Shrinkage mitigation in alkali-activated composites: A comprehensive insight into the potential applications for sustainable construction


Abstract

The extant body of literature articulates a noticeable disparity in the susceptibility to cracking and concomitant material degradation between alkali-activated composites (AAC) and ordinary Portland cement (OPC), predominantly attributable to shrinkage and subsequent drying phenomena. This divergence derives from the nanoscopic porosity of AAC binders, which is substantially finer than their OPC counterparts. However, experimental research validates that the judicious incorporation of alternative cementitious materials and fibrous reinforcements enriches the shrinkage characteristics of AAC, thereby enhancing its overall structural performance. Given the crucial role of shrinkage in defining the material integrity of AAC, especially under constrained environmental conditions, an in-depth understanding of shrinkage mechanisms materializes as a necessity for conceiving efficient shrinkage-mitigating strategies. In light of the growing interest in optimizing AAC through various material integrations and methodological innovations aimed at shrinkage diminution, this scholarly review undertakes an extensive synthesis of the laboratorial investigations focused on AAC shrinkage behavior and mitigation. However, this article critically evaluates widespread strategies for shrinkage mitigation, explicating their operative mechanisms. Moreover, it is outlined gaps in the existing research paradigm, promoting for targeted scholarly endeavors to yield a more clear understanding of shrinkage dynamics and to facilitate the advancement of environmentally sustainable AAC composites. Meanwhile, this study intended to consolidate existing research on developing trends in order to gain a comprehensive understanding of the possible uses of AACS and identify viable strategies for addressing AAC shrinkages. By addressing the challenges related to microcracking and shrinkage, the long-term durability of AACS may be improved, leading to increased adoption of these materials as sustainable building options in the construction industry today.

1. Introduction

The formation of cracks in concrete structures increases their exposure to weathering attacks and decreases resistance to deterioration, thus reducing service life [1]. The mechanical performance of concrete-based infrastructure may also suffer due to cracking [2]. The shrinkage process occurs while the concrete hardens and is primarily responsible for crack formation. Specifically, concrete’s contraction while still in a semi-liquid state is known as plastic shrinkage [3]. This naturally occurs in freshly placed concrete when the surface water evaporates before the concrete fully hardens. Plastic shrinkage cracking can occur if evaporation occurs faster than infiltrating water rises to the surface [4]. Therefore, during the time between the installation and when the concrete is completely set, the internal constraint of the surface plastic shrinkage could potentially result in the cracking of concrete surfaces [5]. In addition, exposing concrete to certain weather conditions, such as wet-dry and freezing-thawing cycles, can hasten the

Keywords:
- Shrinkage behavior
- Fibers
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- Alkali-activated composite

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ABSTRACT

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1. Introduction

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propagation of those cracks produced by plastic shrinkage on concrete surfaces [1]. Recent years have seen the emergence of environmental issues related to the production of Portland cement (OPC) [6]. Related to this, alkali-activated composite (AAC) has drawn great interest as a more sustainable alternative [7]. Ensuring AACs’ long-term durability is critical to their adoption in the mainstream concrete industry [8]. Moreover, the performance of such OPC-free binders in terms of shrinkage and creep is one aspect that has attracted further research attention [9]. As an example, Fig. 1 shows a schematic representation of the ratio of autogenous shrinkage to drying shrinkage that occurs throughout the total shrinkage of conventional and high-grade concretes (Fig. 1) [10]. Initially, the investigations conducted by Glukhovsky, who pioneered the utilization of indigenous materials for alkali activation, marked the inception of employing sodium silicate solution as an activator [11]. This practice remains prevalent in contemporary applications. Glukhovsky’s novel approach involved amalgamating several types of fine soils, such as loess, sandy loam, river sand, ravine sand, loam, and brown clay, alongside industrial by-products like fly ash or slag. These materials were combined with solutions containing sodium hydroxide or sodium silicate, either with or without other substances. The materials utilized in the study consisted of soil silicates or foamed silicates. The initial formation of a cementitious substance involved the chemical reaction between sodium silicate and other additives, while solid precursors were employed as aggregates [12]. The resulting products of the reaction consisted of metal silicates that exhibited notable mechanical properties and long-lasting durability. Glukhovsky enlarged these elements for the construction project. The utilization of high-temperature curing in the second category of cementitious materials facilitates the dissolution of silicon (Si) from solid precursors, producing a silica anhydride with reduced solubility. Glukhovsky’s research findings indicate that this particular approach has the potential to enhance the structural integrity of soils and effectively manage SiO₂-rich waste materials that are dispersed [13]. The solidification process of the third category of materials involves the dissolution of aluminum (Al) and calcium (Ca) to produce N-A-S-H and C-A-S-H gels. These materials can be classified under geopolymers, alkali-activated materials (AAMs), or inorganic polymers [14]. For examples, Wallah and Rangan [15] reported the particular case of the effect of low-calcium fly ash-based geopolymer concrete by exhibiting minimal drying shrinkage, measuring around 100 microstrains over a period of one year. The aforementioned figure is notably lower when compared to the range of values between 500 and 800 microstrains for Portland cement concrete. In addition, to understanding alkali-activated materials by identifying and modeling alkali-activated pastes and concretes’ rheological properties, including the impacts of novel water reducers, shrinkage reducers, foaming agents, and others [16].

The risks of shrinkage represented by cracking, deflection, and pre-stress loss can happen to concrete structures, affecting the structures’...
drying shrinkage than OPC; [26] were found to be significant determinants in determining the distribution of slag in terms of [25], and ameliorating circumstances addition, the type of activator and the amount of it [24], the particle size [27].

In addition, the type of activator and the amount of it [24], the particle size distribution of slag in terms of [25], and ameliorating circumstances [26] were found to be significant determinants in determining the shrinkage of AAS. However, limited studies have been done on shrinkage of AACs since it is necessary to know their durability features in order to expand the usage of AACs in the concrete industries (Fig. 2 [20]) [21]. The shrinkage of AAC is an essential engineering characteristic that affects the likelihood of such a material cracking under constrained conditions [22]. Previous investigations showed that alkali-activated slag (AAS) shrunk more than OPC [23]. In addition, alkali-activated slag-fly ash (AAF) mortar and shrinkage of AAS. However, limited studies have been done on shrinkage, principally the autogenous shrinkage of alkali-activated fly ash (AAFA). Meanwhile, it was shown that heat-cured AAFA mortar and concrete experienced significantly less drying shrinkage than OPC; samples of AAFA treated at room temperature experienced far slower drying shrinkage rates than those cured in a controlled environment [27].

Most studies on the plastic shrinkage process in concrete have determined that capillary stresses adjacent to exposed concrete surfaces are the main driving forces behind plastic shrinkage movements, which are usually caused by an imbalance between how fast they bleed and how fast they lose water [28]. Furthermore, Settlements made of plastic can affect how much concrete shrinks [29]. Most of the processes involved in shrinking plastic involve some physical activity [30]; whereas chemical phenomena may have an insignificant effect on the shrinkage of concrete in its plastic early age stage. Several investigations have been conducted to examine ways by which to minimize or avoid the development of cracks due to plastic shrinkage. In this regard, plastic shrinkage-reducing admixtures (SRAs) (Fig. 3) have been utilized to reduce capillary pressure by lowering the rate of moisture evaporation, resulting in the production of concrete with greater higher stability [31]. As for AAS, it has been reported that it can display significantly more drying shrinkage than OPC binders [32]. The high propensity of AAS for shrinkage and cracking has prompted numerous hypotheses. According to speculation, AAS binders contain a higher mesopore content (2–50 nm) than OPC, which could cause a greater degree of saturation to exist at any given relative humidity (RH), thereby leading to greater drying shrinkage [33]. Moreover, due to the AAS matrix’s low elastic stiffness, drying causes significant shrinkage [8]. A previous study found that reduced pore size and carbonation shrinkage are potential causes of the significant drying shrinkage in AAS [34]. A time-dependent influence on the shrinkage behavior of AAS has also been reported; therefore, it is postulated that drying-induced creep is likely largely responsible for the extreme shrinkage of AAS [35].

To control plastic shrinkage cracking, the use of superabsorbent polymers (SAP) [30] or cellulose-based stabilizing agents [50] can decrease the likelihood of concrete cracking as a result of plastic shrinkage. Polypropylene fibers (PPFs) and other fibrous materials were also utilized [51]. To avoid plastic shrinkage, precautions should be taken during construction, watering down concrete, applying curing chemicals [52], or covering it with sheets to prevent moisture loss [53]. However, despite such efforts, concrete cracking due to plastic shrinkage remains a significant issue, especially when there are large, visible surfaces to repair or replace [54]. Various efforts and studies to mitigate the shrinkage behavior of alkali-activated slag-fly ash (AASFs) blends remain insufficient (Fig. 4) and efficient solutions have rarely been framed [55]. Nevertheless, a few studies have been conducted in this regard [19,56]. Some of these emphasized that for AAs based on FA, class F (AAFA) must be subjected to heat and steam curing for at least one day to effectively gain strength and avoid developing plastic shrinkage cracks within it [57]. According to the findings of previous researchers, Table 1 provides a summary of the effects of different supplementary cementitious materials (SCMs) and parameters on the shrinkage of AACs [58].

Therefore, this paper scientifically reviews the shrinkage behavior of ACC and evaluates the common shrinkage alleviation strategies and their shrinkage-reducing mechanisms. Furthermore, it provides a critical evaluation of the shrinkage-reducing mechanisms, envisaged prevention measures, and areas that require additional research to comprehensively grasp the factors that influence shrinkage and investigate research strategies to encourage the development of renewable AAC composites. This paper also aims to identify the areas that require
additional research to grasp the factors that influence shrinkage comprehensively and to devise research strategies to encourage the development of sustainable AAC composites. In doing so, limitations in terms of long-term durability against micro-cracking and shrinkage can be tackled, thereby facilitating broader industry acceptance of AACs as viable construction eco-products.

2. Shrinkage

Shrinkage is a significant factor for all cementitious systems; however, the OPC system is the one that has received the most research attention [82]. It is possible to divide concrete shrinkage into four distinct categories (Fig. 5 [86]): drying shrinkage [87], plastic shrinkage [88], carbonation shrinkage [89], and autogenous shrinkage [90]. Most of these are associated with Portland cement-based concrete, although they can also occur in cementitious systems, such as AA systems. Based on the shrinkage behaviour of AAMs discussed by Radlinksa et al. [91, 92], alkali-activated slag mixtures, commonly referred to as AAMs, have been shown to possess strength values comparable to those of regular Portland cement (OPC). However, it has been observed that these AAMs also display a heightened degree of autogenous and drying shrinkage. The augmented autogenous shrinkage of alkali-activated slag (AAS) may be ascribed to many causes, including reduced elastic stiffness, elevated saturation, and heightened chemical shrinkage. An inverse relationship exists between elastic stiffness and drying shrinkage, whereby a decrease in elastic stiffness is correlated with an increase in drying shrinkage. However, it is important to acknowledge that other variables, like reduced pore size and carbonation shrinkage, are likely to play a role in the observed elevated drying shrinkage in AAS.

2.1. Plastic shrinkage

Many researchers have investigated plastic cracking in unconventional concretes like AACs [1,93]. In this way, some researchers came up with the prediction, modeling, and numerical simulation of plastic cracking to understand better how cement-based materials crack plastically [94]. Their models and findings revealed that the consolidation of the solid components of concrete, which affect the bleeding, and the subsequent rapid loss of bleed water through the concrete’s exposed surface, are the two main trigger mechanisms for the plastic cracking of concrete [95]. Furthermore, it has been confirmed that capillary shrinkage results from the development of high tensile capillary pressures inside concrete pores in a plastic state due to evaporation [31,95]. It has also been revealed that volume contractions are linked to particle consolidation and capillary shrinkage. For cases where steel reinforcement prevents such shrinkage [9,96]. Past studies have reported that the mechanics of plastic shrinkage may be accelerated or slowed down by several contributing factors; factors such as relative humidity (RH), w/c, admixtures, hydration heat, additives, and the size of concrete members are all important, concrete surface temperature, and the sharp change in surrounding atmosphere temperature [97]. Fig. 6 illustrates the concrete plastic cracking processes and associated phenomena [98].

