surface can also be colourless fluid, viscous yellowish, or rubber-like in terms of colour and shape [97]. Though these colour traces may not show ASR related distress effects (suggesting that the traces are caused by frost action); however, the presence of gel formation on the crack surface ascertains ASR. These can be increased in the presence of frost action, frost susceptible aggregate, and the presence of moisture. According to Poole [107], surface discolouration has been revealed to be common in bridge decks that appear in combination with cracking. This surface discolouration area is seen as bleached brown or pinkish and extending several inches from crack regions (see Fig. 6j) [46].

4. Evaluation of alkali-silica reaction (ASR)

Since ASR was recognised as a durability challenge on concrete structure more than 70 years ago by station [1], several comprehensive test proposals have been developed and proposed to assess and evaluate concrete sample’s susceptibility to ASR. Furthermore, efforts are continually made to develop better versions of earlier test methods to address potential aggregate reactivity in concrete. Fig. 7 shows an illustration of major published test methods for ASR evaluation. However, some of the method reported in

Fig. 7 has been withdrawn, such as the ASTM C289 [109] which was withdrawn in 2016, ASTM C856 [110], and ASTM C227 [111] which was withdrawn in 2018 because other tests appear to be far more reliable than these older test methods. Other test methods still active in evaluating aggregate or concrete susceptibility to ASR include ASTM C 295: Aggregate petrographic examination [22]; ASTM C 1260: accelerated mortar bar test [112]; ASTM C 1293: concrete prism test (CPT) [24], and the new testing method; AASHTO TP 110: miniature concrete prism test, (MCPT) [30]. These well-adopted ASR evaluation methods are discussed below.

4.1. Aggregate petrographic examination - ASTM C 295

This method was first developed in 1954 by Mather [113] and later modified in 2008 (and called ASTM C295−08) [22]. Mather developed it to determine the chemical and physical properties of aggregates, classify and quantify particle elements present in the aggregates, and differentiate aggregate samples from a specific source from another source with known performance data [113].

Similarly, a visual and microscopic examination is performed on the prepared aggregate samples using a sieve analysis or optical microscope (where a thin section of aggregates is carefully examined). In another case, the petrographic examination can be achieved by using X-ray diffractions (XRD), scanning electron microscopy (SEM), or infrared spectroscopy (IR). However, some limitations of the ASTM C295 examination made them unsuitable for characterising some specific aggregates for ASR, leading to the preference for other ASR test methods. These shortcomings are the inability to characterise slow reactive aggregates, inability to determine the level of reactivity (deleterious expansion) of aggregate in concrete, a need for an expert and skilful petrographic examiner, and that the process involved consume a lot of time and energy to identify aggregate reactivity [61]. Also, the obtained result depends on other test methods' findings to evaluate aggregates' susceptibility to ASR [61,114]. Another popular test method used together with the petrographic examination is the chemical method (ASTM C289). The ASTM C289 testing method is for testing the chemical reactivity of aggregates [109]. Using ground aggregate, the amount of silica dissolved in sodium hydroxide at 80 °C for 24 h is determined, and the decrease in the solution alkalinity is measured. However, this method was withdrawn and became inactive in 2016.

4.2. Accelerated Mortar bar test (AMBT) - ASTM C 1260

The accelerated Mortar bar test, ASTM C 1260, was invented in South Africa by Oberholseter and Davies in 1986 at the National Building Research Institute (NBRI), which was later approved in 1989 and revised/reapproved in 2007 as ASTM C1260 [112]. The test method involves preparing 25 mm x 25 mm x 285 mm (1-in x 1-in x 11.25-in) mortar samples following the standard aggregate gradation of ASTM C33 specifications or ASTM C150. However, the autoclave expansion of the cement is limited to 0.20 %. The test procedure is carried out by complete immersion of the samples in 1 N of NaOH solution at 80 °C (176 °F) for 14 days. The results are produced within 16 days from the casting date.

An expansion of less than 0.10 % of the mortar bar is considered harmless and a non-reactive aggregate to structures. If the average expansion is between 0.10 % and 0.20 %, the aggregates are considered slow reactive aggregates, requiring other test methods (1-year concrete prism test - CPT) or field performance to determine their reactivity. An expansion greater than 0.1 % is considered to be reactive and considered deleterious. Some researchers [115–117] concluded that the expansion threshold of 0.10 % is inadequate to characterise some aggregate susceptibility to ASR expansion; hence, Hooton [63] proposed the extension of the testing days to 28 and 56 days with an expansion limit of 0.28 % and 0.48 % respectively, for proper classification of slow reactive aggregates [63].

