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Alkali-Silica Reaction (ASR) and Mitigation Methods for Addressing the Negative Durable Impact in Glass-mix Concrete: A Comprehensive Review

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Abstract: Material scarcity and environmental concerns have strengthened interest in waste glass utilization in concrete, offering enhanced mechanical properties through pozzolanic reactions. However, the high reactivity of glass waste presents significant durability challenges through the Akali-Silica Reaction (ASR). This comprehensive review systematically analyzes ASR development mechanisms in glass-mixed concrete, evaluating the influence of particle size, glass content, and colour on ASR susceptibility. Critical findings reveal that particle size emerges as the primary ASR susceptibility factor, with fine particles (<300 µm) exhibiting beneficial pozzolanic behavior while coarse particles (>1 mm) demonstrating high reactivity. Glass colour significantly influences ASR potential, with chromium-rich green and brown glasses showing superior resistance compared to clear glass due to modified chemical composition. Increased glass content correlates with enhanced ASR risk, though fine glass particles (<100 µm) can mitigate these effects through pozzolanic reactions. Mitigation strategies demonstrate varying effectiveness: pozzolanic materials show superior performance with silica fume (10% replacement) > fly ash (30%) > Ground Granulated Blast Furnace Slag (GGBFS) (60%), effectively limiting alkalinity and controlling moisture availability. Chemical inhibitors using lithium/aluminum compounds modify ASR gel composition, while mechanical reinforcement through steel fibers and rubber particles reduces post-ASR internal stresses. Despite promising mitigation approaches, significant knowledge gaps persist in long-term performance data, scale-dependent behavior understanding, and standardized testing protocols. Future research must prioritize predictive model development, protocol standardization, and comprehensive field validation studies. Successful glass waste integration requires systematic research, bridging laboratory findings with field performance requirements, while ensuring structural durability and safety.

Keywords: Glass mixed concrete, Alkali-Silica reaction, Durability, Pozzolanic reaction, Mitigation methods

1. Introduction

Glass offers numerous beneficial properties that makes it suitable for incorporation into concrete in multiple forms. Crushed glass, rich in silicon and calcium with an amorphous structure, demonstrates considerable promise as both a pozzolanic and cement-like material [4]. The process of creating glass-modified concrete closely parallels that of conventional concrete across preparation, mixing, and curing stages. Glass can be utilized as a partial substitute for either fine or coarse aggregates (termed glass aggregates) or as a replacement for cement (known as glass powder) (Figure 1).

Additionally, waste glass sludge, a by-product generated during glass panel fabrication in manufacturing plants consisting primarily of glass powder, can also serve as a replacement for concrete raw materials [5].

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To effectively utilize glass as a concrete additive, it is essential to understand its fundamental composition and properties. Glass is produced through the controlled cooling of a molten mixture of specific raw materials heated to extremely high temperatures. Glass primarily consists of silicates and compounds, such as silicon dioxide, sodium oxide, and calcium oxide [6,7].

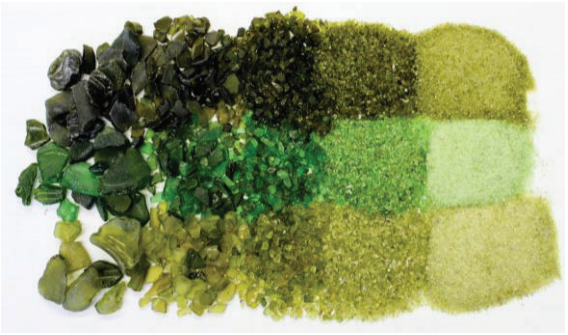

Figure 1 – Glass colour and particle size variation

Glass exists in multiple forms, including soda-lime, lead, vitreous silica, borosilicate, alkali silicates, aluminosilicates, and barium glasses [8]. Different glass colours, including brown (amber), transparent, blue, and green, possess distinct melting points, with each colour requiring different temperatures to melt due to their unique chemical compositions [9]. These different coloured glass particles contribute diverse chemical and physical properties to concrete mixtures.

Glass exhibits distinctive characteristics that make it particularly suitable for concrete applications, including high abrasion resistance, transparency, significant toughness, incombustibility, corrosion resistance, and high ductility at elevated temperatures [4]. This synthetic, inorganic, non-metallic material demonstrates resistance to natural decomposition and incineration [4]. These characteristic properties potentially enhance corresponding concrete characteristics, including abrasion resistance, toughness, fire resistance, and chemical resistance.

The application of glass waste in concrete varies significantly based on factors such as glass type, particle size, and pozzolanic capabilities [4]. Numerous studies have investigated and reviewed the use of glass waste as a substitute for Portland cement or natural aggregates in concrete, examining mechanical properties and microstructural characteristics [4,10]. Many investigations have demonstrated that glass-mixed concrete exhibits comparatively higher compressive strength than conventional concrete at considerable replacement ratios [11,12,13].

The compressive strength of concrete with glass aggregate depends on several critical factors, including glass waste replacement percentage, particle size, and water/cement ratio [11]. Studies indicate that replacing fine aggregates with waste glass up to 20% can enhance compressive strength, while higher replacement percentages lead to decreased compressive strength [11]. However, Singh *et al.* [13] demonstrated that waste glass could effectively replace fine aggregates up to 40% without compromising strength characteristics. It is suggested that the optimal replacement percentage varies depending on specific mix conditions. This apparent contradiction can be attributed to the particle size of waste glass aggregates, which plays a crucial role in determining compressive strength outcomes. Moreover, smaller glass waste particles (100 µm) exhibit pozzolanic behaviour that enhances compressive strength [10]. This pozzolanic activity contributes additional binding properties to the concrete matrix, thereby mitigating any potential strength reduction and allowing for higher replacement percentages without experiencing strength loss.

