STRUCTURAL IMPLICATIONS OF INTERNAL SWELLING REACTIONS IN CONCRETE: A REVIEW

Martin Noël[1]*, Leandro Sanchez[1],Renaud-Pierre Martin[2], Benoît Fournier[3], Josée Bastien[3], Denis Mitchell[4]

[1]University of Ottawa, Ottawa, ON, CANADA

[2]Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, Paris, FRANCE

[3]Université Laval, Laval, QC, CANADA

[3]McGill University, Montréal, QC, CANADA

Abstract

While the chemical and physical processes associated with alkali-aggregate reaction and delayed ettringite formation, otherwise known as internal swelling reaction mechanisms, have now been the subject of considerable research spanning several decades, the actual implications for affected structures are still open to debate. This may be partially attributed to the fact that parameters affecting structural response such as confinement effects, boundary conditions, anisotropy and loading conditions vary greatly among various structures. It is also worth noting, however, that the correlation between data obtained from material-level analyses and the in-situ performance of large-scale structures is still not well understood even at a fundamental level. This paper aims to synthesize our current knowledge of the structural implications of internal swelling mechanisms in concrete structures, in order to highlight major knowledge gaps and contribute towards a critical discussion of the importance of pursuing multi-scale testing regimes for the assessment of aging infrastructure.

Keywords: Alkali-aggregate reaction; delayed ettringite formation; structural implications; aging infrastructure; concrete structures.

1 INTRODUCTION

Internal swelling reactions (ISR) is a term used to describe various reactive chemical pathologies, such as alkali-aggregate reaction (AAR) and delayed ettringite formation(DEF), that lead to the expansion of affected concrete elements, especially in the presence of moisture. This expansion is generally associated with a change in the mechanical properties of the concrete material resulting from the formation of microcracks propagating through the aggregate particles and/or cement paste. While petrographic and microscopic analyses, together with mechanical testing of concrete cores retrieved from the affected structure, can provide a great deal of useful information regarding the degree of damage and the potential for further expansion, a direct correlation between these results and observed changes in structural performance at the serviceability and ultimate limit states does not currently exist. This presents a major challenge as to the practical applicability of test results, analytical methods, and the various commonly used laboratory procedures which focus largely on small-scale specimens.

As much as our knowledge and understanding of ISR mechanisms (i.e. AAR and DEF) have increased in recent decades, leading to more effective prevention and mitigation strategies, understanding their effect on the overall behaviour and remaining service life of deteriorated structures has been a challenge. Structural concrete elements are inherently anisotropic and vary in terms of geometry, confinement, reinforcement ratio and configuration, localized stress concentrations and gradients, and distribution of applied loading. They are also influenced by size effects, boundary conditions, chemical prestressing, and loading history, not to mention temperature variations, moisture effects, environmental effects and other types of damage mechanisms such as corrosion and freeze-thaw cycles. Furthermore, the specific characteristics of various ISR mechanisms will drastically impact not only the free expansion potential of the affected concrete, but also the

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* Correspondence to: MartinNoel@uOttawa.ca

distribution of stresses in cases of restrained expansion in reinforced concrete members. The influence of any one of the above parameters can be difficult to ascertain, and in combination it becomes a particularly arduous and ambiguous task to produce quantitative predictions or even to draw general conclusions about the structural consequences of ISR damage. Thus, stochastic analysis simulating a number of different parameters rather than pursuing a deterministic solution could be a promising solution.

Nevertheless, despite all the challenges, a comprehensive evaluation of the structural implications of ISR is a critical step towards the development of effective rehabilitation and management strategies for critical aging infrastructure. To this end, the following paper summarizes some of the progress made in this regard and aims to highlight areas for future work. One of the goals of this paper is to generate discussion and interest regarding the importance of multi-scale experimental investigations, including large-scale structural testing, for the future development of comprehensive guidelines for engineers and infrastructure owners to make informed management decisions regarding ISR-affected infrastructure.

2 MATERIAL PROPERTIES

While the main scope of this paper focuses on structural implications of ISR, a brief review of the effect of AAR and DEF on the mechanical properties of concrete is presented here for reference. In general, ISR damage results in a loss of strength and stiffness of the affected concrete, although the degree varies considerably depending on the expansion level, distress mechanism type and associated microstructural features of damage, confinement conditions, and material property being investigated. The main mechanical properties of interest for structural concrete are compressive strength, tensile strength, and modulus of elasticity (stiffness), as described in the following sections.