Plastic cracking usually develops when the cumulative tension strain exceeds the plastic concrete’s tension capability; plastic cracking typically ensues when the total tensile strain exceeds the plastic concrete’s tensile strength [99]. Cracks developed by plastic shrinkage manifest as meshed or parallel damage patterns and can be as wide as 1 mm in width and as long as 50–1000 mm in length [100]. Various investigations have found that, compared with normal concrete, AAS experiences higher plastic shrinkage than OPC [92]. For instance, the plastic shrinkage rates of four different AAS mortars were tested using varied activator types and dosages. Their study established that AAS had lesser rigidity, finer pore size distribution compared with OPC [23,77]. The precise scientific justification for the high plastic shrinkage characteristic of AAS remains to be fully understood. The measured cumulative water loss rates after exposing Portland cement and AAC specimens to drying conditions over a 6-h period were 2.2% and 0.5%, respectively [1]. These reduced moisture loss figures indicate that free water in AACs is leaking minimally, thus leading to the development of higher internal stress and greater plastic shrinkage cracks.
Table 1
Summary of the effects of different materials utilization in alkali-activated concrete and shrinkage parameters [7, 51, 58–84].

<table>
<thead>
<tr>
<th>Type of SCM</th>
<th>Year of publication</th>
<th>Type of expansive agent</th>
<th>Type of parameter</th>
<th>Content, % Volume of alkaline dosage</th>
<th>Activator 1. Na₂O, Na₂SiO₃ 2. NaOH 3. KOH 4. CaO 5. K₂SiO₃</th>
<th>Curing condition Temp., °C RH, %</th>
<th>Compressive strength at 28-day, MPa</th>
<th>Type of shrinkage 1. Drying 2. Autogenous 3. Carbonation 4. Chemical</th>
<th>Recorded Shrinkage Max., με</th>
<th>Time, days</th>
<th>Rate of reduction, %</th>
<th>Refs.</th>
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<tr>
<td>SF</td>
<td>2007</td>
<td>PPFs</td>
<td>0.1–0.3</td>
<td>– – 3 – 20 ± 3 3% 5% 69 at 60 d 55 ± 66 2 60–66</td>
<td>1</td>
<td>2000</td>
<td>60</td>
<td>33–87</td>
<td>[51]</td>
<td></td>
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<tr>
<td>Slag</td>
<td>2007</td>
<td>PPG</td>
<td>0, 1, 2 4 2 1–1.2</td>
<td>20 ± 3 60 ± 70 5 9 50 ± 4 8</td>
<td>1</td>
<td>440</td>
<td>27 27–80</td>
<td>[60]</td>
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<tr>
<td>2014</td>
<td>Quick lime</td>
<td>EAs</td>
<td>2, 4, 6, 8 –14 ✓ 1 ± 2 1.5 20 ± 3 60 ± 78 2 5</td>
<td>1</td>
<td>13,770</td>
<td>91</td>
<td>5–36</td>
<td>[65]</td>
<td></td>
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<tr>
<td>2014</td>
<td>MgO₂H</td>
<td>SAs</td>
<td>2.5–7.5 4 ✓ 1 ± 2 1.35 21 ± 2 50 ± 74–86 5</td>
<td>1</td>
<td>950</td>
<td>28 12–46</td>
<td>[61]</td>
<td></td>
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<tr>
<td>2014</td>
<td>nano-TiO₂</td>
<td>SAs</td>
<td>1, 3, 5 14.5 ✓ 1 ± 2 1.6 20 ± 5 95 ± 62–75 2 2</td>
<td>1</td>
<td>1,130</td>
<td>20 56–70</td>
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<tr>
<td>2016</td>
<td>CCA</td>
<td>SAPs</td>
<td>0, 0.3, 0.6 4 ✓ 1 – 23 ± 1 100 ± 25–29 5</td>
<td>1</td>
<td>5 ± 97</td>
<td>28 60–75</td>
<td>[63]</td>
<td></td>
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<tr>
<td>2017</td>
<td>Gypsum</td>
<td>EAs</td>
<td>3.8, 7.7 6 ✓ 2 – 23 ± 0.5 50 ± – 5</td>
<td>1</td>
<td>12</td>
<td>43</td>
<td>52</td>
<td>[63]</td>
<td></td>
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<tr>
<td>2016</td>
<td>PPGS</td>
<td>SRAs</td>
<td>0.25–1 4 ✓ 1 ± 2 1.5 23–25 50 ± 99–121 5</td>
<td>1</td>
<td>7240</td>
<td>24 6–82</td>
<td>[64]</td>
<td></td>
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<td>2017</td>
<td>Microsilica</td>
<td>EAs</td>
<td>5, 10, 15 15.5 – 1 ± 2 4 22 ± 3 65 ± 43–72 5</td>
<td>3</td>
<td>–</td>
<td>28 16–34</td>
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<td>2018</td>
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<td>SRAs</td>
<td>0, 0.5 10 K₂O 5 0.78 – 50 ± 65–67 5</td>
<td>1</td>
<td>4850</td>
<td>28 12</td>
<td>[66]</td>
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<tr>
<td>2018</td>
<td>PEG</td>
<td>SRAs</td>
<td>0, 1, 2 8 ✓ 1 2.1 23 ± 5 50 ± 115–129 5</td>
<td>1</td>
<td>4207</td>
<td>28 14–25</td>
<td>[67]</td>
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<td>Alkyl polymerizer</td>
<td>0, 1, 2, 3 4 ✓ 1 ± 2 1.2 20 ± 3 10 ± 58–60 5</td>
<td>1</td>
<td>1,970</td>
<td>56 35–44</td>
<td>[66]</td>
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<tr>
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<td>Ca(OH)₂</td>
<td>EAs</td>
<td>0, 5, 10 5 ✓ 1 ± 2 1.2 20 ± 5 55 ± 58–41 5</td>
<td>1</td>
<td>1,110</td>
<td>180 33–41</td>
<td>[68]</td>
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<tr>
<td>2018</td>
<td>CaO-type, CFAE</td>
<td>EAs</td>
<td>0, 6, 10 4 ✓ 1 ± 2 1.2 20 ± 3 50 ± 58–60 5</td>
<td>1</td>
<td>1,970</td>
<td>56 43–54</td>
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<tr>
<td>2019</td>
<td>MgO</td>
<td>EAs</td>
<td>0, 3 4 ✓ 1 ± 2 1.0 20 ± 1 50 ± – 3 5</td>
<td>1</td>
<td>4,160</td>
<td>56 25%</td>
<td>[69]</td>
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<tr>
<td>2018</td>
<td>Ca(OH)₂</td>
<td>EAs</td>
<td>5, 10 5 ✓ 1 1.2 20 ± 2 55 ± 41–37 5 1 ± 2</td>
<td>1 1109</td>
<td>180 10–52</td>
<td>[68]</td>
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<tr>
<td>2020</td>
<td>CaO</td>
<td>SAs</td>
<td>0, 3, 5 7.5 ✓ 1 ± 3 0.48 20 ± 60 93–97 5</td>
<td>1</td>
<td>3,920</td>
<td>150 48</td>
<td>[7]</td>
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<td>2020</td>
<td>PPGS</td>
<td>SRAs</td>
<td>0, 0.5, 1 4.3 ✓ 2 – 20 ± 0.5 43 ± 41–45 5</td>
<td>1</td>
<td>1,7680</td>
<td>77 10–19</td>
<td>[70]</td>
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<td>Polyether</td>
<td>SRAs</td>
<td>0, 3 6.2 ✓ 1 ± 2 1.2 20 ± 50 86–88 5</td>
<td>1</td>
<td>8570</td>
<td>56 58</td>
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<tr>
<td>2019</td>
<td>Nano-magnesia</td>
<td>NPs</td>
<td>0, 2, 3 3 ✓ 1 ± 2 1.0 23 ± 5 70–27 70–70</td>
<td>1</td>
<td>4920</td>
<td>56 10–55</td>
<td>[72]</td>
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<tr>
<td>2020</td>
<td>CCA</td>
<td>SRAs</td>
<td>0, 0.26, 5-7 ✓ 1 ± 2 1.5 20 ± 0.1 – 31–63 5</td>
<td>2</td>
<td>5970</td>
<td>7 54–58</td>
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<tr>
<td>2021</td>
<td>Sodium polyacrylate</td>
<td></td>
<td>0, 0.3 4 ✓ 1 ± 2 0.8–1.4 20 ± 1 100 45–57 5</td>
<td>2</td>
<td>5,060</td>
<td>7 72–81</td>
<td>[74]</td>
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<td>2020</td>
<td>Ethylene glycol</td>
<td>SRAs</td>
<td>0, 1.5 7.5 ✓ 1 ± 3 0.48 20 ± 60 81–97 5</td>
<td>1</td>
<td>3,920</td>
<td>150 38</td>
<td>[7]</td>
<td></td>
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<tr>
<td>2019</td>
<td>Oxyalkylene alcohol</td>
<td></td>
<td>0, 3 4 ✓ 1 ± 2 1.0 20 ± 1 50 ± – 5</td>
<td>1</td>
<td>4,160</td>
<td>56 35–64</td>
<td>[69]</td>
<td></td>
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<tr>
<td>Slag</td>
<td>2020</td>
<td>Solution-polymerized</td>
<td>0, 0.16 6 ✓ 1 ± 2 1.5 23 ± 1 – 62–76 5</td>
<td>2</td>
<td>3,530</td>
<td>7 54</td>
<td>[73]</td>
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<tr>
<td>Slag FA</td>
<td>2019</td>
<td>PEG</td>
<td>0, 2.5 12 ✓ 1 ± 2 3.96 22 ± 2 50 ± – 4</td>
<td>1</td>
<td>1780</td>
<td>60 45</td>
<td>[75]</td>
<td></td>
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</tbody>
</table>

(continued on next page)
Table 1 (continued)

| Slag/FA | 2016 | CaO | 6 | 1.3, 3 | 1.4 | 1 | 2180 | 56 | 7.17 |
| Slag/FA | 2016 | Gypsum | 1 | 1.2, 3 | 6 | 1 | 3180 | 56 | 7.17 |

**Annotations**: Superabsorbent polymers (SAPs), Polypropylene glycol (PPG), shrinkage-reducing admixtures (SRAs), High-performance concrete EA (HPC-EA), Cross-linked copolymer of acrylamide and acrylate (CLCAA), Nano particles (NPs), Coal gangue (CG), Polyethylene glycol (PEG), Fly ash (FA), Calcium sulfoaluminate-type EA (CSEA).

6. Sand-to-slag ratio was increased [108]. In contrast, the ratio of water to shrinkage. One study found that drying shrinkage was reduced when the amount of water present is not the only factor determining drying [109]. However, the degree of hydration were reported to be influential factors in the shrinkage [104]. The effects of the different curing conditions are depicted in Fig. 7 [105].

Continuous drying will result in shrinkage, continuous wet curing will result in expansion, and autogenous shrinkage will only result from sealed curing [106,107]. With each cycle of alternate soaking and drying, swelling and shrinkage are likely to occur, with the overall impact depending on the mix [106]. The type of compounds generated during the activation and curing processes controls the drying shrinkage of AAACs [110]. After testing the effects of the internal curing (IC) of AAS concrete, it was discovered that the drying shrinkage was reduced when fully saturated slag coarse aggregate was used instead of normal weight coarse aggregate. It is clearly reported by Matalkah [1] that one study investigated how the properties of AAS concrete were affected by increasing the curing temperature and concluded that heat curing significantly reduced the drying shrinkage of AAS concrete [109]. Furthermore, the quantities of alkaline solution, porosity, and the degree of hydration were reported to be influential factors in the shrinkage actions [101].