Most studies have observed increased workability when using waste glass as fine aggregate in concrete mixtures. For example, Juj *et al.* [14] concluded that increasing the percentage of waste glass as fine aggregate significantly enhanced workability, achieving a maximum improvement of 111.5% compared to ordinary concrete with 40% glass content. This workability enhancement is attributed to the non-water-absorbent nature of waste glass compared to natural sand [13]. Glass demonstrates minimal water absorption with a rate of approximately 0.007% [15].

Furthermore, studies have shown that incorporating waste glass as a replacement for fine aggregate in self-compacting concrete leads to improved flow properties. As waste glass is added to the concrete mix, it integrates with the cement paste and increases the mixture's ability to flow smoothly without segregation [16]. These enhanced flow characteristics can be attributed to the fundamental physical properties of glass particles.

The density of glass depends on its type, manufacturing process, and recycling method, with previous research establishing that the specific gravity of different glass types ranges between 2.27 and 2.60. Scanning Electron Microscopy (SEM) analysis reveals that glass particles exhibit more angular, denser, and prism-like shapes compared to cement and conventional aggregates [17]. These morphological characteristics, combined with the non-absorbent nature of the material, help explain the observed improvements in workability and flow properties when glass is incorporated as fine aggregate in concrete mixtures.

However, the most significant barrier to widespread glass utilization in concrete stems from ASR concerns. Historical attempts to incorporate glass waste into concrete, dating back to the 1960s [18], consistently encountered substantial expansion, cracking, and long-term structural reliability issues due to ASR [19]. This phenomenon, resulting from interactions between silica in glass particles and alkalis in cement paste, has remained a persistent challenge despite decades of research.

Building upon this critical need for solutions, this review analyzes how particle size, glass replacement percentage, and glass colour influence ASR development in concrete containing glass particles. The study examines the interplay between these key factors and their collective impact on ASR formation. Through a comprehensive investigation of these variables, this research seeks to provide insights into optimizing glass incorporation in concrete applications while minimizing durability concerns. The review also evaluates the effectiveness of various mitigation methods currently available for reducing ASR in glass aggregate concrete.

2. Methodology

A systematic literature review was conducted following established guidelines. Comprehensive searches were performed in Web of Science, Scopus, and Google Scholar databases using keywords including "ASR in glass concrete," "glass waste in concrete," "ASR mitigation," and "waste glass aggregates."

The review encompassed peer-reviewed journal articles, conference proceedings, and technical standards published between 1960-2024, with particular emphasis on studies published within the last two decades. Initial screening identified 158 potentially relevant articles, with 63 studies meeting the inclusion criteria based on their relevance to ASR in glass-mixed concrete and focus on particle size, glass content percentage, or colour effects.

Moreover, inclusion criteria comprised experimental studies examining ASR in glass-mixed concrete, quantitative data on expansion measurements, clear documentation of glass characteristics and testing methods, and ASR mitigation strategies. Studies were excluded if they focused solely on other alkali-aggregate reactions, lacked quantitative data, or were purely theoretical without experimental validation.

Data extraction focused on glass type and source, particle size distribution, replacement percentage, testing methodology, expansion results, and mitigation strategies employed. Critical analysis highlighted identification of contradictory findings, methodological differences, and research gaps to provide a comprehensive understanding of current knowledge limitations and future research needs.

3. Alkali-Silica Reaction (ASR)

ASR is a subcategory of Alkali–Aggregate Reaction (AAR). AAR is an adverse chemical process triggered by the interaction between reactive, amorphous, or poorly crystallized compounds in natural aggregates and alkali ions released from Portland cement, aggregate particles, or chemical admixtures in the presence of the concrete pore solution [1]. This reaction is mainly classified into two types: ASR and Alkali–Carbonate Reaction (ACR) [20].

ASR, initially identified by Stanton [21], involves multiple sequential stages. In aggregates containing reactive silica components, these siliceous materials interact with alkalis from cementitious materials to produce alkali-silica gel. This gel exhibits hygroscopic properties, enabling it to absorb water and expand under moist conditions (Figure 2) [22]. In addition to that, temperature fluctuations and the strategic incorporation of chemical admixtures significantly influence the intensity and rate of ASR development. Moreover, the porosity of aggregate particles represents a critical factor affecting the rate of ASR expansion [22]. For instance, research by

Haha *et al*. [23] demonstrates that aggregates with higher porosity experience more pronounced ASR expansion compared to those with lower porosity. This phenomenon occurs because alkali ions penetrate more easily through porous aggregate structures, facilitating aggregate dissolution and subsequently triggering ASR development.

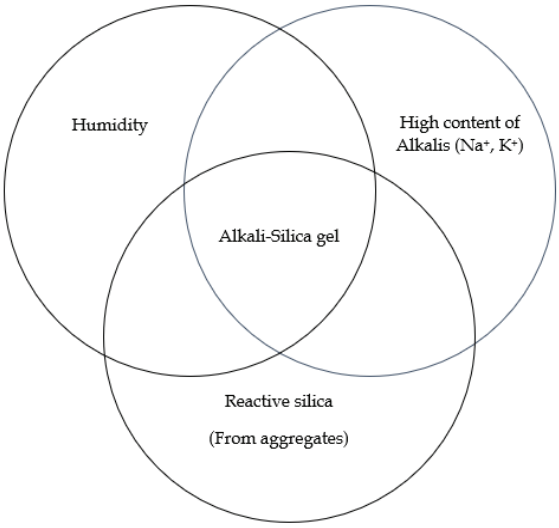

Figure 2 – Interaction between raw materials to produce ASR gel

The development of ASR-induced damage in concrete is characterized by the continuous formation and expansion of alkali-silica gel, which generates progressive internal stresses leading to cracking in concrete structures. This process progressively compromises the durability and service life of concrete elements [20,21].