2.1 Compressive strength

Although measurement of the compressive strength of concrete cores or cylinders is one of the simplest test protocols to perform, compressive strength is unfortunately not a strong indicator of ISR-induced damage[1,2]. Concrete can sustain a considerable amount of compressive loading despite the presence of a large number of microcracks, and, especially in the case of AAR, may still have a compressive strength that is fairly close to the original design strength, even for moderate levels of expansion [3]. Indeed, this could be linked to AAR microscopic damage features that develop themselves mostly within the aggregate particles [3]. In the case of DEF, however, significant reductions in compressive strengths of up to 80% are found for high and very high expansion levels due to the pattern of its distress features which are found mainly in the cement paste and the interfacial transition zone (ITZ) [3,4,5].It is unclear whether, for similar levels of expansion, the different distress features of AAR and DEF would cause a noticeable difference in the compressive strength of affected concrete. Nevertheless, studies suggest that well-confined structural members that are mainly loaded in compression (i.e. columns) may not necessarily suffer from a noticeable reduction in load carrying capacity[6],(although it is worth noting that their bond strength or shear capacity may be detrimentally affected). This is also important to note with respect to flexural capacity, as a drop in concrete compressive strength would cause concerns that the mode of failure of heavily-reinforced beams could change to a compression-controlled failure with a significant loss of ductility; fortunately, this is not likely to be the case for most structures. Of course, it is nevertheless prudent to check for changes in compressive strength by testing cores from various parts of the affected structure.

2.2 Tensile strength

The effect of ISR-induced damage on direct tensile strength is generally more pronounced, and can result in significant strength reductions[1,2,7]. Tensile stresses, according to fracture mechanics concepts, tend to cause further propagation of existing microcracks, which, for plain concrete, quickly leads to tensile rupture as cracks link together across the concrete cross-section. However, it is important to note that splitting tensile tests are not effective in representing the reductions of tensile strength in ISR-affected concrete[5,8], and whenever possible direct tensile strength tests should be performed. Nevertheless, splitting tensile tests remain one of the most used techniques in many laboratories; further research focusing on useful interpretations of these test results could thus be valuable.

While a loss of concrete tensile strength in reinforced concrete elements is not necessarily problematic on its own due to the presence of reinforcing steel, the relationship between tensile strength and other load transfer mechanisms such as shear capacity and bond strength suggests that regions of the structure subjected to high shear stresses as well as anchorage zones may be critical areas for rehabilitation [9,10]. Increased cracking can also result in serviceability and durability issues which should be considered in any comprehensive structural assessment.

2.3 Stiffness

The modulus of elasticity of concrete is greatly affected by the presence of microcracks resulting from ISR expansion, either AAR or DEF, and can be reduced significantly even by modest expansion levels[3,4,5,8,11,12]. However, the results from small scale material tests must be applied in a broader context, in order to appraise the stiffness of structures and structural members. Hence, the influence of ISR on the serviceability of aging structures (e.g. deflections) is, in many cases, more likely to govern management decisions than safety considerations. Furthermore, large changes in the stiffness of structural elements may result in load redistributions and/or secondary effects in statically indeterminate structures, which can lead to overloading adjacent structural elements or supports. Lower concrete stiffness can also result in increased stresses in compression steel reinforcement which, in some cases, could lead to reinforcement yielding. Strategies for retrofitting damaged structures to increase stiffness can include providing additional external confinement, and/or reducing stresses by increasing member size or adding reinforcement, such as externally applied fibre reinforced polymer sheets [6].

3 CONFINEMENT, ANISOTROPY, AND REINFORCEMENT

One of the principal factors influencing the structural response of ISR-affected structures is that, unlike many laboratory specimens, expansion is restrained by a combination of applied loading, boundary conditions, and internal reinforcement (Figure 1a). Since each of these parameters is inherently directional, the resulting confinement is ostensibly anisotropic. Expansion will be limited in the direction of reinforcement/principal compressive stresses/confinement, but unrestrained perpendicular to it. According to [13], ISR volumetric expansions are believed to be constant in the range of stresses they investigated: in other words, if a restraint is applied in one direction, expansions are reported in the less restrained direction. However, this effect has not been systematically observed: [14,15] verified a complex coupling between stress state and volumetric expansion (Figure 1b). Similarly, few data concerning the effect of restraint on DEF is available: [16] didn't observe any expansion transfer for mortar specimens restrained in one direction. Thus, effects of restraint and stresses remain difficult to analyse and deserve more research both at the material and structural scale.