As mentioned previously, the drying shrinkage increases with the rise in water content [110] as also reported by Matalkah [1]; however, the amount of water present is not the only factor determining drying shrinkage. One study found that drying shrinkage was reduced when the sand-to-slag ratio was increased [108]. In contrast, the ratio of water to cement is a crucial factor in determining the rate of drying shrinkage [103], in which the proportion of water to binder decreases, causing the drying shrinkage to increment too, on average, decrease in size as a result [111]. The primary effect of the drying process is a reduction in volume, which is caused by changes in the hydration product’s physical
structure and the porosity network. As a result, reducing the amount of binder and water content in AAS pastes and mortars can positively impact the drying shrinkage of the materials. That is because less water and binder are needed. There are two leading causes of AAC's more significant shrinking. For starters, alkali aluminosilicate hydrates have much free water that evaporates and contracts as they dry. Because of the changes in the pore solution, the AAC structure has a higher capillary stress, which results in larger drying shrinkage. Since drying shrinkage in AAC paste is affected by micro-cracks caused by water loss in capillary pores, increasing the W/B ratio increased drying shrinkage.

Drying shrinkage is also heavily influenced by aggregate size and has been examined in numerous studies [1]. Intriguingly, using finer aggregates improves mechanical performance while causing increased dry shrinkage. Previous work examined how changing the proportion of sand to silica fume in cementitious materials affected drying shrinkage [112]. Using finer particles improved mechanical properties while causing an increase in drying shrinkage [113], as shown in Fig. 8. This might be justified by expanding the total surface area, which increases the reactivity of binder materials, thus consuming more water to hydrate and producing higher gel pore content. Limestone aggregate has been found to reduce the mass lost during drying, thereby decreasing the rate of drying shrinkage [103]. The cement paste and limestone aggregate particles could be reacting chemically, explaining this phenomenon, which strengthens the weak interfacial transition zones (ITZ) [113]. Accordingly, the amount of shrinkage that occurs during the drying process of OPC-based concrete increases by increasing both the average specific surface area of binder components and the volume and structure of the pores. Utilizing finer slag aggregate can lead to higher drying shrinkage. Moreover, using higher reactive SCMs, such as silica fume, produces denser gels and greater capillary tension because of the water meniscus and, ultimately, greater dry shrinkage from the increased hydration products and gel pores [114].

The degree of pore connectivity and porosity has a major impact on drying shrinkages [113]. The porosity structure of the compositions can be used as an essential indicator of drying shrinkage; because of its greater porosity, cellular concrete contracts at a rate 10 times faster than conventional concrete [88,113]. The relationship between the porosity

![Fig. 6. Concrete plastic cracking phenomena and processes (Adapted from Ref. [98]).](image)

![Fig. 7. Influence of the different curing conditions (Adapted with improvement from Ref. [105]).](image)

![Fig. 8. Some of the identified general causes of drying shrinkage.](image)
distribution and drying shrinkage rate in cement-based materials was examined in certain investigations. Schubert, for example, introduced a correlation between moisture content and porosity in examining this phenomenon [115]. An additional study demonstrated that drying shrinkage was enhanced by the incorporation of sisal fibers into the matrix [116]. It has also been shown that special chemical treatments, such as 10% KOH or 6% KOH and 10% KOH, can control the effect of natural fibers like luffa on the resistance to cracking and drying shrinkage [103]. Using chemical treatments increases luffa fiber crystallinity, improves crack resistance, and slows drying shrinkage in reinforced formulations [117]. In addition, researchers showed that the rate of shrinkage in aerated concrete increases as the number of finer pores increases [118]. This is because the size and number of micropores affect how much something shrinks when it dries [119]. Moreover, numerous investigations have shown that, in most cementitious compositions, the rate at which it shrinks as it dries could be proportional to its porosity [103]. Fig. 9a demonstrates that AAS experiences greater loss of moisture and shrinkage strain than OPC, which is consistent with Gibbs-Bangham hypothesis [120]. However, it was noted that the drying rate significantly impacts AAS shrinking behavior [121]. The Gibbs-Bangham shrinkage principles are violated because the estimated shrinkage strain can differ significantly despite the same level of loss of moisture at different exposed RHs (Fig. 9b).

2.3. Autogenous shrinkage

Alkali-activated mortar (AAM) has been the subject of increasing studies [122]. AAM systems have been shown in one study to experience much larger amounts of autogenous shrinkage and drying shrinkage than OPC systems [123]. Additionally, the degree to which an AAM system contracts depends on several factors, such as the activator used and its concentration, and the conditions under which it is cured [124]. Different types of alkaline activators, as well as the effects of FA and slag quantities, have been studied about the shrinkage of AAFS compositions (paste, mortar, and concrete) [125]. However, only a few investigations on the shrinkage of AAFS have been published. According to one study, for instance, significant AAS and drying shrinkage would occur if the slag content of the AAFS mixtures was increased while the sodium silicate to sodium hydroxide ratio was decreased [78,122]. However, exactly how AAF systems undergo autogenous contraction is still a mystery [122]. Lee et al. [108], at 28 days, researchers looked into the autogenous shrinkage of AAFS pastes and mortar and found that the shrinkage was caused by self-desiccation rather than chemical shrinkage. It has also been demonstrated that AASF concrete experiences slower autogenous shrinkage development than AAS concrete [35, 55,126,127]. As shown in Fig. 10a and b, there is a reasonable consistency between measured and computed stress evolutions in AAC when the elastic component of autogenous shrinkage and the relaxing of the stress over time are considered in the calculation [55]. However, the drying shrinkage of slag and high-calcium FA-based concrete is still greater than the respective AS rates of AAS and AASF concrete [128].

Reportedly, the effects of 99% relative humidity on AAM sample shrinkage (which can be regarded as autogenous conditions) decreased when SRA based on polypropylene glycol were added to water glass-activated slag mortars [59]. Including 1% SRA caused a ~200 με expansion over a 25-day curing period. However, the expansion was reduced by increasing the SRA to 2%. Although the authors noticed some OPC sample growth, it was much more subtle than the AAS [129]. However, AAS volume changes are thought to be caused by various mechanisms, but researchers are divided on which ones are most important: autogenous or drying shrinkage [130]. It has been reported that the AAS pastes demonstrate higher cracking than Portland cement, even in conditions that prevent them from drying [131]. The current findings and claims are consistent with the hypothesis that this is...
partially caused by AAS paste’s increased chemical shrinkage [132]. These micro-cracks can be attributed to the tensile stresses produced by chemical or autogenous shrinkage during the specimens’ moisture-curing processes. This is consistent with research conducted by Bakharev et al. [133], who found that the crack intensity in the matrix phase rises as the ratio of silica to sodium oxide values increases [134].

It is common knowledge that the chemical shrinkage that occurs during the liquid stage is the cause of autogenous shrinkage in PC systems. As was stated earlier, as the material becomes harder, the amount of shrinkage caused by autogenous processes is reduced relative to the amount of shrinkage caused by chemical processes because the volume change resulting from autogenous shrinkage becomes more difficult due to the increased degree of restriction caused by the hardening of the hydrated cement paste [29,33]. Likewise, creating a skeletal microstructure restrains the contraction of chemical shrinkage, producing voids. In addition, Continuous hydration causes RH to drop and water molecules to curve more sharply due to changes in water molecule shape and pore emptying. The menisci’s extreme curvature increases surface tension around the pore, compresses capillary hole and solid hydrate wall surfaces, and ultimately leads to a contraction in the hardened cement paste [135–137]. This is known as self-desiccation [138]. A higher rate of autogenous shrinkage would result from the increased curvature of the menisci and capillary due to the small diameter of the pores, so the theory goes [139].

However, the autogenous shrinkage mechanism that occurs in AAFS systems within the first 24 h due to a potentially distinct chemical reaction after casting the process after drying out could be unlike the well-known self-desiccation method [122]. Two primary reaction mechanisms of isolated AAM systems make up the alkaline reaction of AAFS, thereby making it a very complex process. Gel sodium aluminosilicate hydrate (N-A-S-H) and sodium hydroxide are the two most common byproducts of this reaction [140] using the AAF and C-A-S-H gel [141] from the AAS system do not undergo independent evolution, but rather undergo a shift in their structural and compositional structure [122]. Thus, to learn more about how AAFS pastes shrink on their own or autogenously, further investigations into autogenous shrinkage are required, especially immediately after casting.

2.4. Chemical shrinkage

Changes in composition result from chemical reactions; a material may undergo either chemical shrinkage or expansion, which indicates a quantitative shift in the amount of substance [142]. The dissolution of aluminosilicates causes shrinkage within the first few hours; After about 8 h, gels composed of Al-rich products form, expand, and then contract as the Al species polymerize further with available silicate oligomers to form a Si-rich network [143]. It is also found that when the Al species polymerize with the readily available silicate oligomers, a Si-rich network is formed, causing the material to contract. In addition, the RH drops and the curvature of water-air menisci increase due to

![Fig. 10. Computed stress in AAS (a) and AASF (b) concrete using the concrete’s elastic component of autogenous shrinkage (Adapted with improvement from Ref. [55]).](image)

![Fig. 11. Chemical shrinkage of AAFS with different amounts of slag: a) AAFS = 0.1, 0.2 and 0.3; and b) Na$_2$SiO$_3$-to-binder ratios = 0.12, 0.16 and 0.20 (Adapted from Ref. [108]) [Annotations: alkali activator (A) and slag (S)].](image)
continuous hydration because the water molecules shift and pores empty [144]. Meniscal curvature causes a compression of capillary pore walls and solid hydrates, which in turn increases surface tension and causes the hardened cement paste to contract [135,142]. This kind of drying-out process is referred to as “self-desiccation” [138]. This theory proposes that a tightening of the capillary wall and meniscal curvature result from pore diameters that are too small to accommodate the increased pressure; this would result in increased shrinkage [139]. There is a well-established link between chemical reactions and the shrinkage rate, and the amount of shrinkage is known to be directly proportional to the hydration level of the binder [145]. For instance, it has been shown that the chemical deformation evolution of metaaolin-based AAC (MK-AAC) differs significantly from that of OPC, which shows monotonic chemical shrinkage after casting [145]. It has been revealed that MK-AAC undergoes chemical shrinkage, physical growth and shrinking in the second, second, and third stages, respectively [143]. Recent studies, however, contradict that finding [78]; this idea of enhancing the hydration reaction in the presence of SCMs is at odds with the fact that a higher slag content would result in a smaller chemical shrinkage. The effects of varying alkali activator concentrations in the mixtures are likely to blame for the observed inconsistency.

Similarly, in the case of zeolites, and due to the small pore diameters, which are mostly in nanoscales, a significant portion of the volume contained within the water vapor diffusion channels inside the crystal is blocked or sealed off, which hinders the hydration process and result in lower chemical shrinkage [146]. Conversely, the inclusion of amorphous SCMs Si-rich creates mostly gel or capillary pores, with nanoscale diameters, due to their high reactivity [147]. In this case, it is unlikely that the pores could be clogged because of silica particles’ high pozzolanic activity, which raises the hydration heat, hence forming more capillary spaces and denser gels. Support for this opinion has been provided through an atomic simulation, which showed that the geopolymer gel has less space between its molecules. Because of this, it is denser than crystalline zeolites like sodalite, which have been shown to have denser gels than crystalline zeolites [148]. Thus, the chemical shrinkage of MK-AAC in the later stages of polymerization may be attributed to the increase in tensile stresses on the capillary network of the pores, which in turn increases the stiffness of the microstructure [143]. Moreover, the slag’s glassy structure causes a low atomic packing density in the un-hydrated material and is likely linked to the large chemical shrinkage seen in AAS hydration [132]. Researchers have found that the rapid self-desiccation of AAFA/AAS caused by a drop in internal relative humidity (RH) in the hardened mesopores is the primary driving mechanism behind this type of autogenous shrinkage.

![Fig. 12. Content of CaCO₃ and fitting curves in carbonated (a) AAS and (b) AAFS blended cements with various Ms (Adapted the average lines (reading) from Ref. [168]) [Annotations: mixture proportions of AACs (M) and slag (S)].](image)

![Fig. 13. Fourier transform-infrared spectra of bulk AAS paste samples exposed to various environmental conditions (Adapted with improvement from Ref. [157]).](image)
The mesopores comprised between 60 and 80% of the total pore volume compared with 36% in the OPC paste. According to another study, around 90%–95% of the total pore volume in AAS is composed of mesopores [23]. The effects of chemical shrinkage may be compounded by the fact that AAS pastes form with a decreased permeability. This prevents water from penetrating the specimens’ interior while curing in a saturated environment (underwater), which in turn causes differential stresses that may result in cracking [131]. Briefly, autogenous shrinkage is caused by chemical shrinkage, which occurs when the volume occupied by the products of the reaction is less than that of the initial reactants. It refers to the stage at which AAC develops a sturdy skeleton to resist chemical shrinkage.