The detrimental effects of ASR on concrete structures develop gradually over extended periods, as the ongoing interaction between silica and alkalis persists in humid environments. This continuous reaction leads to progressive expansion, resulting in substantial infrastructure damage and deterioration (Figure 3). ASR adversely affects numerous mechanical properties of concrete over time, including compressive strength, tensile strength, flexural strength, and elastic modulus. Additionally, ASR can induce deflection, relative displacement, permanent deformation, cracking, surface deterioration, joint material extrusion, surface deposits, discolouration, and other forms of structural degradation [22].

4. Evaluation Techniques to Identify ASR

The assessment of ASR potential in concrete requires systematic evaluation techniques that can reliably identify reactive aggregates before their incorporation into concrete structures. Several standardized methods have been developed to evaluate ASR susceptibility, including the Aggregate Petrographic Examination (ASTM C 295-08), Accelerated Mortar Bar Test (AMBT-ASTM C 1260), Concrete Prism Test (CPT-ASTM C 1293), and Miniature Concrete Prism Test (MCPT-AASHTO TP 110/AASHTO T 380). Each method offers distinct advantages and limitations in terms of testing duration, accuracy, and practical applicability. Understanding the characteristics of these evaluation techniques is essential for selecting the most appropriate method for specific applications. This section provides a comprehensive comparison of these methods, highlighting their applications, advantages, and limitations to enable informed selection of suitable testing approaches. It is particularly important to evaluate ASR potential in glass-mixed concrete.

4.1 Aggregate Petrographic Examination (APE) – ASTM C 295-08

The petrographic examination of aggregates was first introduced by Mather in 1954 and later formalized as ASTM C 295-08 in 2008 [24]. This method combines visual and microscopic inspection of aggregate samples, typically involving the preparation of thin sections for detailed mineralogical analysis. The examination employs multiple analytical techniques, including visual inspection, mineralogical identification, and advanced instrumental methods such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Polarized Light Microscopy (PLM), and Infrared spectroscopy (IR) [24].

The method identifies aggregates with high ASR potential through their reactive silica content and physical characteristics. Highly reactive aggregates typically exhibit distinctive features, including pre-existing cracks or high porosity that accelerate reaction kinetics, and strong responses to chemical staining tests. Conversely, slowly reactive aggregates do not display these characteristic features and may show no obvious signs under standard examination protocols [2, 24].

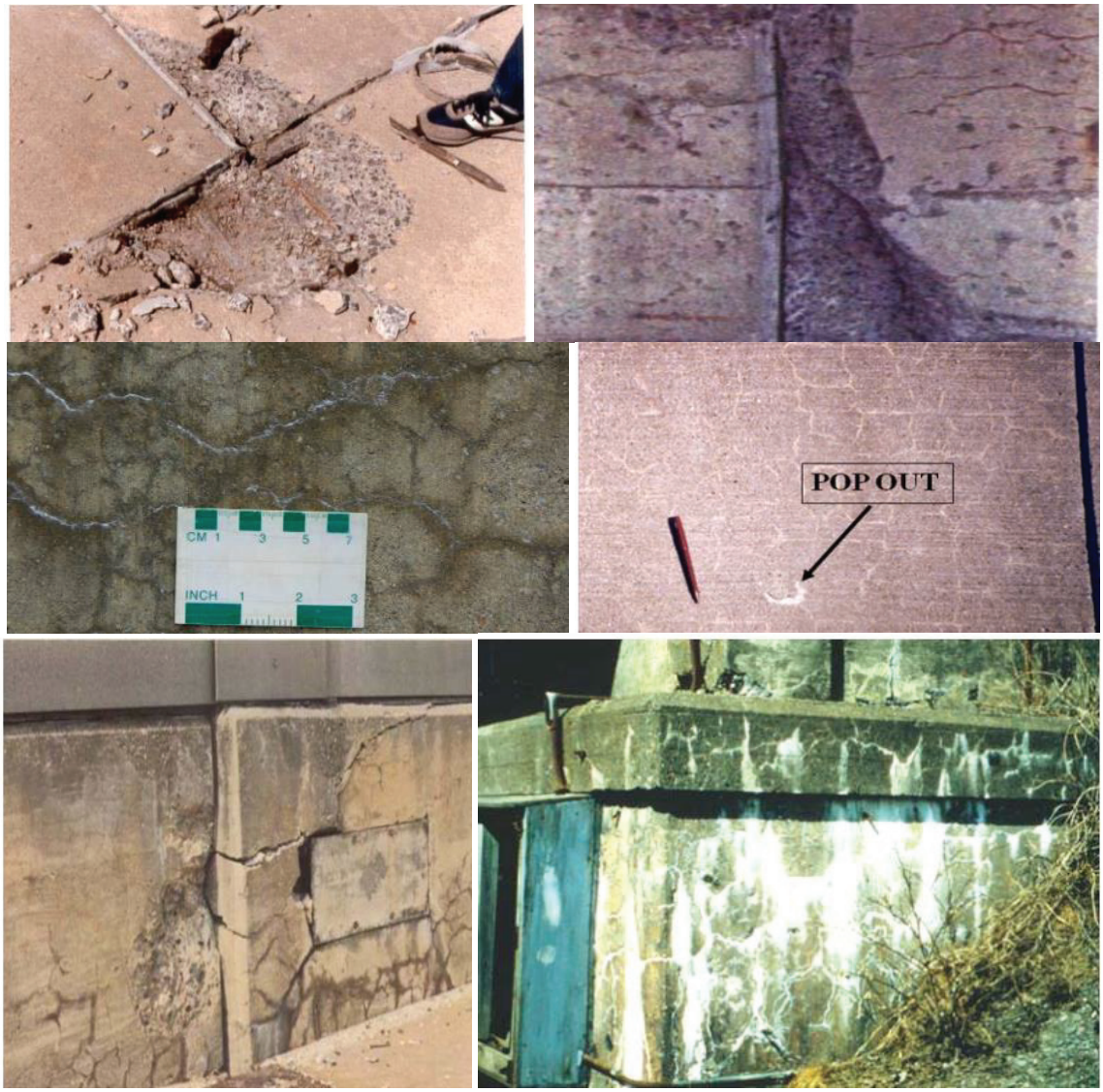

Figure 3 – ASR induces damages in concrete structures [1]