This restrained expansion will also induce mechanical stresses in the concrete, reinforcement, and adjacent elements, often referred to as a *chemical prestressing effect*, which should be accounted for in forensic analyses. As a result, cracks tend to orient themselves in the direction of principal confinement, and curvatures may result in members which are not uniformly restrained (e.g. due to the concentration of internal reinforcement in the tension regions of flexural members) [17].

Chemical prestressing can actually improve structural performance, particularly with respect to shear capacity and serviceability issues, and resulting concrete stresses are generally limited to 3.5-4.0 MPa for AAR [18,19]. [16] reported compressive stresses of about 4.2 MPa for restrained mortar specimens with a free expansion potential of more than 2%. The confinement provided by transverse shear reinforcement is also a critical factor influencing the structural integrity of ISR-affected concrete elements, which helps maintain the integrity of the concrete core in various element types; however, under large expansive stresses, stirrups can actually yield or even rupture, as discussed later.

Smaoui[18] examined the effects of confinement provided by transverse and longitudinal reinforcement on small beams (810 x 228 x 228 mm) affected by ASR. The results demonstrated that a longitudinal reinforcement ratio of 1.53% reduced longitudinal expansion by almost 60% compared to similar beams with no reinforcement. The effects of longitudinal and transverse reinforcement are further examined in Section 5.

4 SIZE EFFECTS

It is often difficult to reproduce and test full-scale structural elements in the laboratory with realistic environmental and boundary conditions, as well as stress and strain distributions induced by a combination of complex time-dependent chemical and physical processes. On the other hand, data collected from in-service structures is inherently constrained by limited access, continuity of service, and the preclusion of destructive testing. Therefore, it is always necessary to critically assess the limitations of the conclusions derived from either laboratory results or site investigations. Ideally, a comprehensive investigation should include a multi-scale approach incorporating both laboratory and field studies, with both small-scale specimens for microscopic analysis and determination of material properties, and large-scale testing for evaluating the structural consequences of ISR damage.Full-scale loading tests of existing structures permit an assessment of the actual behaviour of an affected structure [20,21,22].

Size effects are an important consideration with respect to the structural implications of ISR, due to the influence of size on confinement, crack distribution and crack widths, as well as thermal and moisture content gradients; anisotropy, directional restraint, and non-uniformity of environmental conditions will cause differential ISR development and expansions [4,23]. Experimental research on the size effects of ISR-affected members is limited, particularly given that most structural testing in the laboratory has been conducted on relatively small-scale specimens. Additional testing on large-scale specimens is needed to provide more conclusive results [24]. This is currently a major gap in knowledge, which is critical to understand in order to apply the results of laboratory studies to real structures.

5 SERVICEABILITY AND ULTIMATE LIMIT STATES

5.1 General

When considering the structural implications of ISR damage based on its deteriorated material properties, it is important to consider that the relationship between compressive strength, tensile strength, and modulus of elasticity are not generally the same as for sound concrete. Compressive strength is usually the least affected mechanical property of ISR damaged concrete (especially for AAR). Although fairly different in DEF cases, this parameter should not be used as a primary indicator for predicting structural response; doing so may lead to significant errors [25]. The performance of concrete structures at the serviceability and ultimate limit states are more sensitive to changes in tensile strength and modulus of elasticity, which will influence cracking, deflections, bond strength, shear capacity, etc., and must be carefully considered [25]. Designs for retrofitting and rehabilitating severely damaged structures will generally need to provide additional strength in locations of high tensile and shear stresses, as well as anchorage zones, while increasing stiffness in areas with excessive deflections or in statically indeterminate structures where load is being redistributed to adjacent members and supports.

5.2 Cracking

The first outwardly visible signs of deterioration due to ISR are typically a network of surface cracks, with their orientation influenced by the presence of internal reinforcement, geometrical discontinuities, stress states, and pre-existing cracks. Depending on the type of structural element, reinforced concrete is often already cracked at service conditions long before ISR develops, due to a variety of factors including structural loading, shrinkage, temperature, foundation settlement, or even other deterioration mechanisms such as freeze-thaw and/or corrosion. The true cause(s) of cracking should be determined through a careful diagnostic examination [26].Nevertheless, cracking can be a good indicator of the evolution of degradation and expansion [9,27].