2.5. Carbonation shrinkage

Carbonation is one of the main issues with the durability of reinforced concrete structures. A reaction between two different substances is what brings about this process by CO$_2$; the calcium hydroxide and calcium silicate hydrate gel are two examples of hydration products that can seep into pores [11], which raises the probability of corrosion in steel bars by lowering the pore solution pH [149]. Accelerated testing has revealed that the carbonation of alkali-activated binders could be a severe issue in some crucial applications, with laboratory experiments frequently revealing rather high carbonation rates [150]. However, AACs that exceeded the specific service age have not typically displayed carbonation-related issues [151]. This implies that, in contrast to OPC-based systems, the accelerated test results do not accurately anticipate the actual performance of AACs [152]. Thus far, only a few studies have attempted to characterize the parameters contributing to AAC carbonation [153]. These parameters include precursors, the activator’s type and dosage, the concentration of CO$_2$, and similar phrases, referring to an environment’s relative humidity. Furthermore, a recent study [154] explored the influence of the slag/FA ratio on the carbonation-induced phase change in Na$_2$SiO$_3$-activated cement systems and found that a good slag/FA ratio could make reaction products more resistant to carbonation [155]. However, the process by which the silicate modulus of Na$_2$SiO$_3$ activators (Ms, SiO$_2$/Na$_2$O molar ratio) is unknown how the factor in question affects the carbonation process. Few studies have been done that focus solely on the carbonation of these systems and have been carried out under various exposure conditions, with concentrations of carbon monoxide ranging from one percent to one hundred percent [156]. However, there are still unanswered questions about the frequency with which this second step occurs in AAFA binders, as the Ca content in gel phases is in the minimum phase [157]. Although the durability indexes, including carbonation, are based on the porosity and permeability of AACs and OPC, their carbonation mechanisms are still distinct. For instance, in terms of carbonation, dissolved carbon dioxide in the pore solution may react with AAC reaction products, resulting in a decrease in the pore solution pH and an increase in the potential for reinforcing steel to corrode as a result of depassivation [158]. However, according to the findings of accelerated carbonation tests, the carbonation rate appears to be quicker than that of OPC because of the absence of calcium hydroxide in AAS systems. This information was obtained from several different reports [159]. Nonetheless, there is a possibility that the results of accelerated
carbonation testing will not be relevant to the actual condition (0.03–0.04% $\text{CO}_2$) [160]. According to related literature, AASC has a natural carbonation rate that is only marginally ahead of OPC in terms of speed [161]. Because of this, accelerated carbonation tests conducted cannot properly mimic the normal carbonation behavior of AAMs [36–40]. Several studies [162] have explored the carbonation of GGBFS-GPC and related geopolymer materials. This research reveals that geopolymer concrete has a higher carbonation rate than OPC while maintaining the same compressive strength; however, their carbonization mechanisms are distinct [163,164]. The higher carbonation rate of SCM leads to increased degradation in performance, resulting in a higher rate of compressive strength loss [164].

Related research has demonstrated that activators significantly alter the reaction kinetics of CSM materials [165]. For example, the rate of contribution of silica reaction in the case of the activated reaction differs with the variation of Na$_2$O activator concentrations [166]. Furthermore, NaOH activation of the system results in a much quicker reaction time than Na$_2$SiO$_3$ activation [9]. On the one hand, compared to Na$_2$SiO$_3$-activated slag, slag that NaOH has activated has C-S-H gels that are more crystalline [167]; longer periods of hydration lead to the formation of a C–N–S–H structure that is enriched in sodium. On the other hand, the slag hydrates gradually in the Na$_2$SiO$_3$-activated system, which leads to decreased porosity and increased compressive strength while maintaining the same reaction degree. Even though it has been reported that hydrotalcite-like phases that share the same chemical makeup can be found in both systems [74], the formation of additional hydrotalcite phases is favored by the high pH of the NaOH solution [165].

In addition, carbonation depths in alkali silicate-activated slag concretes were between 13 and 25 mm after 240 h of exposure to 7% carbon dioxide [168]. Compared with the Na$_2$SiO$_3$-activated slag, the NaOH-activated slag is assumed to be more susceptible to carbonation due to the lower degree of reactivity and the denser C–S–H gel composition (Fig. 12a and b) [168]. It is found that when the Ms value reaches 1.0, there is a slight reduction in both the quantity of CaCO$_3$ and the rate at which carbonation occurs. For concrete manufactured with OPC, 7 days of exposure to 4% carbon dioxide is roughly equivalent to one year of natural carbonation. The information serves as a point of reference [169]. This finding suggests that the accelerated carbonation test is approximately one thousand times more demanding on AACs than on OPC concrete [170]. Another investigation on carbonation rates in AAS/MK concretes revealed that the carbonation rate is also highly influenced by the carbon dioxide concentration employed during accelerated testing [166].

This can be ascribed to the increased leaching rate with rising $\text{CO}_2$ concentration, in which higher $\text{CO}_2$ concentrations have a greater ability to filtrate into the capillary pore structure. Recent studies on the carbonation of AAS binders [150,171]. Carbonation in highly alkaline solutions has been modeled using thermodynamic techniques [171], and has demonstrated that calcium-rich activated binders likely undergo a two-step carbonation process. The 1-st stage is the carbonation of the pore solution, which happens when the pore solution absorbs carbon dioxide from the air. As a result, the pH drops, and Na-rich carbonates eventually precipitate out of the solution [150]. The second step is when the dissolved carbonates react with the solid binder. This makes Ca-rich carbones by partially decalcifying the Ca-rich binder phases [150].

Several researchers have been examining the carbonation phenomenon of the AAS binder under various activated cementitious systems, including AAS, GGBFS-AAC, MK-AAC, and FA-AAC, as well as in various exposure conditions (CO$_2$, RH) [171,172]. The results of the associated tests and the microstructural examination of the AAS concrete constitute the second stage and have revealed that this type of concrete system has higher durability, can serve for an extended period, and increases in strength over time [151]. Although studies on powdered pastes are useful in comprehending the carbonation mechanism of AAS, these studies cannot capture the impact of carbonation on the pore structure and mechanical properties of the material [173]. The most fundamental characteristic of cementitious systems is their pore structure. Thus, grinding reduces the capillary porosity, eliminating the mechanism leading to the collapse of the large gel pores [157]. The pore structure of the porous medium controls any diffusion mechanism that takes place within the porous medium.

Regarding the path taken by $\text{CO}_2$ through the bulk paste of AAS, in the research that has been done, the pore structure’s effect on the carbonation rate has gotten very little attention [157]. As seen in Fig. 13 [157], The conditions for accelerated carbonation did not accurately mirror the carbonation rate that took place in AAS concretes when they were subjected to natural conditions. In particular, less carbonation depth was found in AAS concrete after seven years of exposure in natural carbonation settings, with RH fluctuating between 70% and 76% and temperatures varying between 19 °C and 38 °C than was expected in places where carbonation happened more quickly (1% v/v $\text{CO}_2$) [173]. The carbonation depth of the AAS paste activated with Na$_2$SiO$_3$ was somewhat less than that of the AAS paste activated with NaOH [174]. A smaller average pore size and smaller overall porosity are the results; the carbonation resistance of AAS mortars has been shown to increase with an increase in Ms from 0 to 2 [175]. The carbonation depth of AAS with Ms = 2.0 is larger than that of AAS with Ms = 2.4 due to a higher calcite concentration and enhanced capillary absorption [172]. The pore-blocking impact that prevents carbonation caused by calcium carbonate precipitation is microstructural degradation, such as decalcification of C-A-S-H gels and carbonation-induced microcracking, which has a lower impact [141]. However, When comparing the carbonation characteristics of AAS and FA-AACs, Ms has no significant impact [176]. Another investigation found that AAS concretes with Ms values of 0.75, 1, and 1.25 all had equal carbonation depths. Additionally, using a phenolphthalein indicator to test the carbonation depth of geopolymer concretes revealed no discernible carbonation front [177]. According to a study, to a greater extent (more than 20% of the total depth studied), the pace of future carbonation is determined by the diffusion of dissolved carbon dioxide via the pore system of the carbonated concrete layer [157]. Compared with mortars made using Na$_2$SiO$_3$-activated slag, those made with NaOH-activated slag were proven more resistant to carbonation [162]. The decalcification of C–S–H was seen when Na$_2$SiO$_3$ was utilized as the activation in AAS mortars under CO$_2$-saturated conditions led to a loss of matrix cohesion, a greater number of holes, and a 14% drop in mechanical strength after four months of carbonation. However, mortars’ matrix cohesiveness rose, their overall porosity decreased, their mean pore size shrank, and their strength increased by as much as 93% [178]. A greater binder content (400–500 kg/m$^3$) led to shallower carbonation for AAS concretes. Raw GGBFS’s MgO content, for instance, was found to be strongly influenced by the binder chemistry in addition to the binder content. As a result, the carbonation behaviors in NaOH-activated slag cement and Na$_2$SiO$_3$-activated slag cement may not be the same due to the varied reaction mechanisms and products produced by these cement.

3. Reduction in shrinkage

A variety of scholars may be connected to the matrix type, SRA type, alkaline content, and curing circumstances to minimize shrinkage, which is the phenomenon of the volume reduction of the binders in the absence of external forces and at a temperature that remains constant. Shrinkage may be defined as the decrease in the volume of the binders. The significant shrinkage that occurs in alkali-activated systems is mostly due to including a high proportion of mesopores in pastes and the absence of crystalline phases (such as AFT, AFm, and CH) in the reaction products. These are the two primary causes. Several pozzolans may be used to lessen the shrinkage in AAC composites. This is because AAC compressive strength and it pointed out that it was due to the pozzolanic reactions of pozzolan. This is why, especially silica fume, slag and silica
adhesive is compressed by the gel that is generated, which increases fume). Because of the pozzolanic reactions, the porous structure of the adhesive is compressed by the gel that is generated, which increases compressive strength.

3.1. Using alkali-activated composites

3.1.1. Alkali-activated slag

Alkali-activated slag (AAS), a potential substitute concrete system with lower emissions of CO₂ than that based on OPC, has higher fire resistance and excellent mechanical properties [2,179]. However, unfortunately, autogenous and drying shrinkage contribute significantly to the high risk of cracking that prevents AAS from being used on a broad scale [180]. The substantial shrinkage of AAS has inspired the development of several different solutions, including compensating for the volumetric reduction with water or supplying additional volume to offset the effect of the volumetric reduction [2].

Because of its substantial shrinkage, AAS-formed C-A-S-H is likely a coagulated colloid or granular material with micro-defects. Because of AAS’s granular nature, the time-dependent rearrangement and redistribution of C-A-S-H nanoparticles produce visco-elastic and viscoplastic shrinkage during drying. Thus, AAS reduces at high RH (N50%) because tighter nanoparticle packing compresses gel pores and refines pore morphology. C-A-S-H nanoparticles compress into smaller gel holes when subjected to capillary pressure. Micropores shut as drying continues, resulting in nitrogen-inaccessible zones. Because of C-A-S-H nanoparticle rearrangement, AAS deforms irreversibly. At high RH, stable capillary meniscus formation drives C-S-H nanoparticle rearrangement. When C-A-S-H nanoparticles collide and rearrange, Si micropores close. Previous research found that NaOH-activated slag was stiffer than OPC, which enhanced elastic deformation but not viscous characteristics. Due to the composite nature of cementitious materials, dispersed inclusions significantly impact their mechanical properties.