This test's shortcomings have been reported to include its severe (aggressive) approach, thereby producing a false-negative and false-positive result. False-positive results show an aggregate as deleterious when its field performance is good, while a false-negative test result is when the test identifies an aggregate as not deleterious but fails other tests [63,115]. For example, Folliard et al. (2006) reported four aggregates passing the ASTM C 1260 (the mortar bar test) failed the 1-year ASTM C 1293 (concrete prism test) [115]. Likewise, false-negative cases of aggregates were recently reported by the Idaho Transportation Department (ITD) report on ASR [118]. Meanwhile, these aggregates were reported as non-reactive aggregates when using the AMBT method and noted reactive when the 1-year CPT method was used. Although this test method is widely accepted by many agencies, other studies have indicated some critical limitations. One of the controversies associated with ASTM C 1260 is the test duration [90,115,119].

For instance, Shi et al. (2015) concluded that 16 days of testing is sufficient to characterise aggregates with slow reactiveness, and Fernandez-Jimenez et al. (2007) also supported this recommendation, confirming that some special aggregates (for instance: Zeolite) could exhibit greater expansion even before the end of 14-day [120,121]. This is against the earlier noted recommendation of Hooton [63] for an extension of testing to 28 and 56 days. Likewise, Palacious and Purtas (2006) proposed that the test method be extended further to 28 days and above [122]. Another shortcoming of ASTM C 1260 is the extensive crushing and aggregate treatment that alters the expansion result [123,124]. The test samples are subjected to an aggressive environment of high test temperature and harsh curing medium [125]. For example, Ideker et al. [126] found that the expansion result of many tested aggregates is inconsistent with the field performance result because AMBT samples are subjected to a very harsh medium compared to what is experienced in the field. Based on the highlighted shortcomings, the test procedure is handicapped to the job mix design or for mitigation purposes. Some authors generally concluded that this method should be utilised mainly for accepting aggregates and not for rejection [126,127]. This gave room for the development and the adoption of the ASTM C 1293.

4.3. Concrete prism test (CPT) - ASTM C 1293

4.3.1. One-Year CPT

This is a standard test method for determining the expansion (change in length) of concrete over time using a concrete prism sample

Table 3
Mixture proportion and storage conditions for the MCPT Specimens [86].

Item Mix	Proportion
Specimen size	50 × 50 × 285-mm (2-in x 2-in x 11.25-in)
Test duration	56 days – 84days
Storage temperature	60 °C (140 °F)
Storage environment	IN NaOH solution (Soak)
Initial length (zero)	24 h in H_20 @ 60 °C (140 °F)
Cement Type	Type 1 of 420 kg/m^3
Cement alkali content	0.9 % +/- 0.1 Na_2O_{eq}
Alkali boost (total alkali content)	1.25 % Na_2Oeq
Coarse aggregate (dry volume fraction)	0.65
Coarse aggregate	Maximum size of: 12.5 mm (1/2 in.)
Coarse aggregate proportion (% by weight)	1) 9.5 mm size 2) 4.75 mm size
12.5 mm – 9.5 mm:	57.5 %
9.5 mm – 4.75 mm	42.5 %
Fine aggregate (% by weight)	Determined based on ACI 211; Absolute Volume Method: (1 – V_{H2O} + Vcg + Vcem)
Water-to-cement ratio:	0.45

[24]. This method was found to overcome the limitations of other test methods used in assessing aggregates' susceptibility to ASR by using a concrete test method (instead of an aggregate test or mortar bar test). Swenson and Gillott developed this test during the 1950s in Canada [128]. The test procedure involves using high-alkali cement, meeting an alkali content of 0.90 % ± 0.10 % and adding sodium hydroxide to the mix water to raise the cement alkalis to 1.25 %. Concrete prism (from such mix) measuring 75 mm x 75 mm x 285 mm (3-in x 3-in x 11.25-in*)* is cured in water for one full year at 38 °C (100 °F). A concrete prism expansion less than 0.04 %, after one year, is considered acceptable; values above this is considered reactive. As for mitigation purposes, a concrete prism expansion less than 0.04 % for 2-year is considered acceptable. Unlike the AMBT method, this test method is utilised to assess both fine and coarse fractions of aggregate using the concrete prism without excessive crushing. From the numerous methods developed to assess reactive aggregate to ASR, the ASTM C1293 has been proven to be the most consistent and dependable [123,126,127].