The presence of pre-existing cracks can provide some stress relief for ISR expansion and will affect the local state of stress of the concrete in the vicinity of the cracks. The result, in general, will likely be wider spacing of cracks and greater crack widths than if the expansion were to take place on originally uncracked concrete. Hence, preloading concrete has a significant effect on the cracking and expansion of ISR-affected concrete [28]. (As an aside, it is important to note that many experimental studies apply structural loading after the ISR-induced cracks are present, which is not generally representative of real-life scenarios!)

Since ISR-induced cracks generally form after cracking caused by structural loading has developed, the primary distribution of structural cracking (e.g. main flexural cracks) in pre-cracked elements is not likely to be greatly affected. However, existing cracks will become longer and wider over time and new secondary cracks may form throughout the structure which will lead to other performance issues and/or durability concerns [29]. Furthermore, cracks may form along orientations other than the direction of the expected principal tensile stresses which are not well-restrained by internal reinforcement (e.g. longitudinal cracking in concrete beams), as well as in members that were not designed to resist large tensile stresses (e.g. longitudinal cracking in concrete columns).

5.3 Deflections

Steel reinforcement tends to be concentrated in portions of structural members which are expected to experience tensile stresses under service loads, such as the bottom portion of a beam in positive bending. Hence, the restraint provided against ISR is not uniform throughout the depth of the member resulting in a stress and strain gradient. This so-called “chemical prestressing” effect induces a negative curvature (i.e. upward deflection) [17], which, when superimposed with the deflections under applied loads, results in a net reduction in deflections. However, this effect is typically counteracted by a significant reduction in elastic modulus, increased cracking, and possibly even bond slip. Therefore, observed deformations under loading may be greater than in similar unaffected members, as seen in Figure 2a[30,31]. Nevertheless, studies have found that the behaviour of ISR-affected structures may be reasonably predicted using elastic models if the actual modulus of elasticity of the concrete is obtained from cores extracted from the structure [31]. In some cases, however, the yield stress of the reinforcing steel may actually be exceeded as a result of ISR expansion, which could potentially result in large plastic strains and permanent deformations [31].

5.4 Stress distribution

ISR expansion, when restrained by steel reinforcement, generates compressive stresses in the concrete (Figure 2b) and tensile stresses in the reinforcement. The maximum compressive stress in the concrete due to chemical prestressing in real structures subjected to either AAR or DEF is typically not greater than 4 MPa [16,19], which is more than 10% of the concrete capacity in the case of a 35 MPa concrete mix. The distribution of stresses and strains is largely dependent on the distribution of steel reinforcement, with higher stresses occurring in regions with more reinforcement, and larger strains occurring in regions with less reinforcement. Differential expansion will generally result in a linear strain distribution over the depth of the member, which is much more pronounced in singly-reinforced members than for members containing compression reinforcement[31,32]. It is important to note that significant strains can develop in both the concrete and reinforcing steel as a result of ISR expansion; it is possible for the tensile reinforcing steel to reach or exceed its yield stress, which may result in load redistribution and/or a reduction in ductility [19,31]. The expansion of the concrete and restraint provided by internal reinforcement also induces bond stresses at the interface between the two materials [19], which, when combined with the reduction of bond strength in ISR-affected concrete (see following section) presents an important consideration for structural assessment.

5.5 Flexural capacity

While the moment resistance of an under-reinforced member is not likely to be significantly reduced as a result of ISR damage, other factors can affect the performance of flexural members in ISR-affected structures. Bond between concrete and steel reinforcement, for example, can be detrimentally affected by ISR as a result of a reduction in mechanical interlock between the concrete and rebar ribs, as well as a loss of integrity of the concrete cover due to spalling or cracking. Due to the preferential orientation of ISR-induced cracks parallel to the reinforcement, as well as the possibility of delamination and spalling, the ability of the concrete cover to transfer stresses through bond can be substantially reduced, in some cases by up to 50% depending on the presence of transverse reinforcement and thickness of the concrete cover [19,28,33,34]. This effect is exacerbated by the fact that bond stresses in anchorage regions can be significantly increased as a result of the chemical prestressing effect. Even when flexural and shear capacity are not greatly affected, anchorage failure may govern the ultimate load capacity of reinforced and prestressed concrete elements [11,35]. Proper anchorage and detailing is therefore critical to the performance of ISR-affected structures [19,32].