4.2 Accelerated Mortar Bar Test (AMBT) – ASTM C 1260

The AMBT was developed by Oberholster and Davies in 1986 at the National Building Research Institute (NBRI) in South Africa. The test was subsequently standardized as ASTM C1260 in 1989 and revised in 2007 [3]. The method involves preparing mortar bars using standardized proportions and measuring length changes over 14 days to evaluate ASR expansion potential. The AMBT classifies aggregate reactivity based on 14-day expansion percentages as non-reactive, moderately reactive, highly reactive, and very highly reactive, as shown in Table 1.

4.3 Concrete Prism Test (CPT) – ASTM C 1293

The CPT was developed by Swenson and Gillott in Canada during the 1950s [25]. This method addresses the limitations of aggregate-based and mortar-based tests by employing actual concrete specimens, providing a more realistic assessment of ASR potential under field-representative conditions.

One-Year CPT (Standard Version):

The standard test involves storing concrete prisms at 38°C and 100% relative humidity for one year. Expansion of less than 0.04% after one year is considered acceptable, while materials and methods that provide expansions of less than 0.04% over two years are acceptable for mitigation evaluation purposes [25].

Six-Month CPT (Accelerated Version):

This modification, proposed by Ranc and Debray [62], reduces the testing period from one year to six months by exposing specimens to more aggressive conditions (60°C instead of 38°C). All other test parameters remain identical to the standard one-year procedure.

Table 1 - Comparison of aggregate reactivity limits of different methods [22]

Reactivity	*AMBT (%)	**MCPT	***CPT (%)
Non-reactive	≤ 0.10	≤ 0.040	≤ 0.040
Moderately reactive	0.101 ~ 0.300	0.041 – 0.120	0.041 – 0.120
Highly reactive	0.301 ~ 0.450	0.121 – 0.240	0.121 – 0.240
Very highly reactive	≥ 0.451	≥ 0.241	≥ 0.241

*14-Day expansion percentage of sample (AMBT); **56-day expansion percentage of sample (MCPT)
***1-Year expansion percentage of sample (CPT)

Table 2 - Comparison of advantages and limitations of different methods [2, 3, 22, 24, 26, 62]

Methods	Advantages	Limitations
APE	• Provides direct mineralogical identification of potentially reactive phases • Enables detection of various reactive silica forms (opal, chert, volcanic glass) • Offers permanent record through thin-section preparation • Can identify both fast and slow-reacting mineral phases	• Difficulty in reliably identifying slowly reactive aggregates • Expansion-based reactivity assessment may be unreliable for certain aggregate types • Requires highly skilled and experienced petrographers • Time-intensive analysis process • Subjective interpretation may lead to inconsistent results
AMBT	• Rapid results (14 days) suitable for routine screening • Standardized procedure with clear acceptance criteria • Cost-effective and relatively simple to perform • Widely adopted internationally	• Limited to mortar mixtures only, cannot evaluate concrete behaviour • High frequency of false-positive and false-negative results • Excessive crushing of fine aggregates (<4.75 mm) may not represent field conditions • Harsh test conditions (80°C, 1N NaOH) may not correlate with field performance • Cannot evaluate the effectiveness of supplementary cementitious materials
CPT	• Uses actual concrete specimens representing field conditions • Can evaluate the effectiveness of supplementary cementitious materials • Provides reliable correlation with long-term field performance • Internationally recognized as the most reliable ASR test method	• Extended testing period (1-2 years) impractical for routine assessments • High cost and resource requirements • Potential alkali leaching due to 100% relative humidity storage conditions • Limited applicability for time-sensitive projects requiring rapid decisions
MCPT	• Shorter testing duration compared to CPT (56-84 days vs. 1-2 years) • Uses concrete specimens rather than mortar bars • Avoids excessive fine aggregate crushing associated with AMBT • Intermediate test temperature reduces alkali leaching issues • Cost-effective alternative to long-term CPT	• Limited to specific coarse aggregate size fractions (12.5 mm and 9.5 mm) • May not represent the full range of coarse aggregate sizes used in practice • Limited research database, particularly for low to moderately reactive aggregates • Relatively new method requiring further validation across diverse aggregate types • Potential gaps in understanding long-term correlation with field performance

The CPT uses 1-year expansion percentages for reactivity classification: non-reactive, moderately reactive, highly reactive, and very highly reactive, as detailed in Table 1.

4.4 Miniature Concrete Prism Test (MCPT) – AASHTO TP 110

The MCPT was introduced by Latifee and Rangaraju in 2014 [26] to address the specific limitations of both AMBT and CPT methods. This innovative approach combines the practicality of accelerated testing with the reliability of concrete-based evaluation. The MCPT involves immersing concrete prisms for 56 days when testing highly reactive aggregates and 84 days for less reactive aggregates. The method evaluates ASR expansion using length measurements, which is shown in Table 1.

4.5 Comparison of the Techniques

The selection of appropriate evaluation techniques should consider project requirements, time constraints, aggregate characteristics, and the intended application of the concrete. A detailed comparison of the advantages and limitations of each testing method is presented in Table 2, which assists in understanding the suitability of different approaches for specific scenarios. For glass-mixed concrete, the high silica content and rapid reactivity of glass aggregates may influence method selection, with accelerated tests providing quick screening and long-term tests ensuring reliable performance prediction. A combination of methods often provides the most comprehensive assessment of ASR potential, enabling informed decision-making regarding glass aggregate suitability and mitigation strategies.