The two major limitations of this test method are the long test duration. The exposure of the concrete prism in water for 1-year is impractical for specific project aggregates screening and ASR evaluation when dealing with short-term projects. The other limitation is alkali leaching. Researchers have shown that about 35 % of the alkalis originally in the concrete prism, over 1-year, leached into the water storage with about 20 % leaching just after 90 days [7,129,130]. Such leaching potentially leads to undesired low ASR when measuring the length change after a year. Due to this alkali leaching and the long testing duration, it was proposed by Thomas et al. (2006) and Ideker et al. (2010) to limit the testing method to 13 weeks or 26 weeks [126,127]. Hence, this resulted in a new test method called the accelerated concrete prism test.

4.3.2. *Six-month CPT (Accelerated)*

This method is a modification of the ASTM C 1293 test introduced by Ranc and Debray [131] to overcome the earlier highlighted shortcomings of the 1-year CPT method. The idea was to reduce the test duration from 1-year to 6 months by subjecting samples in a more aggressive environment compare to 38 °C (100 °F) employed for the 1-year CPT. The test procedure also uses high-alkali cement meeting an alkali content of 0.90 % ± 0.10 % and adding sodium hydroxide to the mix water to raise cement alkalis to 1.25 %. Like the 1-year CPT test, a 75 mm x 75 mm x 285 mm sample size is prepared and cured over water for six months at 60 °C (140 °F). Other test periods have been suggested; for instance, a test period of 26-weeks within the expansion limit of 0.04 % was adopted by [124]. Also, Thomas et al. [127] found that the accelerated concrete prism tests' expansion results showed a good correlation ($R^2 = 0.97$) with results from the extended 1-year concrete prism test. Ideker et al. (2010) also used the accelerated CPT to evaluate the expansion of aggregate due to ASR. Contrarily, it was reported that a huge reduction in ASR expansion was observed when reactive aggregates were tested with the CPT (6-month) compared to CPT (1-year) method [126].

The14-day AMBT and 1-year CPT have been generally adopted for ASR testing in the mortar bar and concrete prism, respectively. However, the two methods were found to be either inconsistent with one another. Therefore, there was a need for a well-validated method that can be used to evaluate the susceptibility of aggregates to ASR within a reasonable time frame. This initiated the new test development: AASHTO TP 110 – miniature concrete prism test (MCPT).

4.4. *Miniature concrete prism test (MCPT) – AASHTO TP 110*

Latifee and Rangaraju developed the miniature concrete prism test (MCPT) method in 2014 [124]. The test procedure was developed to overcome the challenges encountered when using ASTM 1260 and ASTM 1293 test methods. The MCPT method was reported to provide good correlations with ASTM C 1293 results [124]. Also, it has been found to yield reliable and dependable results on aggregate susceptibility to ASR [124]. In achieving this reliable outcome through the new method, characteristics of AMBT and CPT features were adequately modified. For instance, the shortcoming of the short time duration, excessive crushing and treatment of fine aggregates (< 4.75 mm), the high storage temperature of 80 °C (176 °F), and small test specimen size employed in the assessment of ASTM C 1260 (AMBT) were changed and revised. Likewise, the ASTM C 1293 (CPT) undesired features, such as lower test temperature

Table 4
Classification of Aggregate Reactivity [124,135].

Reactivity	14-Day Expansion in AMBT (%)	56-day Expansion in MCPT (%)	1-Year Expansion in CPT (%)
Non-reactive	≤ 0.100	≤ 0.040	≤ 0.040
Moderately reactive	$0.101 \leq X \leq 0.300$	$0.041 \leq X \leq 0.120$	$0.041 \leq X \leq 0.120$
Highly reactive	$0.301 \leq X \leq 0.450$	$0.121 \leq X \leq 0.240$	$0.121 \leq X \leq 0.240$
Very highly reactive	> 0.451	> 0.241	> 0.241

that resulted in longer test duration and the storage of test specimens in a 100 % RH environment that allowed for alkali leaching from specimens, were also modified.