Even when bond failure is precluded through proper anchorage of the reinforcement, the flexural strength of beams affected by ISR may be lower than corresponding beams without ISR and the failure mode may be more brittle; reductions in flexural failure loads as high as 26% have been reported [28]. Other studies suggest that the effect of ISR on flexural strength will not be significant as long as the free expansion does not exceed about 0.6% [7,19],and some have even found small increases in flexural capacity in heavily reinforced members due to the chemical prestressing effect [36].

5.6 Shear capacity

The influence of ISR on shear capacity is not well understood, due to the simultaneous occurrence of multiple phenomena which affect various shear stress transfer mechanisms before and after the formation of diagonal shear cracks. Chemical prestressing, for example, will generally improve aggregate interlock by closing existing cracks, while the presence of micro-cracks through and around the reactive aggregates will likely reduce the maximum shear stress that can be achieved across the plane of a shear crack by the same mechanism. The relative importance of these two phenomena depend on the specific characteristics of the distress mechanism, crack width, member size, reinforcement ratio, degree of damage, etc. Hence, various studies have reported both increases and decreases in the one-way and punching shear capacity of ISR-affected members [32] and slabs [37].

Tests have shown that any observed decrease in shear strength will likely not be significant as long as sufficient shear reinforcement is provided, and the shear strength may actually increase due to the self-prestressing effect [19,24]. In several cases, an increase in shear capacity in ISR-affected beams has been found to change the mode of failure from shear failure in sound concrete members to flexural failure in damaged beams [36,38,39,40].If no shear reinforcement is provided, reductions in shear capacity of up to 25% have been reported [19,41], as have strength increases of more than 25% [32]. In the case of slabs, free expansions of up to 0.6% have not resulted in significant reductions in punching shear strength, although if the expansion exceeds this value strength reductions of up to 30% can result [19]. Nevertheless, the shear capacity of field structures remains of great interest, especially since the ends of girders, which are subjected to the highest shear stresses, may be located below deck joints where they are exposed to substantial water infiltration and thus to higher imposed expansions [9].

[42] and [43] evaluated the shear capacity of thick concrete slab sections, 610 x 750 x 4500 mm in size, affected to various degrees by ASR. Despite increasing damage (cracking) and losses in concrete mechanical properties with increasing distances from flexural reinforcement, the ASR-affected slabs exhibited higher shear capacity than non-reactive ones, which could not entirely be explained by the chemical prestressing phenomenon.

Tensile stresses will also be induced in closed stirrups in ISR-affected members due to the confinement provided against lateral concrete expansion. Depending on the expansion potential of the concrete and the amount of transverse reinforcement provided, these tensile stresses can actually exceed the yield strength of the steel [24]. In extreme cases, fracturing of steel stirrups due to concrete expansion has even occurred [44,45,46]. In this scenario, the shear capacity of the structural member will be highly compromised, and immediate restorative action may be required to increase the shear capacity of the affected members if the structure will remain in service.

5.7 Columns

The strength and stiffness of reinforced concrete columns can be influenced by changes in the mechanical properties of the affected concrete. The elastic modulus, and in some cases the compressive strength of the concrete, can be reduced due to the internal cracking resulting from ISR expansion and damage [5]. Lower stiffness of the concrete will result in more stress carried by the compression reinforcement which may lead to yielding. As a result of delamination of the concrete cover, buckling of the longitudinal reinforcement is also possible if the spacing of the transverse ties is too large, and external confinement may be necessary to prevent brittle failure. Finally, the restrained expansion will increase the compressive stress present in the concrete and may lead to premature concrete crushing before the steel yields in compression, although this is not likely to occur in practice [19].

On the other hand, the post-cracking stiffness and yield strength under axial compression loading can also increase as a result of the initial ISR-induced tensile strain in the reinforcement coupled with the volumetric expansion of the concrete which engages the longitudinal and transverse reinforcement leading to better confinement of the core concrete [47]. Therefore, the actual response of the structural column is highly dependent on the level of expansion, reinforcement ratio, and level of confinement provided by transverse ties.