Among the proposed solutions is the inclusion of SRA and IC agents [47,59,62], which are the approaches utilized most of the time. Using IC agents like lightweight aggregates or SAP reduces mixing water demand (Fig. 14a) [59,62] and even nano-particles (Fig. 14b). This, in turn, reduces the capillary pressure brought on by the decline in RH [181]. However, the incorporation of IC agents could cause a reduction in the mechanical properties of AAS, especially in systems made up of lightweight particles, because of the porosity of these materials [47,62]. SRA reduces pore solution surface tension, lowering capillary pressure and increasing relative humidity [185]. No effective remedy exists for AAS’s natural attrition while drying. 10 times and 3 to 6 times higher than OPC levels [47,103]. Evaporation or transpiration might cause AAS to shrink [47,63]. The continual water consumption during the slag reaction lowers internal relative humidity and forms a water-air meniscus in the AAS, causing autogenous shrinkage [47,63]. Since the surrounding air has a lower RH than the AAS air, shrinkage happens during drying. AAS has higher drying shrinkage than OPC, restricting its usage in buildings [186]. The capillary pressure created by the pore wall’s wettability in porous environments is also important [71]. The hydrophobic modification reduces capillary forces in porous materials, affecting liquid flow and evaporation [187].

Hydrophobic glass beads inhibit the capillary rise in a porous medium by 10 times compared to hydrophilic [188]. Under similar conditions, evaporation can be decreased by 75%. Hydrophobic compounds in cementitious materials prevent water infiltration and improve durability [189]. However, hydrophobic modification has not been shown to reduce AAS shrinkage [190]. Fatty acids, (polymeric) hydrocarbons, silanes, or siloxanes can make the substance hydrophobic [191]. Environmental concerns have led to studies on biotechnological methods for long-term hydrophobic agent production, considering natural materials’ benign qualities [192].

Biofilms in concrete change its wetting behavior [71]. Previous research [193] shows that water evaporation causes volumetric instability and drying shrinkage. Like the wetting characteristic (Fig. 15a and b), biofilm content affects drying shrinkage and mass loss between 1% and 2%, although this influence decreases as biofilm content increases. Biofilm concentration reduces AAS drying shrinkage [71]. Drying shrinkage was reduced by 58.1% at 3% SRA, 59% at 1%, and 78% at 3%. Biofilm decreased AAS moisture loss. Fig. 15 indicates that 3% biofilm over 35 days reduces moisture loss by 73% [71]. The AAS biofilm has increased hydrophobicity, which lowers capillary tension and slows liquid flow [194]. Due to the difficulty of water absorption in hydrophobic porous media, its role as a hydraulic connector between the interior’s saturated region and the exterior’s evaporation zone is disturbed, reducing evaporation [195]. Meniscus development decreases capillary stress [69,193].

3.1.2. Metakaolin

Crack growth is one of the main drawbacks of metakaolin-based AA binder (AA-MK) dry shrinkage [196]. It is obviously reported by Ref. [1] that MK high surface area and irregular particle form require more water to wet, which increases the potential for porosity and microcrack networks, which contribute to shrinkage [143]. The presence of MK results in a significant reduction in the autogenous shrinkage of AAS. MK increases the dissolvable Si and Al in the system while decreasing the amounts of Na⁺ and OH⁻ in the pore solution. Consequently, slag hydration and the creation of CASH gels are prevented as also reported in Ref. [1]. Even though certain NASH type gels are produced in MK mixes at an early stage, CASH gels are the primary reaction products of the
The addition of MK hinders the development of chemical shrinkage and the improvement of pore structure. The self-drying process and the pore pressure that builds up in the paste are significantly slowed down.

In order to control drying shrinkage in AAM binders, many studies have been conducted. According to research, the precursor quickly dissolves in the first stage of chemical shrinkage, while reaction products form in the second stage [197]. The predicted strain emerged after 7 days when the three mixes had autogenous shrinkages of 530, 313, and 257 μ (Fig. 16a and b). Discrepancies are twice as large as for OPC pastes.

Table 2

<table>
<thead>
<tr>
<th>Types of raw materials</th>
<th>Content, by wt. %</th>
<th>Fineness modulus</th>
<th>w/c</th>
<th>Type of curing Temp, °C</th>
<th>RH, %</th>
<th>Age, days</th>
<th>Decrease, %</th>
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<td>23</td>
<td>115</td>
<td>12.5</td>
<td>41.7</td>
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<td>23</td>
<td>115</td>
<td>5.8</td>
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<td>180</td>
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<td>27</td>
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<td>23</td>
<td>50</td>
<td>–180</td>
<td>9.9</td>
<td>17.8</td>
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<td>–</td>
<td>–180</td>
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<td>15</td>
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<td>90</td>
<td>16</td>
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<tr>
<td>BFS</td>
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<td>11.5</td>
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<td>23</td>
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<td>90</td>
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<td>12</td>
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<td>23</td>
<td>50</td>
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<td>29</td>
<td>35</td>
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<tr>
<td>MK</td>
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<td>23</td>
<td>50</td>
<td>60</td>
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<td>18</td>
</tr>
<tr>
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<td>23</td>
<td>100</td>
<td>28</td>
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<td>Calcined clays</td>
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<td>0.4</td>
<td>23</td>
<td>50</td>
<td>60</td>
<td>3.7</td>
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</tr>
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<td>Pumice powder</td>
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<td>0.48</td>
<td>23</td>
<td>50</td>
<td>–</td>
<td>115</td>
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<td>Silicon carbide waste</td>
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<td>20</td>
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<td>90</td>
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<td>42.4</td>
</tr>
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<td>–</td>
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<td>–</td>
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<td></td>
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<tr>
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<td>–</td>
<td>20</td>
<td>60</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>30</td>
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<td>50</td>
<td>14</td>
<td>37</td>
<td>44.3</td>
</tr>
<tr>
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<td>–</td>
<td>–</td>
<td>180</td>
<td>37</td>
<td>37.17</td>
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<tr>
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<td>90</td>
<td>90</td>
<td>12.6</td>
<td>31.9</td>
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<td>0.42</td>
<td>20</td>
<td>60</td>
<td>30</td>
<td>15.8</td>
<td>68.4</td>
</tr>
<tr>
<td>FA</td>
<td>30</td>
<td>0.44</td>
<td>23</td>
<td>50</td>
<td>1000</td>
<td>15.8</td>
<td>50.9</td>
</tr>
<tr>
<td>Superabsorbent polymer</td>
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<td>0.5</td>
<td>50</td>
<td>7</td>
<td>73.8</td>
<td>80.6</td>
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</tr>
<tr>
<td>SBT (I)</td>
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<td>4</td>
<td>–</td>
<td>–</td>
<td>90</td>
<td>27.1</td>
<td>68.7</td>
</tr>
<tr>
<td>PVC granules</td>
<td>5</td>
<td>4.4</td>
<td>–</td>
<td>23</td>
<td>50</td>
<td>112</td>
<td>18.1</td>
</tr>
<tr>
<td>Propylene glycol</td>
<td>2</td>
<td>–</td>
<td>23</td>
<td>50</td>
<td>180</td>
<td>–</td>
<td>38.9</td>
</tr>
<tr>
<td>Light weight aggregate</td>
<td>5</td>
<td>0.2</td>
<td>20</td>
<td>50</td>
<td>3</td>
<td>31.9</td>
<td>78.4</td>
</tr>
<tr>
<td>General glycol ethers</td>
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<td>0.5</td>
<td>20</td>
<td>5</td>
<td>300</td>
<td>13.8</td>
<td>62</td>
</tr>
<tr>
<td>Synthetic</td>
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<td>3</td>
<td>–</td>
<td>20</td>
<td>60</td>
<td>91</td>
<td>21.9</td>
</tr>
<tr>
<td>Low molecular polyether</td>
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<td>–</td>
<td>20</td>
<td>60</td>
<td>28</td>
<td>19.2</td>
<td>44.4</td>
</tr>
<tr>
<td>SiO$_2$–Na$_2$O</td>
<td>–</td>
<td>0.4</td>
<td>20</td>
<td>50</td>
<td>180</td>
<td>16</td>
<td>68</td>
</tr>
<tr>
<td>Eclipse Floor</td>
<td>12.5</td>
<td>–</td>
<td>–</td>
<td>20</td>
<td>&gt;90</td>
<td>–</td>
<td>13.3</td>
</tr>
<tr>
<td>High ash</td>
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<td>0.35</td>
<td>23</td>
<td>50</td>
<td>90</td>
<td>7.7</td>
<td>22.3</td>
</tr>
<tr>
<td>Iron ore tailings</td>
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<td>–</td>
<td>23</td>
<td>50</td>
<td>90</td>
<td>24</td>
</tr>
<tr>
<td>Recycled glass</td>
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<td>–</td>
<td>20</td>
<td>60</td>
<td>180</td>
<td>10.9</td>
</tr>
<tr>
<td>General glycol ethers</td>
<td>1</td>
<td>4</td>
<td>–</td>
<td>23</td>
<td>50</td>
<td>120</td>
<td>21</td>
</tr>
<tr>
<td>SRA, ECC</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>180</td>
<td>–</td>
<td>25</td>
</tr>
<tr>
<td>Na$_2$SiO$_3$</td>
<td>20*</td>
<td>0.35</td>
<td>50</td>
<td>&gt;50</td>
<td>7</td>
<td>7</td>
<td>46</td>
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<tr>
<td>Propylene glycol</td>
<td>1.5</td>
<td>–</td>
<td>–</td>
<td>20</td>
<td>50</td>
<td>120</td>
<td>29</td>
</tr>
</tbody>
</table>

Annotations: Shrinkage reducing admixture (SRA); relative humidity (RH); supplementary cementing material (SCM), *substitution for alkaline activator(Na$_2$SiO$_3$), blast furnace slag (BFS), adapted agent (SBT®- SRA (I)), and expended agent (EA).

Fig. 17. a) Autogenous and b) drying shrinkages of AAFS mortars with different w/b ratio and Na$_2$O (Adapted with improvement from Ref. [108]).
At a w/c of 0.3, OPC paste autogenous shrinkage is about 5.5 times bigger than experimentally determined [198]. Sant et al. [197] found a four times difference in OPC with a 0.3 water-to-cement ratio. According to the author [1], structural water is the minimum amount needed to maintain a gel from shrinking. Structural water is lost first [103] because the open macroporous network can remove this water since the microporous network has no capillary pressure [103]. More water removal shrinks [59]; as a result, AAM mortar gel density and sample porosity do not affect dry shrinkage [199]. When its MK dissolving degree was increased, the AAM’s molar Si/Al ratio increased up to 2.4, producing more water and improving gelation and matrix packing [103]. Water content, Si/Al and Na/Al ratios, and Na⁺/K⁺ cations affected AAM mortar drying and cracking [196]. Free water, which is not chemically bonded, is eliminated before the drying shrinkage in AAM pastes [200]. Flexural strength also correlates with drying shrinkage [82]. Further, shrinkage can be reduced or exacerbated by additive type and content [201, 202]. For example, replacing 20% MK with dolomite or calcite increased the toughened properties of AAM binders [203]. However, replacing more than 20% reduces mechanical properties and shrinkage. AAM pastes with ammonium molybdate have also been studied. Ammonium molybdate concentrations can be increased by about 1.6% without affecting crystallization temperature or shrinkage rate [103]. The material hardens poorly at 1.6%. However, ammonium molybdate regulates network formation, and geo-polymerization improves AAM paste thermal performance [204]. Changing the amount of alkali allowed researchers to examine mineral formation in AAM mortars at an early age [205]. Reducing AAM water content reduces dry shrinkage and cracking.

### 3.1.3. Fly ash

It is reported that FA-AAC can decrease less than cement pastes [1, 19]. This is because the AAFA reaction is similar to the sol–gel process, where small colloidal particles (sol) produce a continuous solid phase as the gel. Gel syneresis occurs when hydroxyl groups, such as Si(OH)₄ and Al(OH)₃ – (dissolved from fly ash particles), link to form new-fangled Si–O–Al and Si–O–Si bonds and water byproducts. When the free water in AAFA pastes dissolves both in the cavities left by the dissolved fly ash particles and in the aluminosilicate gel pores. This occurs when the aluminosilicate gel pores are porous. When water is evaporated from AAFA pastes, a meniscus forms, causing tensile stresses in the capillary water. The paste’s contraction primarily caused by these tensile stresses becoming balanced by compressive forces acting on the solid portion of the materials.