Thus, the MCPT method provides a suitable approach for ASR evaluation, in which concrete prisms are stored in a 1 N NaOH solution at 60 °C for 56 days (or 84 days for slow reactive aggregates). Contrarily to the AMBT method, the specified temperature of 60 °C minimise the potential for achieving false-positive result due to aggressive condition while the 56 days of testing limits the possibility of alkali-leaching observed in the CPT method. However, the increase of temperature from 38 °C (as used in the CPT method) to 60 °C in the MCPT method may influence the concrete's ASR mechanism and reaction products. Maraghechi et al. and Kleib et al., reported on the kinetics and product of ASR formation in terms of temperature change [132,133]. It is shown that portlandite saturated solution slows down the dissolution of silica at low temperatures. At increased temperature, a greater rise in the OH^- ions are observed (present in the pore solution), which attacked the silanol and siloxane groups. The continuous attack then results in the formation of dissolved silica ions; hence these ions are then precipitated by the action of the cations forming alkali-silica gel [133].

Table 3 summarized the main features of the MCPT method [86]. This method adopts the use of a concrete prism of 50 mm x 50 mm x 285 mm (2-in x 2-in x 11.25-in), instead of using the bar 25 mm x 25 mm x 285 mm or the 75 mm x 75 mm x 285 mm adopted in ASTM C 1260 and ASTM C1293 respectively, accommodating the evaluation for both fine and coarse aggregates to expansion due to ASR [5,26]. A concrete prism expansion less than 0.04 % after 56 days is considered acceptable; values above this are considered reactive. Furthermore, allowance is made for an additional 28 days (making 84 days) to determine any slow reactive aggregates. The MCPT adopted the storage of test specimens in 1 N of NaOH solution and a temperature of 60 °C to accelerate ASR used in the AMBT method. Likewise, it implements the CPT method's beneficial feature, such as boosting equivalent alkali to 1.25 % in concrete and using the concrete prism instead of mortar specimen [124].

The test employed 12 mm (1/2 in. maximum coarse aggregate size rather than 19 mm (¾ in) maximum size (as used in CPT) without crushing the aggregates (as used in the AMBT) to accelerate the ASR reaction. However, this MCPT method has not been proven effective to field performance as only a few studies [26,124,134] have been carried out on the use of the method, and further investigation is needed to shed light on this aspect along with a correlation and calibration with field performance of aggregates to validate the test results. Again, the test only considered two coarse fractions of aggregate gradation (12.5 mm and 9.5 mm); this is insufficient to evaluate the performance of other coarse size fractions that are used in the field. In the previous research on MCPT [124], many of the aggregates assessed were either highly reactive aggregates or non-reactive aggregates. As a result, there is not sufficient information available to assess the reactivity of many other types of aggregates (low and moderate reactive aggregates). In essence, the versatility of MCPT requires further study.

4.5. Classification of aggregate reactivity to ASR under each method

Table 4 shows the classification of Aggregate Reactivity under the different test methods [124,135]. A mortar bar that shows expansion values less than 0.10 % at 14 days is considered non-reactive using the AMBT method. In comparison, a mortar bar that shows expansion values between 0.30 % and 0.45 % at 14 days method is considered to contain highly reactive aggregates. For MCPT and CPT methods, the expansion values that are less than 0.040 % at 56 days and 1 year, respectively, are considered for non-reactive aggregates. Concrete prisms that show expansion values between 0.040 % and 0.120 % at 56 days (MCPT method) and 1-year (CPT method) are considered to represent moderately-reactive aggregates, while concrete prisms that show expansion values between 0.120 % and 0.240 % at 56 days (MCPT method) and at 1-year (CPT method) are considered to represent highly-reactive aggregates. Concrete prisms that show expansion values of more than 0.240 % represent very highly reactive aggregates.