5.8 Long-term behaviour

The long-term behaviour of ISR-affected structural members is presently not well known, and only a small number of studies have reported findings related to the effects of sustained or repeated loading (e.g. [13,15]). The creep behaviour of ISR-affected concrete is greatly affected by the level of restraint provided (which affects the internal stresses generated) and the magnitude of applied stresses (due to either external loading or prestressing) [48]. However, a comprehensive investigation of this effect is currently lacking from available literature.

Similarly, ISR can reduce the fatigue life of reinforced concrete beams subjected to repeated loading, although this effect is less pronounced when bond failure is precluded [30]. [32] also reported that the fatigue life of ASR-affected shear critical beams increased when ASR expansion resulted in an increased shear capacity. More research in these areas is needed to provide more conclusive results and provide a better understanding of the effects of ISR on structures over time.

5.9 Boundary conditions and applied loads

The expansion of concrete members with ISR may be restrained by either internal or external forces (or, in many cases, a combination of both). Adjacent structural elements and supports which are not designed to allow lateral expansion (i.e. fixed or pinned supports) will induce compressive stresses in the expanding member. A number of studies have found that concrete stresses due to restrained ISR expansion could reach up to approximately 5 MPa [14,49,50,51,52]. [53] found that it is possible to confine both ASR and DEF expansion, and interestingly, that the levels of confinement required for both distress mechanisms are similar.

Similarly, deep beams, corbels, supports, and other disturbed regions with high compressive stresses or arching action will form compressive struts; the effects of ISR damage in these regions with high compressive and tensile principal stresses is not well known. Further research is needed to establish whether disturbed regions, which are often designed using strut-and-tie methodologies and rely both on good anchorage and plasticity of reinforcement, would be detrimentally affected by ISR damage, although [9] has reported that this approach could still be used in some cases provided that the compressive strength is modified to account for strength reduction due to ISR.

Stresses caused by applied loading will also have a significant effect on expansion. External compressive loading and/or prestressing forces restrain expansion and align cracks parallel to the direction of the applied stress [e.g. 13,19,48,52]. Only limited data exists to quantify this effect, although the applied stress required to suppress ASR expansion completely in a given direction has been found to lie between 3 and 10 MPa [54], whereas expansion due to DEF could exceed 0.2% under applied stresses of 4 MPa [52]. The expansive pressure generated by ISR-affected concrete is not necessarily proportional to the free expansion potential of the concrete [55], and is generally not affected by the applied stress [16]. Nevertheless, it is of great interest to better understand the effects of stresses on the expansive processes since they are very often involved in rehabilitation techniques; indeed, affected structures might be treated by confinement techniques (with external active or passive reinforcement) or stress release by slot cuts (especially for dams) corresponding respectively to an increase or a decrease of the stress state. It is thus necessary to be able to predict the expansive behaviour of the structures after these operations to better design them.

It is also important to note that the expansion of ISR-affected structural members may affect the overall behaviour of the structure. For example, the expansion of a member in a framed structure may impose lateral forces on other members, and therefore the distribution of forces throughout a structure may change over time [19]. The effects of ISR on various structural types and connections has not been explored, and presents an important area for future study.

6 CONCLUSIONS

While significant progress has been made in recent decades to better understand the underlying processes which lead to AAR or DEF in concrete structures, much work remains to be done related to expanding and applying our current knowledge to predict the short and long-term performance of affected structures. This paper has presented a summary of available research related to the structural implications of ISR. Some of the main conclusions which can be drawn from this review include the following:

- The issue of assessing the current and future structural consequences of ISR damage is absolutely critical to the development of effective management and rehabilitation strategies. However, it is also very complex, with a wide range of important parameters affecting structural behaviour. To better study this problem, comprehensive, multi-scale investigations and stochastic approaches are needed in order to develop useful prognostic models.
- The effects of confinement, boundary conditions, and anisotropy are currently understood at a very basic level; studies on the performance of structural members with various realistic reinforcement configurations and different forms of external restraint need to be further investigated.
- Although it is an important consideration for the application of laboratory test results to real structures, very little is known about size effects in ISR-affected members. The size of a member influences confinement efficiency, crack distribution and crack widths, as well as thermal and moisture content gradients. Test data on the performance of large and full-scale structural members affected by ISR is currently limited.
- The serviceability of structural members affected by ISR is influenced by several factors, including the chemical prestressing effect and the significant reduction in the modulus of

elasticity of the concrete. More data is needed to better quantify the relationships between these phenomena for large-scale structural elements under different loading conditions.