However, using FA rather than OPC may extend curing but decrease early compressive strength [205]. The most common precursor to AAGs is FA, a solid Al-rich aluminate silicate made from coal [148]. Amorphous aluminosilicate gel is the primary byproduct of FA-AAC [140]. Nonetheless, the limited reactivity of FA particles and the sluggish rate of development in compressive strength when cured under normal conditions limit its application in geopolymer synthesis [1, 206]. Providentially, shrinkage may be regulated by changing the type and concentration of an activation solution, adjusting the alkali activator to the binder ratio, and changing the binder [207]. Class F and Class C FAs, which make up the majority of FAs, have low calcium (high calcium) but high amorphous silica and aluminum, which are essential to hydrate formation.

The AAC-FA shrinkage can be reduced by increasing activator molarity [207]. However, silica coagulates faster over a certain sodium hydroxide level and decreases compressive strength [208]. A compact, robust geopolymer matrix develops as NaOH concentration increases, enhancing paste compressive strength [209]. Increased compressive strength and matrix density reduce drying shrinkage in FA-AAC [210]. Microscopic organization, compressive strength, hydration, initial surface hydration, and permeability of FA-AAC mortars have also been studied [39, 211]. FA-AAC mortars with different alkaline solutions were made by mixing sodium oxide and liquid sodium silicate equal to binder ratio up to 0.65 [206]. Synthesized FA-AAC mortars had higher length fluctuations than cement-based mortars, implying longer change lengths. Variations depend on alkaline solution/binder ratios [1]. Increased sodium oxide in FA-AAC mortars reduced drying shrinkage, porosity, and initial surface absorption [206]. Reduced sodium silicate in the alkali activator reduces FA-AAC drying shrinkage [103].

The drying shrinkage exceeds the AA-FA shrinkage after the early ages. AAFA drying shrinkage and mass loss are not directly connected like cement pastes. Capillary pressure and permeability fluctuations may explain this [77, 108]. AAFA drying shrinkage decreases with activator sodium oxide [212]. Refining high-calcium materials FA increases the specific surface area, filling some spaces between particles and providing a denser matrix. AA-autogenous FA shrinkage is substantially reduced beyond the early ages, and drying shrinkage eventually dominates [87, 145]. Also, AAS’s finer pore structure and higher capillary tensile strains diminish drying shrinkage in AAFA [202, 213]. Minimizing matrix porosity improves AAFA toughened properties [104, 200]. SCM, aggregates, SRA, and powder reduce drying shrinkage [214]. Precursor reactivity, chemical composition, and fineness affect AAM shrinkage [215]. It is well-known that sodium oxide and silica increase autogenous and drying shrinkages [Fig. 17] [108]. Autogenous shrinking decreases when the alkali activator decreases. All sodium oxide, the amount of powder and slag in the AFS, is also a major influence in autogenous shrinkage, along with the weight-to-bulk ratio. Notwithstanding AAAS processes used more water, specimens with higher sodium oxide concentrations dissipated less water [108]. Despite the higher weight-to-volume ratio, mass change was slower [108]. The elliptical ring test evaluated mix compositions’ early breakage under limited conditions [103]. This approach concentrates autogenous shrinkage-induced tensile stress for examining cracks [142, 216]. If a large autogenous strain is measured under constrained conditions, fracture development is likely, although not always at early ages [35, 55, 122].

Numerous factors have been found to influence the efficiency of fibers, including the compactness of the matrix, type of fiber, length, shape, and inherent chemical and mechanical properties [1, 217]. Polymeric fibers reduced drying shrinkage and increased AAFA fracture breadth up to 0.8% of the binder weight [218]. It is also found that thermal curing also reduced AAFA drying shrinkage [62, 219]. Thermal curing to about 50 °C reduces drying shrinkage by 75% compared to ambient curing [123]. Heat-curing increases volumetric stability and decreases overall porosity, reducing dry shrinkage [220]. Adding fibers to ordinary AAFA increases ductility and lowers dry shrinkage [221]. It is also reported that AAFA shrunk when dried. was reduced up to 800 µm/m when NaOH dosage in the activator increased up to 6% [213]. Hydration product synthesis increased compressive strength and dry shrinkage [103, 108]. In fluidized bed AAFA pastes, nano-TiO₂ affects compressive strength, drying shrinkage, carbonation, and microstructure, especially, TiO₂ up to 5%, enhanced AAFA mortar compressive
The main reason for incorporating fibers into cementitious concrete composites is to modify the post-peak behaviors of the material in order to lower its brittleness. The tensile behavior of cementitious composites, Fiber reinforcement has the potential to considerably increase several mechanical properties, such as post-peak strength and strain capacity. In addition, the incorporation of microfibers has been shown to have beneficial impacts on strain hardening and multiple cracking behavior. These advancements, including the ability to heal itself, self-consolidating, high-early-strength material, have resulted in various examples of how cementitious composites can be used in the real world from the published literature.

### 3.2. Using fibers

#### 3.2.1. Recycled tire polymer fibers

Steel fibers have demonstrated a considerably positive role in controlling shrinkage; however, their relative cost is the main reason that limits their widespread utilization. RCSF could also be a successful option for SFs. However, only a few studies have investigated the potential use of RCSF as a substitute for steel fibers in concrete. A past study reported that incorporating moderate quantities of RCSF into concrete helps improve both its compressive and flexural strengths [250, 251]. The first highlight in using RCSF filaments extracted from pre-vulcanized rubber belt offcuts was introduced by some researchers at Sheffield University (Fig. 18) [252].

Steel reinforcements that are frequently used in the manufacture of tires consist of parallel filaments of incredibly fine wires, with diameters ranging between 0.1 and 0.4 mm, which are then twisted together to form a cord with a diameter of 0.5–1.0 mm [253]. However, information regarding their use in concrete is limited; hence, additional research is necessary. To date, We have a limited understanding of how industrial fibers affect calcium aluminate (CA), and there are no published data on how RCSF calcium sulfo-aluminate (CSA) cement matrices respond to the presence of industrial fibers [254] and RCSF in general [255]. RCSF can be partially added to many applications, including roller-compacted concrete [256, 257]. According to some reports, RCSF requires less than 5% of the energy needed to generate traditionally made steel fibers. RCSF-only mixes perform worse in flexure than MSF-only mixes at the same fiber dose, especially when fractures emerge [259]. Conventional concrete mixing requires 30 kg/m$^3$ of RCSF [257]. If the dosage is increased above this threshold, RCSF mechanical properties could decrease and fiber balling may develop if the concrete is overworked [252]. In concrete, RCSF can be used with SF in trace levels to provide mechanical properties comparable to, or even better than, those of MSF-only mixtures. MSF-only mixtures had lower flexural performance than those with SF and mixed mixes and 10 kg/m$^3$ of RCSF [257]. Tlemat et al. found similar results [252]. SF increases concrete instability because it is necessary for the field of concrete science to prioritize developing improvements in ductility [260].

To minimize rust patches on concrete surfaces caused by steel fibers and a high water-to-cement ratio of 0.5, it is recommended to provide a minimum of 0.2 mm of cover; otherwise, fibers made from galvanized steel need to be used [261]. In contrast to commercial steel fibers with a quality defined during the manufacturing process, RCSF is a combination of fibers that have previously been processed through a plant and subjected to varying degrees of stress. For this reason, It is possible that RCSF fibers degrade more rapidly in cement-based products when subjected to harsh conditions [250, 252, 253]. Concretes made using commercial steel fibers and RCSF were subjected to accelerated corrosion to see which would hold up better. Researchers found that specimens containing RCS exhibited significantly more severe surface corrosion, although both fibers exhibited minimal corrosion activity when completely embedded in concrete [261]. Moreover, adding silica fume and other minerals as admixtures makes concrete more susceptible to early-age cracking due to shrinkage [106]. One technique that has been utilized for decades includes the reinforcement of brittle materials, such as cement composites or concrete with short fibers. Several types of fibers currently used in commercial applications include stainless steel, tempered glass, synthetics, and even some natural fibers [262].

#### 3.2.2. Steel fibers

Fibers are useful because they reduce the likelihood of cracks developing, reducing the likelihood of shrinkage [263]. One study found fiber-reinforced concrete (FRC) had dry shrinkage between 8% and 65%, lower than ordinary concrete [9, 87, 264–266]. Steel fiber in concrete may minimize shrinkage cracking [267]. Steel fiber improves concrete’s tensile strength, fracture resistance, impact resistance, and lifespan [268–273]. Fiber-reinforced concrete’s properties depend on its shape, distribution, orientation, type, and content [274–276]. Polymer or steel fibers improve flexural strength, toughness, post-failure ductility, crack management, compression and energy absorption at

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**Fig. 19.** Effects of the length and steel fiber content on the drying shrinkage of Alkali-activated slag/silica fume mortars (Adapted with improvement from Ref. [295]) [Annotations: fiber (F)].

**Fig. 20.** Effects of polypropylene fibers volume fraction on dry shrinkage (Adapted with improvement from Ref. [249]) [Annotations: without polypropylene fiber (W-PPFs), and fiber volume fraction (FVF)].
Fiber in AAS improved tensile, flexural, and durability performance, shrinkage, and energy absorption by reducing fracture spread [264]. Wears out [293]. Fibers added to concrete could improve ductility, matrix interface. OPC mortar, a popular building material, cracks and performance indicators [9, 292]. Fiber dispersion helps the fiber-AAM performed standard binder systems in most mechanical, durability and performance indicators [290]. It proves bond strength and pull-out failure ductility [9], with both the matrix and fibers showing increased binding strength [287-289], including composite structures [290].

It is reported by author [291] that steel fibers and AAM outperformed standard binder systems in most mechanical, durability and performance indicators [9, 292]. Fiber dispersion helps the fiber-AAM matrix interface. OPC mortar, a popular building material, cracks and wears out [293]. Fibers added to concrete could improve ductility, shrinkage, and energy absorption by reducing fracture spread [264]. Fiber in AAS improved tensile, flexural, and durability performance characteristics. Fiber inclusion decreased AAS concrete compressive strength [294]. Scientists use steel fibers in OPC mortar or concrete to reduce shrinkage deformation [295]. Fibers in AAS mortar minimize composite shrinkage and deformation [296]. Other investigations [291] show that adding discrete fibers to concrete reinforcement does not prevent shrinkage [297]. Fiber inclusion in concrete may reduce FRC creep [215,294] but may also enhance it [215,264]. Concrete and fiber characteristics affect concrete performance. In steel FRC, aspect ratio and fiber proportion determine concrete quality [298]. Fig. 19 shows that steel fiber length and volume percentage substantially influence shrinkage [299]. Fiber prevented 24% of simple AAS mortar drying shrinkage and at constant fiber dosages, integrated AAS mortars had equivalent drying shrinkages of conventional mortars [299]. AASS mortars had better mechanical performance than OPC control mortars, and drying shrinkage decreased with fiber dosages. The increased consumption of fibers is to blame for both of these outcomes [291]. This allows carbon fibers to control AAS composite drying shrinkage [300].

Other research [111,291,303] found that increasing steel fiber % prevents drying shrinkage. However, fiber aggregation reduces efficiency, especially above 2% [304]. It is clearly reported in Ref. [5] that the internal restriction prevents matrix dispersion, aggregating it. This adverse event challenges the compression of the granular skeleton, increasing the amount of entrapped voids and decreasing the pore structures’ size [305-307]. This increases drying shrinkage. Adding up to 30% slag to concrete creates a thick composite with reduced drying shrinkage [108]. Materials, additives, curing type, temperature, and water content affect AAC drying shrinkage. It is also reported that up to 14% reductions, respectively, when comparing the results of an example generated with 2% straight steel fiber to those obtained from a mixture containing 2% corrugated and hooked steel fibers [308]. Adding 1%

---

**Table 3**

Drying shrinkage reduction by using fiber as a reinforcement material [81, 178, 99, 116, 117, 117, 214, 215, 218, 216, 296, 302, 308, 249, 326-335].