5. Effect of Glass Waste in Concrete Mixture on ASR

A comprehensive analysis of published literature reveals significant variations in ASR susceptibility based on experimental conditions and glass characteristics. The initial reports on ASR resulting from waste glass as a partial replacement in concrete aggregates date back to 1974 [27]. In 1981, subsequent research by Figg [63] confirmed similar findings, highlighting pronounced ASR expansion and cracking with the use of coarse glass aggregates in concrete mixtures. Table 3 presents a critical evaluation of key findings, highlighting both consistencies and discrepancies in reported results.

5.1 Influence of Particle Size and Glass Content on ASR Development

The incorporation of glass waste into concrete exhibits a complex dual behaviour that is fundamentally governed by particle size distribution and replacement percentage [4]. This dual nature appears as detrimental ASR in coarser fractions while simultaneously demonstrating beneficial pozzolanic activity in finer particles [28]. Understanding this size-dependent behaviour is crucial for optimizing glass utilization in concrete applications.

5.1.1 Scientific understanding of size-dependent behaviour

The fundamental mechanisms underlying glass behaviour in concrete are governed by surface area-to-volume ratios and dissolution kinetics. Coarse glass particles (>1.25 mm) primarily exhibit ASR characteristics due to their limited surface area and manufacturing-induced microcracks [29]. When exposed to an alkaline environment of concrete, these particles undergo a two-stage deterioration process: alkali elements are first leached into the glass surface, followed by breakdown of the internal silicate structure [30]. This reaction produces an ASR gel (Ca-Na-K-Si-H) that swells significantly when absorbing moisture, causing concrete expansion and cracking.

Conversely, fine glass particles (<0.6 mm passing #30 sieve) demonstrate predominantly pozzolanic behaviour [31]. The increased specific surface area enhances the rate of silica dissolution, allowing rapid consumption of available portlandite ($Ca(OH)_2$) to form stable calcium silicate hydrate (C-S-H) gel. This reaction effectively counteracts with slow rate ASR gel formation, as demonstrated by Taha & Nounu [32], who observed reduced OH^- ion concentrations in the pore solution with increasing fine glass content.

5.1.2 Microstructural evidence and scientific insights

Recent advanced microscopy studies have challenged the conventional understanding of ASR development in glass concrete. Unlike typical reactive aggregates, where ASR occurs at the aggregate-cement interface, glass-induced ASR exhibits a unique mechanism in which the reaction predominantly develops within pre-existing microcracks in the glass particles themselves (Figure 4) [33, 34]. The incorporation of high-content glass aggregates leads to ASR-induced expansion, causing microcracks and damage in both the cement

matrix and the glass aggregates themselves, particularly affecting larger glass particles (Figure 5) [35]. This internal crack propagation mechanism has significant implications for understanding ASR kinetics and mitigation strategies. Corinaldesi *et al.* [40] identified the optimal size of glass particles resistant to ASR. They observed that glass particles smaller than 100 µm exhibited no adverse effects. Furthermore, finely powdered glass promotes a rapid pozzolanic reaction over the slower ASR reaction, indicating its potential as a beneficial concrete additive [41]. Studies by Abalouch *et al.* [39] and Khalooee *et al.* [42] used fine glass particles in concrete replacements, ranging from 10% to 80%. They also found no harmful ASR using SEM and Energy-Dispersive X-Ray Spectroscopy (EDS) analysis, with the subsequently observed ASR expansion attributed to the size effect behaviour of glass. SEM and EDS analyses reveal that ASR gel formation within glass particles follows a distinct pathway.

Table 3 - Critical analysis of ASR in glass-concrete systems

Glass Application	Concrete Type	Replacement (%)	Key Findings	Critical Observations	Reference
Fine aggregate replacement	Normal concrete	50-100% (three colours)	ASR expansion increased with replacement ratio; colour-dependent variation observed	Limited long-term data; potential confounding effects of glass source and processing methods not adequately controlled	[36]
Fine aggregate replacement	Normal concrete	25-100% (three colours)	Green/brown glass showed decreased expansion; clear glass showed increased expansion	Contradicts chromium hypothesis; suggests processing-related factors may be more significant than chemical composition	[37]
Graded fine aggregate	Normal concrete	10-100% (size-graded)	Particles <0.6 mm showed pozzolanic behaviour; ASR occurred at the glass-cement interface, contradicting	Methodology limitations: A short evaluation period may not capture long-term ASR development	[33]
Fine aggregate replacement	Normal concrete	0-50%	Maximum size 1.25 mm showed no harmful ASR	Correlation with microcrack density supports the surface area hypothesis but lacks quantitative microstructural analysis	[38]
Powder replacement for silica fume	High-Performance Concrete (HPC)	10-60%	Initial ASR expansion stabilized due to the pozzolanic reaction	Conflicting with size-effect theory, HPC matrix chemistry may influence ASR kinetics differently	[39]
Powder replacement for cement	Self-compacting concrete	5-30%	ASR expansion comparable to control	Self-compacting concrete chemistry and rheology may mask early ASR symptoms	[16]

In some studies, it was observed that the glass-induced ASR gel composition shows higher calcium content (increased Ca/Si ratio) compared to conventional ASR gels, potentially explaining the reduced expansion potential [43]. However, this finding requires validation through systematic compositional analysis across different glass types and concrete matrices.