5. ASR assessment of aggregates - A case study

This section highlights a case study of ASR evaluation for various aggregates using the three test methods (in Section 4), based on recent research studies [26,28,29,124,134]. In this regard, the evaluation of various aggregates using the new test method (MCPT) and previous methods (AMBT and CPT) were quantified and correlated with one other. Comparing the expansion data from the different researchers showcases the MCPT method's performance in relation to other previous test methods. This is done to highlight the best method suitable to assess ASR based on their correlation with one other. Similarly, this will also allow for verification with other independent researchers who have implemented the MCPT method since its conception by Latifee and Rangaraju in 2014 [124]. This is useful as a starting point in adding to the body of knowledge about the need for further studies on MCPT's versatility, as noted in Section 4.4.

The data of each aggregate group in Table 5 was obtained from the research investigation conducted by Latifee and Rangaraju, Rangaraju et al., and Konduru et al., [28,134,136] and their ASR expansion presented. The alkali-silica reactivity of 44 aggregate

Table 5
ASR classifications of aggregates based on the expansion limits of MCPT, CPT, and AMBT methods {data retrieved from [134] (column 1-4) [28]; (column 5 -8), and [136]}.

Aggregate identity	56-day MCPT expansion (%)	365-day CPT expansion (%)	14-day AMBT expansion (%)	Aggregate identity	56-day MCPT expansion (%)	365-day CPT expansion (%)	14-day AMBT expansion (%)	Aggregate identity	56-day MCPT expansion (%)	365-day CPT expansion (%)	14-day AMBT expansion (%)
A-1	0.086	0.026	0.14	A-17	0.086	0.026	0.14	SP-33	0.149	0.181	0.35
B-2	0.048	0.021	0.1	B-18	0.048	0.021	0.1	SD-34	0.099	0.109	0.22
C-3	0.032	0.026	0.07	C-19	0.032	0.026	0.05	NM-35	0.185	0.251	0.9
D-4	0.051	0.021	0.08	D-20	0.051	0.028	0.08	NC-36	0.149	0.192	0.53
E-5	0.026	0.02	0.07	E-21	0.026	0.02	0.07	BB-37	0.017	0.032	0.042
F-6	0.051	0.028	0.012	F-22	0.051	0.021	0.12	GLN-38	0.046	0.05	0.235
G-7	0.047	0.022	0.09	G-23	0.047	0.022	0.09	QP-39	0.07	0.07	0.08
H-8	0.099	0.016	0.24	H-24	0.099	0.016	0.24	SLC-40	0.039	0.03	0.19
I-9	0.094	0.025	0.12	I-25	0.094	0.025	0.12	MSP-41	0.023	0.03	0.1
J-10	0.059	0.022	0.1	J-26	0.059	0.022	0.1	TX-42	0.44	0.59	0.64
K-11	0.032	0.019	0.05	K-27	0.032	0.019	0.07	GI-43	0.091	0.09	0.26
L-12	0.036	0.017	0.07	L-28	0.036	0.017	0.07	SB-44	0.115	0.15	0.46
M-13	0.046	0.05	0.46	M-29	0.046	0.05	0.24				
N-14	0.435	0.59	0.46	N-30	0.435	0.59	0.64				
O-15	0.091	0.09	0.26	O-31	0.091	0.09	0.26				
P-16	0.115	0.15	0.46	P-32	0.115	0.15	0.46				

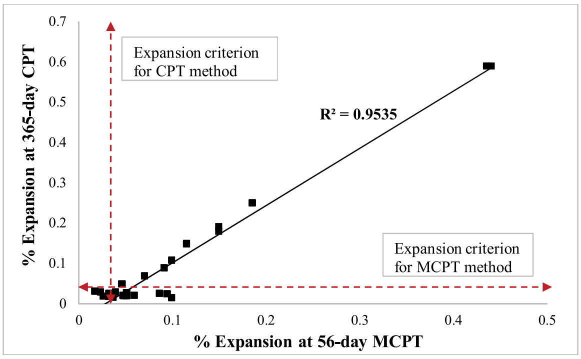


Fig. 8. The correlation between Miniature concrete prism test (MCPT) at 56 days versus concrete prism test (CPT) at 365 days based on 44 aggregates. Data adopted from [28,134,136].