<table>
<thead>
<tr>
<th>Fibre types</th>
<th>Dimension of fiber (mm)</th>
<th>Content, by vol%</th>
<th>Drying condition</th>
<th>Age, days</th>
<th>Decrease, %</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Diameter</td>
<td>Min.</td>
<td>Max.</td>
<td>Temp., °C</td>
<td>RH, %</td>
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<td>0.08</td>
<td>0.8</td>
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<td>65</td>
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<td>2</td>
<td>23</td>
<td>65</td>
</tr>
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<td>55</td>
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<tr>
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<td>–</td>
<td>0.5</td>
<td>2</td>
<td>23</td>
<td>65</td>
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<td>–</td>
<td>–</td>
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<tr>
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<td>–</td>
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<td>0.45</td>
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<td>0.3</td>
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<td>–</td>
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<td>65</td>
</tr>
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<td>–</td>
<td>0.05</td>
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<td>65</td>
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<td>–</td>
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<td>–</td>
</tr>
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<td>0.2</td>
<td>0.3</td>
<td>21</td>
<td>41</td>
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<td>23</td>
<td>50</td>
</tr>
<tr>
<td>PPF</td>
<td>12</td>
<td>0.02</td>
<td>0.2</td>
<td>–</td>
<td>23</td>
<td>50</td>
</tr>
<tr>
<td>PANF</td>
<td>25 × 10^{-3}</td>
<td>1 × 10^{-3}</td>
<td>0.05</td>
<td>0.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Polypropylene fiber</td>
<td>44-54</td>
<td>–</td>
<td>0.4</td>
<td>0.8</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>Steel</td>
<td>53</td>
<td>–</td>
<td>0.4</td>
<td>0.8</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>Glass</td>
<td>10</td>
<td>–</td>
<td>0.5</td>
<td>2</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>Steel</td>
<td>13</td>
<td>0.3</td>
<td>1</td>
<td>3</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>PPF</td>
<td>12</td>
<td>0.035 × (0.25-0.6)</td>
<td>0.25</td>
<td>0.75</td>
<td>22</td>
<td>70</td>
</tr>
<tr>
<td>PVAF</td>
<td>12</td>
<td>80 × 90 × 10^{-3}</td>
<td>0.2</td>
<td>–</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>PPF</td>
<td>20</td>
<td>0.45</td>
<td>–</td>
<td>0.25</td>
<td>1.25</td>
<td>23</td>
</tr>
<tr>
<td>Polyamide</td>
<td>6.12</td>
<td>–</td>
<td>0.4</td>
<td>0.8</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>Steel</td>
<td>6-18</td>
<td>–</td>
<td>0.5</td>
<td>2</td>
<td>20</td>
<td>50</td>
</tr>
</tbody>
</table>

**Annotations:** short polymer hybrid fibres (SPHF), polyolefin fibers (POF), Polyacrylonitrile fiber (PANF), polyethylene (PEF), and polyvinyl alcohol fiber (PVAF).
straight SFs with different sizes to fiber-reinforced AAC (FR-AAC) mortars containing 80% slag and 20% FA Class F and activating with Na$_2$SiO$_3$ and NaOH decreases dry shrinkage of 27.6% [309]. Similarly, the integration of 1.5% steel fibers with different diameters into steel mortars made from fiber-AAC that was activated with a mixture of water, glass, resulted in a 24% reduction in drying shrinkage [299]. The improvement in drying shrinkage resistance resulting from fiber inclusion can be attributed to its high modulus of elasticity and ability to bind strongly [309]. In addition, AACS soaked in calcium water shrank significantly upon drying, but this effect was not seen with other types of water. A mixture of palm oil fuel ash and steel slag has been said to minimize AAC shrinkage by more than 50% [124]. In brief, Because of a powerful anchoring effect, integrating deformed-shaped fibers, such as those with corrugated and hooked-end morphologies, substantially reduced shrinkage.

3.2.3. Polypropylene fibers

Polypropylene fiber (PPF) and concrete compressive strength have been discussed [310,311]. PPF presence had no real effect on concrete compressive strength, according to certain investigations [312]. Richardson noted that cement bond breakdown caused by PPF decreased concrete compressive strength [313]. Adding 0.5 wt% PPF to the matrix enhanced the early compressive strength of FA/calcined kaolin AAC by 68% and 20% on days 1 and 3 [314]. The composite with 0.75% PPF demonstrated an almost two-fold increase in early flexural strength for days 1 and 3, proving that PPF did not negatively impact AACS [313]. Slag-based AAC reinforced with PPF provided similar results: PSH with strain up to 7.5%, multiple microcracks, crack spacings of less than 2.25 $\mu$m, and compressive strength between 36.3 and 54.8 MPa [315,316]. PPF volume fraction up to 0.12% and length between 10 and 20 mm affected drying shrinkage at 20 $^\circ$C ± 2 $^\circ$C and RH of 60% ± 5% (Fig. 20) [249]. It is clearly reported in Ref. [2] that the fiber inclusion reduced shrinkage strain by 24% compared to plain concrete of 579 $\mu$m, reaching a maximum of 441 $\mu$m s after 90 days with 0.12% PPF. As can be observed in Fig. 20, PPFs dramatically lowered the amount of concrete’s dry shrinkage that was caused by the presence of FA and silica fume [249]. The PPF-reinforced AAFA with a high-volume FA had a very low drying shrinkage. Similarly, adding PPFs to cement mortar can reduce the latter’s dry shrinkage [295]. In this regard, researchers concluded that when the percentage of fiber volume fraction increases, drying shrinkage decreases, which can be ascribed to bridging and sewing the tiny gaps and the application of PPFs, which prevented the microlevel in mortar from moving [205]. In addition, using a digital DEMEC strain gauge for measuring the drying shrinkage of concrete containing PP carpet waste is one of the reasons for the positive impact of PPFs [215]. However, the hydrophobic qualities of PPFs, combined with their smooth surface, helped speed up the water evaporation process by deflecting inner moisture outward [317]. This helped speed up the process of water evaporation. Fiber ends near the concrete surface boost this activity. Thus, moisture loss and shrinkage deformation will increase. It is clearly reported in Ref. [2] that PPF and rice husk ash-alone or together-prevented drying shrinkage. PPF and ash alone or both have this impact [224]. The lowest drying shrinkage strain was attained with 0.3% PPF and 30% rice husk ash replacement cement. After 90 days, this combination was reduced 300 $\mu$m s compared to the control [214]. PPFs improve autogenous shrinkage [87]. Autogenous shrinkage is caused by cement paste self-desiccation from continual hydration and hardening. Compared to ordinary concrete, adding up to 0.75% PPF reduced autogenous shrinkage up to 26% after 24 h [87]. Brown et al. [210]
found that ordinary concrete cracked after 36 days, concrete containing sinusoidal fibers cracked after 202 days, and concrete with monofilament threads never cracked. Monofilament strands anchor better, which improves stress distribution [210].

It is reported that adding 0.1% PPFs by volume to the mixture positively affected drying shrinkage, while adding fibers made it worse [318]. A further improvement in the plastic shrinkage behavior of FRC was achieved by mixing multifilament fibers of variable lengths, ranging in length from 6 to 20 mm, as opposed to mixtures holding a fixed fiber length [319]. This was done in contrast to mixtures that contained a fiber length constant throughout the mixture. The concrete’s dry shrinkage strain decreased when fiber volume fractions rose over 0.12%. After 90 days, the dry shrinkage strain fell 24% up to 441 μm as the fiber percentage of PPF grew up to 0.12% [320]. PPFs reduced drying shrinkage in concrete and AAFA (Fig. 21). High-volume PPF-reinforced AAFA demonstrated very low drying shrinkage [321]. Similarly, the addition of PPF to cement mortar assisted in lowering the amount of dry shrinkage experienced by the combination [295].

According to one study [320], the amount of shrinkage caused by drying was shown to be lower when the proportion of fiber volume fraction was raised. The use of polypropylene, which bridged and stitched tiny fissures, prevented mortar from moving at the micro level, supporting this observation [322]. PP fibers and 0.5% SF reduced the drying shrinkage of the FA-based AAC composite, whereas SF at 2% or higher had no shrinkage [323]. As fiber content rose, PPF did not reduce shrinking. Because high-PPF AAC composites were not compact [324]. Due to PPF’s lower rigidity and poorer matrix-PPF bond, composites with significant PPF content perform worse than SF composites. PVA FR-AACs shrink less than PP due to their hydrophilicity and stiffness [205].

It is found that fiber length effect study yielded conflicting results [5]. Long fibers minimize crack widths [200], enhance bending, twisting, and breaking resistance [300], or have little effect [299]. The curing environment and binder affect FR-AAC composite shrinkage. During curing, slag-based AACs shrank less than FA-based composites when exposed to ambient humidity up to 95% [196]. During tests, short recycled PET fibers improved reinforced concrete. These included reducing macro crack formation, postponing drying shrinkage, increasing ultimate strength, and improving ductility [325]. Based on these findings, recycled PET fiber controls crack formation and propagation [5]. In brief, FR-AAC mortars activated with sodium hydroxide had reduced drying shrinkage [205]. PPFs are added to cementitious systems to reduce matrix brittleness, which reduces concrete cracking and fire-spalling in high-strength concrete. Furthermore, Table 3 shows the drying shrinkage reduction rates after using fiber as a reinforcement material.

3.3. Using aggregates

Recycled concrete aggregate (RCA) can improve AAS mortar shrinkage resistance as an IC agent [219]. The aggregates’ composition and structure limit the paste’s volume reduction when their combined

![Graph](image-url)
shrinkage deformation is less than the paste’s. Porosity determines drying shrinkage. After 2 years of exposure at 33 °C ± 2 °C and 65% ± 5% RH, increasing the fine aggregate size from 1.18 mm to 2.36 mm reduced long-term drying shrinkage by 69.8% [336]. To determine how aggregates are held together, a study used theoretical and experimental investigations and a dispersion model of the aggregate skeleton [337].

It is found a clear significant limitation influences increased coarse aggregate volume or aggregate size and decreased ultimate drying shrinkage, as obviously discussed in Ref. [2]. After 112 days, recycled glass reduced drying shrinkage by 17% compared to natural sand, which was ≤10 mm [338]. In a controlled setting with scrap glass diameters from 2.38 to 0.149 mm and 65% RH, drying shrinkage was higher than 19% [339]. Coal gangue has a higher water-absorbing capacity than crushed stone [340]. It was found in previous studies that SAP affected the relative humidity and AS inside the AAS mortar, which was a fascinating finding. They found that increasing the SAP concentration in mortar enhanced the internal RH. Additionally, this lowered the surface tension of the pore solution, which resulted in a considerable reduction in the autogenous shrinkage of AAS mortar. Increased SAP-to-cement mortar ratios did this [62]. SRA slowed the hydration response and coarsened pores, reducing drying shrinkage. On the other hand, the incompatibility of SRA with some AAS materials can cause the material’s pores to become coarser [64]. Crushed glass’s high aspect ratio and low water absorption prevented drying shrinkage [341]. It is also designed as a particles shape tool that can successfully remove the attached old mortars of RA, which has been extensively employed in China to modify RA (Fig. 22a) [342]. This tool has been in use for quite some time. Regular RA was first propelled to 100 m/s by a projecting disc, then hit between different RA at high speed to remove old mortars that had adhered to the surface. In addition, the properties of the altered RA improve as the number of shaping cycles grows, as shown by the properties of the altered RA following a succession of shaping phases that are represented in Fig. 22b [343].

Fig. 23 shows drying shrinkages of fine LWA specimens after various pretreatment methods. After vacuum soaking or saturation, fine LWA drying shrinkage improved dramatically [248]. Delayed water release decreased L-10-V and L-10-S drying shrinkage strains up to 20%, respectively. Because L-10-E included more water than LWA, the LWA’s positive effects were neutralized, and the drying shrinkage increased to levels almost on par with REF. In addition, sand was substituted with 45% scraped PVC granules with a fineness modulus of 4.42, leading to a considerable reduction in drying shrinkage of about 73% after 112 days [238]. Pre-wetting fine lightweight aggregate (LWA) strengthened concrete [299]. Replace 10% of sand with water-soaked, fine, LWA, reducing drying shrinkage by about 20% in 91 days [248]. LWA water enhanced cementitious material hydration, causing hydration heat-induced thermal expansion deformation [345]. It is found that when fine LWA exceeded 10%, an enlargement was observed at around 8 h, confirming prior observations [345]. The hydration of C₃A assisted in accelerating the production of big crystals [346]. It is also reported that water entering the matrix at a young age caused the UHSC pore structure to have capillary pores. Besides, SRA lowers the surface tension of pore water, which in turn lowers the capillary tensile stress [7,242]. This has been an area of investigation by researchers working in various disciplines. Slag and FA can be employed as paste fillers in crystalline form, unlike coal gangue [347]. The spontaneous combustion of coal gangue coarse aggregate and cement mortar formed a well-bonded ITZ.