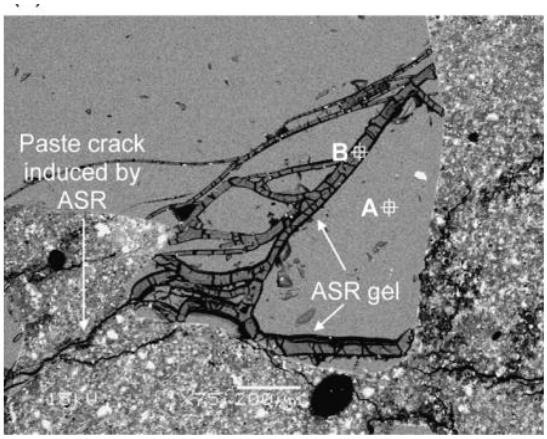

Figure 4 – ASR gel promotion inside the glass particle through the cracks [33]

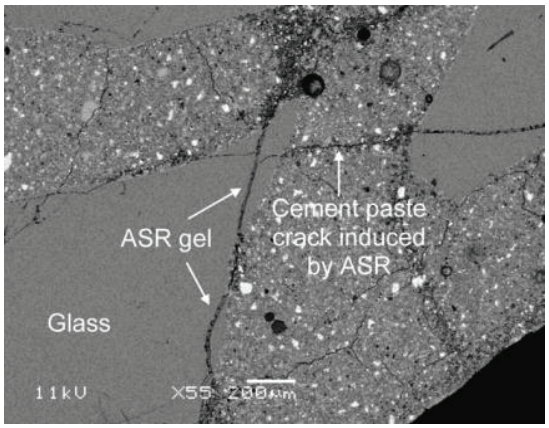

Figure 5 – Crack formation in the cement matrix and glass particle due to ASR gel. [33]

The role of the Interfacial Transition Zone (ITZ) in accommodating ASR-induced expansion presents another critical consideration. Suwito *et al.* [44] hypothesized that fine glass particles enhance ITZ porosity, providing accommodation space for ASR gel expansion without inducing harmful stresses. Lee *et al.* [45] also suggest that increased mortar porosity due to glass sand might neutralize ASR expansion and cracking by more effectively tolerating the ASR gel (Figure 06). Although this mechanism is theoretically sound, it requires further experimental validation and quantitative modelling to be fully established.

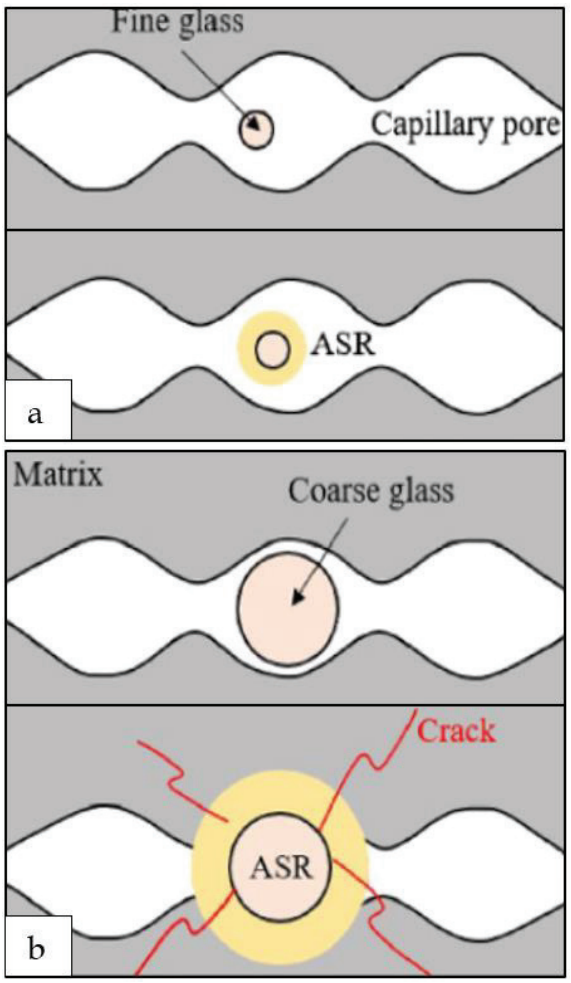

Figure 6 – Effect of glass particle size on its crack promotion (a) small glass particle (b) larger glass particle [4]

5.1.3 Theoretical framework and predictive models

Mathematical models of ASR kinetics in glass concrete are less developed than those for conventional reactive aggregates. Bazant and Steffens [46] created a framework demonstrating that ASR gel swelling pressure reaches its maximum at intermediate particle sizes, with less expansion in very fine and very coarse fractions. Nonetheless, this model falls short in capturing glass-specific behaviors such as the non-linear dissolution kinetics of amorphous glass, the development of microcracks during concrete placement, and the interaction between harmful ASR and beneficial pozzolanic reactions.

According to the framework of Bazant and Steffens [46], glass particles in cement matrices undergo dissolution in the alkaline environment, releasing silica that reacts with available alkalis to form ASR gel. Particle size critically influences this process: smaller glass

particles provide larger surface areas and higher porosity [48], accelerating dissolution and creating more favorable conditions for ASR gel formation. This contradicts the beneficial alkali consumption theory, as smaller particles increase ASR risk rather than limiting it [47].

5.2 Influence of Glass Colour on ASR Susceptibility

The relationship between glass colour and ASR reactivity represents a complex interplay of chemical composition, manufacturing processes, and microstructural characteristics [36]. While initial hypotheses focused on chromium content as the primary controlling factor [49], emerging evidence suggests a more complex relationship involving multiple variables.

5.2.1 Chemical composition analysis

The chromium hypothesis, proposing that elevated Cr_2O_3 content in green glass provides ASR resistance [49], has been challenged by conflicting experimental evidence. Gorospe *et al.* [50] demonstrated that brown glass, despite lower chromium content, exhibits ASR expansion rates comparable to green glass [51]. This finding suggests that chromium may be a correlative rather than causative factor in ASR resistance.