- The bond stresses induced by chemical prestressing, in combination with a loss of bond strength in ISR-affected members, could result in anchorage zones being a critical region affecting the integrity of aging concrete infrastructure. Proper anchorage of reinforcement, and possibly rehabilitation measures, are necessary to ensure the safety and functionality of ISR-affected structures.
- The shear capacity of ISR-affected structural members is not well understood due to the simultaneous occurrence of several different phenomena, including the chemical prestressing effect and a reduction in aggregate interlock caused by internal cracking in and around the aggregate particles. This effect requires further study at a fundamental level to better understand how the various shear stress transfer mechanisms are affected by ISR damage and to quantify changes in shear capacity for structural members with and without shear reinforcement.
- Comprehensive investigations of the behaviour of concrete columns affected by ISR are needed to better understand the effects of tie spacing, confinement, longitudinal reinforcement ratio, etc. on the performance of damaged concrete compression members.
- The long-term behaviour of ISR-damaged concrete under sustained or repeated loading is not well known. Further study in this area is warranted to better predict the changes in behaviour over the remaining service life of ISR-affected structures.
- The effects of ISR damage on support conditions, disturbed regions, and other areas with high localized stresses, as well as the global structural effects for various framed structures and connection types requires further study in order to develop a comprehensive understanding of the influence of ISR damage on load transfer mechanisms in real structures.

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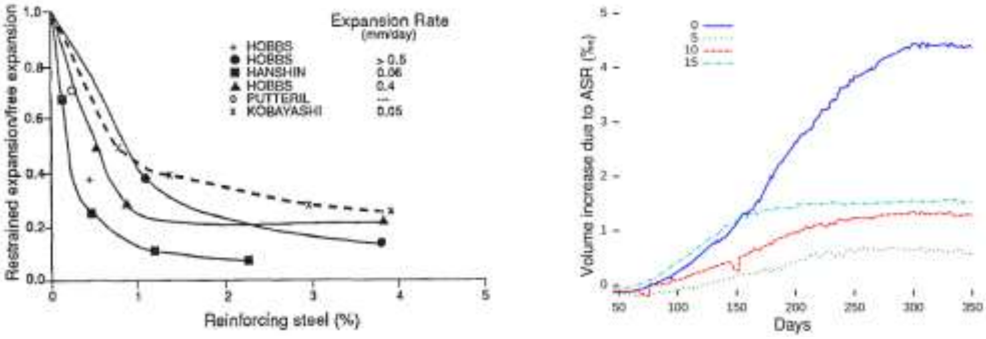

FIGURE 1: A) Restrained vs. unrestrained expansion (left) [19], and B) Volumetric expansion for different vertical compressive loads (right) [15].

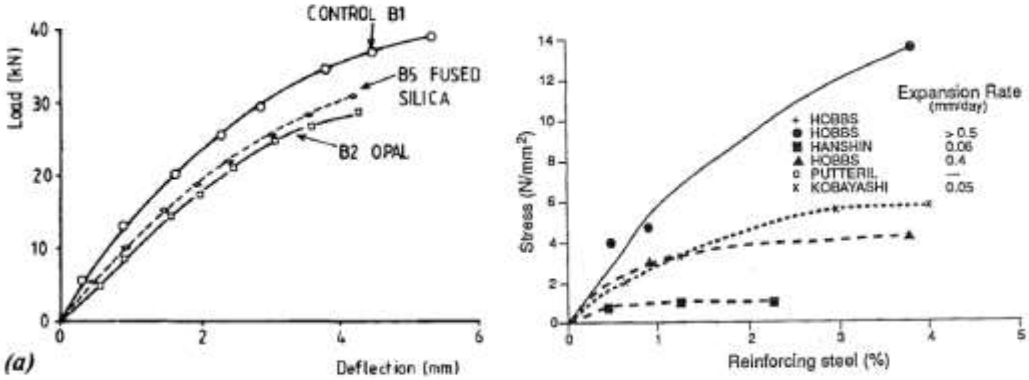

FIGURE : A) Load-deflection response of sound reinforced concrete member (control) vs. ASR-affected concrete (left) [31], and B) Concrete stress due to internal restraint (right) [19].