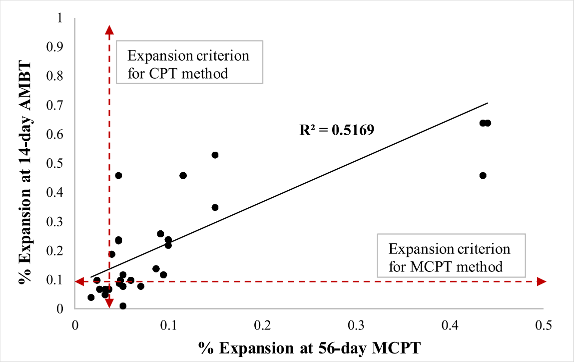


Fig. 9. The correlation between Miniature concrete prism test (MCPT) at 56 days versus Accelerated mortar bar test (AMBT) at 14 days based on 44 aggregates. Data adopted from [28,134,136].

groups was evaluated based on the expansion limits of MCPT, CPT, and AMBT methods [23,24,30]. From the three studies, an expansion limit of 0.04 %, 0.04 %, and 0.10 % for the MCPT, CPT and AMBT were all selected to characterise the aggregate reactivity.

Based on the results obtained (Figs. 8 and 9) from the investigation of 44 aggregates susceptibility to ASR [28,134,136], it can be inferred that the MCPT method is a reliable and much more rapid method to evaluate the reactivity of aggregates when compared with the CPT method. Considering the high degree of correlation (R^2 value of 0.95) between the CPT and MCPT test methods (and the bulk number (44) of aggregates considered for this evaluation), it can be implied that the possibility of characterising aggregates using MCPT as either false-positive or false-negative is significantly low. Contrarily, the correlation between MCPT and AMBT was not as strong (with R^2value of 0.52 in Fig. 9). This suggests that while AMBT may falsely characterise an aggregate to be highly reactive. Thus, the chance of an aggregate being characterised as false-positive in MCPT is much lower than AMBT. Based on these evaluations, it can be implied the MCPT method is a better method for assessing aggregates potentials to ASR than AMBT. However, it is hard to make conclusion because of the inavailability of field performance data of the aggregates assessed in their study and no indication of which aggregate produced false-positives and false-negatives (using the AMBT) as presented in Table 5. Also, based on the correlation, the MCPT method is as reliable as the CPT method in assessing the reactivity of aggregates. For field application, the short term nature of MCPT (56 days) can yield quick but equally reliable results as the long term 365 days of CPT.

6. Conclusion

ASR in concrete is one of the major concerns in civil and construction engineering, which affects concrete structures worldwide. The ASR affects both the durability and mechanical properties of concrete, causing excessive expansion, cracking, discolouration, exudation, and eventually damaging the structures. This article reviews the most recent and relevant progress and the existing knowledge concerning the reaction mechanisms, chemistry, and ASR effects on civil infrastructures (such as pavement and bridges). The common test methods used to evaluate ASR were also reviewed. ASR occurs due to a series of sequential reactions, such as the dissolution of silica, the formation of alkali ions in pore solution, the formation of gel, and the gel's swelling. The multi-stages, complexity, and the dependency on ASR's numerous factors make it challenging to understand this deleterious reaction. Thus, the earliest detection of ASR will assist material engineers and agencies in saving millions of dollars on the cost of repair and rehabilitation of structures affected by ASR and increasing the service life of existing structures through maintenance programs.

Numerous methods have been developed to assess aggregate reactivity to ASR in the United States, in which the AMBT and CPT methods are the two most widely used methods. However, these test methods have some shortcomings; the AMBT exhibits excessive false-positive and false-negative test results. The CPT method (though more reliable) requires an unusually long test duration (1 or 2 years, depending on the purpose) which renders it unsuitable for routine evaluation. Thus, the MCPT method was developed to address the AMBT and the CPT test methods' shortcomings. A review case study was carried out to showcase the MCPT as a better method for assessing aggregates potentials to ASR than AMBT and that it is as reliable as the CPT method. This reinforces the validity of the MCPT method as a rapid and reliable predictor of aggregate reactivity and serves as a useful starting point in adding to the body of knowledge about the need for further studies on MCPT's versatility.

CRediT authorship contribution statement

Ebeneezer Fanijo: Conceptualisation, methodology, investigation, formal analysis, writing –original draft, review, editing, and supervision. **John Temitope Kolawole:** formal analysis, writing - review, and editing. **Abdullah Almakrab:** Writing and reviewing.

Declaration of Competing Interest

The authors report no declarations of interest.

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