Comprehensive chemical analysis reveals that glass colour results from complex combinations of colourants, decolourants, and manufacturing additives. Alkali concentrations remain uniform despite varying glass colours. This raises the possibility that other elements like nickel, rubidium, zinc, and sulphate may also influence ASR tendencies [36]. Clear glass typically contains higher concentrations of alkalis (Na_2O, K_2O) to achieve optical clarity, potentially increasing ASR susceptibility. However, the presence of decolourizing agents (Se, Sb compounds) in clear glass may introduce secondary effects on dissolution kinetics that require investigation [52].

5.2.2 Microstructural considerations

Advanced microstructural analysis using Optical Microscopy (OM) and SEM reveals significant differences in microcrack density between glass colours [50]. Gorospe *et al.* [50] found that transparent glass is more susceptible to microcracks. A closer microscopic examination using OM and SEM found many microcracks in transparent glass particles after crushing. In contrast, green and brown glass types displayed few microcracks, suggesting them as non-reactive components in the aggregate range [50]. Dhir *et al.* [36] suggested that varied glass bottle production methods could explain this difference in micro-crack occurrence.

The correlation between microcrack density and ASR susceptibility supports the surface area hypothesis: increased crack density provides enhanced pathways for alkali penetration and silica dissolution. Therefore, transparent glass is more susceptible to ASR due to its ability to increase the dissolved silica content in the concrete mixture through microcracks, compared to brown and green glass [37]. However, this relationship requires quantitative validation through systematic microcrack characterization and correlation with ASR performance.

5.2.3 Long-term performance variations

Extended monitoring studies reveal time-related variations in ASR behaviour between glass colours that challenge short-term test interpretations [37]. A first look at the ASR expansion pattern showed that both brown and green glass sand mixtures had very little ASR expansion, with rates below 0.1% at 14 days and only slightly above 0.2% at 28 days. However, observations over 63 days showed a noticeable difference between green and brown glass sand mixtures. Green glass exhibited markedly higher ASR expansion rates compared to brown glass. This indicates that brown glass showcases reduced alkali reactivity over longer periods compared to green glass [37].

This time-related evolution suggests that different glass colours may exhibit distinct ASR kinetics rather than simply different ultimate expansion potentials. The mechanisms underlying these kinetic differences remain poorly understood and require systematic investigation incorporating advanced analytical techniques such as X-ray Photoelectron Spectroscopy (XPS) and Nuclear Magnetic Resonance (NMR) spectroscopy.

6. Mitigation Methods of ASR Effect in Glass-Mixed Concrete

Various experimental studies have proposed mitigation strategies categorized into pre-ASR and post-ASR damage approaches. Pre-ASR strategies focus on limiting reactive components and controlling environmental factors, while post-ASR methods aim to reduce internal tensions from gel expansion by

absorbing pressure and preventing further propagation [4, 49, 51, 53]. This section critically evaluates these methods based on their effectiveness, mechanisms, and practical applicability in glass-mixed concrete systems.

6.1 Comparative Analysis of Pozzolanic Materials

6.1.1 Fly ash performance

Fly ash demonstrates superior ASR mitigation efficiency compared to other pozzolans. When 33% fly ash replaces cement in mortars containing 45% glass aggregate (replacing natural sand), ASR expansion reduces dramatically from 0.27% to 0.075% [54]. Studies indicate that 30% fly ash replacement is generally sufficient for effective ASR mitigation in glass-mixed concrete [49]. Schwarz *et al.* [55] confirmed the superior performance of fly ash over alternative methods. The dual mechanism involves pH reduction through alkali consumption and microstructural densification, resulting in reduced porosity and permeability.

6.1.2 GGBFS performance

GGBFS requires higher replacement levels (60%) but achieves dramatic expansion reduction from 0.7046% to 0.012% in 100% glass mortars [49]. Similar to fly ash, GGBFS controls alkali content in the pore solution through pozzolanic reaction. Additionally, the pozzolanic reaction produces denser ITZ and reduced cement paste porosity, decreasing permeability and limiting ASR gel mobility [49]. While effective, the high replacement requirement may impact early-age strength development and construction scheduling, presenting practical limitations compared to fly ash.

6.1.3 Silica fume performance

Silica fume achieves substantial mitigation (0.7046% to 0.0389%) at only 10% replacement [49]. Its ultra-fine particles create superior ITZ densification through pozzolanic reaction, which reduces cement paste pH and forms C-S-H gels with low CaO/SiO_2 ratios [56]. This mechanism reduces pore solution aggressiveness toward glass particles and diminishes their negative surface charge, ultimately decreasing expansive pressure from ASR gel formation [57]. Despite higher cost, silica fume offers the most efficient performance per unit replacement, making it economically viable for high-performance applications.

6.1.4 Critical assessment

Pozzolanic materials demonstrate varying effectiveness-to-replacement ratios. Silica fume shows the highest efficiency, fly ash provides optimal cost-effectiveness, while GGBFS requires impractical replacement levels for routine applications.

6.2 Mechanical Reinforcement Strategies

6.2.1 Rubber particle integration

Rubber particles effectively reduce ASR expansion in concrete. Abbas et al. [58] reported that control specimens expanded by 0.284% after 28 days, exceeding the ASTM C1260 threshold. In contrast, mixtures with 20% and 25% rubber waste showed less than 0.2% expansion, meeting ASTM C1260 criteria. Microstructural analysis revealed that rubber-containing specimens exhibited no surface cracking despite ASR gel formation, while control specimens showed considerable microcracking. This occurs because the lower stiffness and higher deformability of rubber particles compared to stone aggregate allow ASR gels to swell freely, reducing hydraulic pressure and dissipating expansion forces that cause concrete cracking [59].

6.2.2 Steel fibre reinforcement integration

Steel fibers (1.5% by volume) reduce expansion from 0.0304% to 0.0055% through stress redistribution and crack bridging [49]. Unlike rubber particles, fibers actively prevent crack propagation while maintaining structural properties. The random distribution provides multi-directional reinforcement, making this approach suitable for structural applications.

6.2.3 Performance comparison

Steel fibres offer superior structural benefits compared to rubber particles, though both methods address expansion symptoms rather than root causes.

6.3 Chemical Intervention Methods

6.3.1 Lithium and Aluminium compounds

Lithium compounds alter ASR gel chemistry rather than preventing formation. LiCl (1%) outperforms Li_2CO_3, reducing expansion from 0.0304% to 0.0076% versus 0.0166%, respectively [49]. The mechanism involves silica solubility reduction and gel network disruption [32, 60], though a complete understanding remains unclear. Aluminium compounds (20% $Al(OH)_3$ replacement) enhance alkali removal and slow SiO_2 dissolution [61]. While effective, the high replacement percentage required

(20%) and potential delays in concrete setting time limit its practical applications.

6.4 Integrated Mitigation Strategy Assessment

Effectiveness ranking: Based on expansion reduction efficiency: Silica fume > GGBFS > Fly ash > Steel fibers > Lithium/ Aluminium compounds > Rubber particles

Practical considerations: Cost-effectiveness, construction impact, and long-term durability must be evaluated alongside technical performance. Combined approaches may optimize results while minimizing individual method limitations.

6.5 Water Reduction Strategies

Water-reducing admixtures provide supplementary protection by limiting early-age gel development through reduced water availability [34]. This approach complements primary mitigation methods but cannot serve as a standalone solution for highly reactive glass aggregates.

7. Research Gaps and Future Directions

7.1 Critical Knowledge Gaps

The literature analysis reveals fundamental limitations constraining the practical glass-mixed concrete implementation.

Temporal performance: Current research focuses predominantly on short-term ASR expansion (28-365 days), inadequately representing the multi-decade service life of concrete. The transition from initial expansion to long-term stabilization remains poorly characterized, particularly regarding mitigation strategy durability under sustained ASR conditions and potential delayed activation in previously stable systems.

Scale-dependent behaviour: Laboratory mortar bar tests (ASTM C1260, C1293) may not accurately reflect full-scale structural behavior due to complex interactions between structural restraint, moisture gradients, thermal cycling, and loading conditions. Extrapolation from laboratory to field performance remains problematic, limiting reliable design guidance.

Chemical complexity: While chromium content influences ASR susceptibility, the role of other trace elements (Fe_2O_3, MgO, SO_3, Al_2O_3) and their synergistic effects with variable cement chemistries remains inadequately understood. This knowledge gap prevents the development of robust predictive models for ASR risk assessment.

Scientific understanding: Fundamental ASR mechanisms remain incompletely characterized, including gel composition effects on expansion potential, pore structure influence on gel mobility and pressure development, and long-term stability of chemically modified gels.

7.2 Methodological Limitations

Testing inadequacy: Current protocols, developed for natural aggregates, may not adequately assess glass reactivity. The accelerated nature of standard tests fails to capture complex glass-cement system behaviour under realistic exposure conditions. Standardized protocols specifically designed for glass-mixed concrete are urgently needed.

Economic assessment: Life-cycle cost analyses comparing glass-mixed concrete with conventional alternatives are needed. Economic viability of mitigation strategies across different regional conditions requires systematic evaluation.

Predictive modeling: Sophisticated models integrating glass composition, cement chemistry, environmental conditions, and structural constraints are essential for improved ASR risk assessment. Machine learning offers promising potential for robust predictive tools.

Innovative mitigation: Novel solutions are needed to overcome current limitations, including smart chemical inhibitor systems, biological methods, and hybrid approaches combining multiple prevention mechanisms.

Sustainable materials: With traditional pozzolan scarcity increasing, research into alternative supplementary cementitious materials and new chemical inhibitors is crucial for long-term ASR prevention viability.

Monitoring systems: Real-time, on-site techniques for early ASR detection and progression tracking would enable preventive maintenance and validate long-term performance predictions.

8. Conclusions

This comprehensive review reveals both significant opportunities and critical challenges for glass-mixed concrete in sustainable

construction. Glass incorporation can enhance mechanical properties; however, it may introduce durability risks through ASR mechanisms.

8.1 Key Findings

Glass characteristics: Particle size emerges as the primary ASR susceptibility factor, with fine particles (< 300 μm) exhibiting beneficial pozzolanic behavior while coarse particles (> 1 mm) demonstrating high reactivity. Glass colour significantly influences ASR potential, with chromium-rich green and brown glasses showing reduced reactivity compared to clear glass due to modified chemical composition and reduced amorphous silica content.

Mitigation effectiveness: Pozzolanic materials demonstrate superior efficiency with ranking: silica fume (10% replacement) > fly ash (30%) > GGBFS (60%). Mechanical reinforcement strategies provide symptom management rather than root cause mitigation, while chemical inhibitors offer targeted intervention requiring optimization for large-scale applications.

Application limitations: Significant gaps exist in long-term performance data, scale-dependent behavior understanding, and standardized testing protocols. Current mitigation strategies face practical limitations, including material availability, economic constraints, and implementation challenges.

8.2 Practical Applications

Fine glass particles (preferably coloured) combined with suitable pozzolanic materials provide the most effective way to reduce ASR. However, high levels of glass replacement without proper mitigation remain risky. Optimizing the glass-cement system requires balancing mechanical strength and durability.

8.3 Research Priorities

Future research must prioritize: (i) developing predictive models incorporating multiple ASR variables, (ii) establishing standardized testing protocols for glass-mixed concrete, (iii) conducting long-term performance studies under realistic conditions, and (iv) exploring innovative mitigation strategies.

Glass waste integration offers significant opportunities for sustainable construction. However, realizing this potential requires addressing knowledge gaps through systematic research, bridging laboratory findings with field performance requirements regarding the ASR effect. Success demands coordinated efforts combining materials science, predictive modeling, and field validation to unlock the potential of glass-mixed concrete while ensuring structural durability and safety.

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