According to trials using coal gangue coarse aggregate in concrete, its size had no effect [348], as also elaborated by Ref. [2]. However, one study [216] found that the mechanical properties of the concrete, especially its toughness, declined concurrently with the amount of coal gangue in the coarse aggregate. As a result, the damage layer became thicker, and the peak stress-strain decreased. Moreover, broken glass, which has a low water absorption rate and a high aspect ratio, proved to be an excellent alternative to the standard aggregate in terms of its influence on drying shrinkage mitigation; nevertheless, the detrimental effect on alkali-silica reaction expansion increased with the addition of glass (Fig. 24a and b) [349]. If the coarse aggregate is replaced with aggregates with a lower modulus of elasticity, bigger pore volume, or higher water absorption, drying shrinkage deformation may worsen. However, RCA can be coated to reduce drying shrinkage. Immersing RCA in HCl acid, soaking it in purified water, then coating it with CaSiO₂ improves its quality [350]. After 180 days, treated coarse RCA shrank greatly less than untreated coarse RCA and was comparable to natural aggregate. Similarly, the utilization of plastic granules as fine aggregate presents an option for substituting coarse material for drying shrinkage mitigation. Based on this findings, a more research is required to completely understand how the IC mechanism influences the drying down process.

4. Proposed strategies to mitigate the shrinkage

4.1. Expansive agents

Expansive agents (EAs) are powdered materials admixtures that (Fig. 25), when added to concrete, can induce controlled expansion during the early stages of curing. This expansion can counteract the shrinkage that occurs as concrete dries and undergoes hydration. The aim of using expansive agents is to reduce or eliminate cracking that can result from the shrinkage of the concrete. EAs cause a regulated internal
Concrete shrinkage is reduced by using EAs. Previous studies, mainly deliberated by Bertelsen [4], have demonstrated that wollastonite is a mineral that occurs naturally and is white, acicular, and inert. It is a calcium metasilicate (b-CaO-SiO\(_2\)) and is cheaper than steel or carbon microfibers [296]. The possibility of employing natural wollastonite microfibers used in some cementitious compositions as reinforcing ingredients and it is found that when applied to matrices composed of cement and silicate fume, wollastonite microfibers demonstrated a significant enhancement in pre-peak and post-peak loads and flexural toughness and ductility [353]. Wollastonite microfibers, which are frequently utilized in various industrial applications, such as paint, plastics, and ceramics, are considered one of the more promising materials [354]. The microfibers of wollastonite that were implanted in cementitious materials showed a remarkable degree of stability over time, exhibiting neither surface nor bulk deterioration [354]. It is possible to conclude that increasing the dosage of EA can successfully reduce the shrinking of the AAC system and does not have a major impact on its strength development [58]. It is clearly reviewed by Bertelsen [4] that the diverse EA kinds, precursors, alkaline concentrations, and curing settings may have been responsible for some of the discrepancies documented in previous studies on the effects of EAs on the shrinkage and strength of AAC systems [60,63]. Others argued that incorporating EAs promoted strength development [58]. Furthermore, several researchers have proposed that the insertion of EAs can significantly minimize the shrinkage of AAC but inhibit their strength development. For example, it is discovered that the decrease in drying shrinkage due to the inclusion of EAs and SARs was linked to the composites’ decreased internal relative humidity (IRH).

Also studied were the impacts of different types of EAs [60]. The findings demonstrated that using EAs improved the early compressive strength of the AAC, but its later compressive strength was slightly diminished as discussed deeply in Ref. [4]. Likewise, after integrating 8% EAs, it was discovered that the drying shrinkage decreased by almost 80% [58]. The production of portlandite and Aft in the pastes is responsible for the reduced shrinkage since these minerals offset the shrinkage that occurred in AAS composites due to the use of EAs [63]. These crystal phases, known as portlandite and Aft, were tightly attached to the matrix and played a role in preventing C-A-S-H gels from deforming [4]. There is a correlation between the various forms of EA present and the distinct crystal phases that precipitated. Drying shrinkage of AAs was also examined in relation to CE (CaO-type EA) and calcium sulphaolaminite-type EA (CSAE) [66]. Meanwhile, the addition of CE and CSAE to mixtures resulted in a decrease in drying shrinkage of up to 11%, respectively, after 56 days in relation to the concentrations of up to 10% added (Fig. 26) [66], thus, this phenomenon was due to the CSAE being used. Furthermore, a study reported that incorporating 2% latex reduced geopolymer concrete shrinkage by roughly 50% [355]. It is also known that developing these crystal phases affects AAC’s malleability and durability [60]. Bertelsen reported that it is feasible to conclude that the shrinkage strain resulting from water vaporization was marginal and can be made reference to as the total shrinkage strain given that the shrinkage strains due to hydrodynamic tension, surface energy, and disjoining stress were all incredibly close to the drying shrinkage resulting from water evaporation, as studied in Ref. [58]. Another research reported that rubber latex dose affected calcined clay-based AAC’s permeability and contraction. Thus, the impact of different amounts of rubber latex on the porosity and shrinkage of calcined clay-based AAC are investigated and analyzed [355]. Nonetheless, the reduced shrinking seen since latex’s introduction is mainly attributed to

**Fig. 28.** a) Autogeneous and b) drying shrinkages of UHPC made with 2% fibers of various shapes (Adapted with improvement from Ref. [302])  

**Fig. 29.** (a) Time-dependent length change; (b) time-dependent weight loss (Adopted from Ref. [70])  

**Fig. 30.** (Adopted from Ref. [70]) 

\[ \text{(Adopted from Ref. [70])} \]
may be due to the latex polymer's ability to block capillary pores, thereby reducing the interconnectivity of the pores and impeding the transport of moisture [58]. Fig. 27 summarizes the influence of EA admixtures on the relative shrinkage as reported by several researchers. The shrinkage strain for all mechanisms reduced as the amount of rubber latex added to the mix rose. The shrinking is less because the mesopores are smaller and the pore structure is coarser [75,78]. Briefly, the EAs, SRAs, and NPs are primarily reduced drying shrinkage, whereas SAPs can be added to reduce shrinkage in AACS. Additionally, it was discovered that MgO significantly reduced drying shrinkage compared to autogenous shrinkage, but the modulus of sodium silicate also influenced the shrinkage-mitigating action.

4.2. Internal shrinkage restriction

Internal shrinkage restriction in the context of AAC refers to a set of techniques or materials used to control or mitigate the inherent shrinkage that occurs during the drying and curing process of the concrete. AAC, also known as geopolymer concrete, is a type of concrete that relies on the reaction of alkaline materials with industrial by-products like fly ash or slag to create a binder, as opposed to traditional Portland cement-based concrete. Utilizing recycled, partially-hydrated SCMs from surplus concrete helps reduce shrinkage for the same reasons as when utilizing un-hydrated cement particles and aggregate [358]. It has also been noted that the incorporation of shrinkage was effectively controlled by distorted-shaped fibers like corrugated and hooked-end forms thanks to a powerful anchoring effect, in which an interlocking system between the particles resists deformation [304]. It is parratically known that increasing the fiber content to dosages of more than 2% tends to diminish efficiency due to fiber agglomeration [304]. This can be attributed to the internal restraint's strong influence, which makes it more likely that clumping would occur because of the difficulty of achieving homogeneous distribution over the matrix. Hence, this unfavorable occurrence causes disturbance in the granular skeleton's compaction, thereby increasing the amount of trapped voids and degrading the pore structure, related to increased drying shrinkage [359].

For example, the lumen structure of cellulose fibers allows to absorb water and function as an internal constraint and internal water reservoir [360]. As a result, the effectiveness of IC from cellulose fibers can prevent drying shrinkage. The results showed that the UHPC made with cellulose fibers at a ratio of 0.9 kg/m³ had the lowest shrinkage values at 7 and 60 days, approximately 70% and 33% lower than the UHPC used as a reference, respectively [361]. Fig. 29a and b shows the shrinkage deformation in the mixtures and compared the specimen made with 2% straight steel fiber to the sample made with 2% corrugated and 2% hooked steel fibers, showing up to a 14% reduction in weight, respectively [302]. It has been demonstrated that other types of high-modulus fibers, such as alkali-resistant glass fibers and carbon fibers, can also prevent shrinkage and crack propagation efficiently [200,308].

In the case of concrete with no additional SRA, according to the findings, holes with sizes ranging from 6 to 30 nm had a significant connection with the drying shrinkage (with a coefficient of 0.85), and this connection was observed at a temperature of 20°C and relative humidity of 60% [202]. Meanwhile, in the presence of SRA, drying-shrinkable pores were narrowed to under 20 nm [214]. In other words, SRA molecules make pores larger than 20 nm in diameter less capillary stressed, making water evaporation in such pores innocuous in terms of shrinkage [202]. Also, adding 1% SRA successfully prevented drying shrinkage from developing, postponed early cracks brought on by preventing further shrinking and reduced crack width by approximately thirty percent after ninety days [247] as well as to improve pore dispersion and reduced the number of harmful pores by up to 1 μm [142]. Over up to 70 days, an increase in w/b resulted in a reduction in drying shrinkage and this reduction in drying shrinkage was because an increase in w/b decreased the amount of water absorbed by the fabric. Similarly, many researchers have noted that a reduction in drying shrinkage coincides with an increase in the amount of SRA present in the material [64]. Therefore, reducing the number of pores vulnerable to drying shrinkage results in less drying shrinkage. Furthermore, using recycled materials during production, AACSs can mitigate shrinkage and have lower thermal conductivity than normal concrete counterparts.

4.3. Shrinkage-reducing admixture

A shrinkage-reducing admixture (SRA) is a type of chemical additive that is used in concrete to mitigate the drying shrinkage that occurs as the concrete loses moisture and undergoes the curing process. Shrinkage-reducing admixtures are specifically designed to minimize the potential for cracking caused by the volume reduction in concrete. SRA is one of the most commonly used mitigation strategies to eliminate AAC shrinkage [31,82]. The incorporation of SRAs caused a considerable decrease in the drying shrinkage of the composites while having essentially little impact on the compressive strength of the material [67,296], as clearly reviewed in Ref. [3]. It has been reported that the inclusion of SRAs can significantly minimize shrinkage by lowering that decreases capillary strains by raising the surface tension of the pore solution [31,82]. This is because the favorable effect of SRAs on shrinkage behavior is mainly induced by the alteration of the pore structure and surface tension of the pore solution [147,157]. Fig. 29a and b verifies a similar shrinkage reduction mechanism [70] and shows the effects of adding 1% polypropylene glycol (PPG) with higher molecular weights [67], the shrinkage of mortars using AAS had an up to 77% drop, respectively, when exposed to 50% and 99% RH for 180 days,
coarser pore structure. The literature on shrinkage mitigation by using SRAs for AAC systems focused primarily on drying shrinkage; in comparison, only a few studies on autogenous shrinkage have been conducted [70]. Drying shrinkage of FA-GPC matrix was mitigated in pastes containing SRAs [95]. According to the findings, SRA’s shrinkage-reducing effects were associated with expanding the material’s pore structure [77]. The insertion of SRAs facilitated the conversion of more mesopores into mesopores, resulting in a paste with a coarser pore structure. The literature on shrinkage mitigation by utilizing SRAs for AAC systems focused primarily on drying shrinkage; in comparison, only a few studies on autogenous shrinkage have been conducted [70]. Drying shrinkage of FA-GPC matrix was mitigated because these coarsened pore geometries [77]. The mechanism of shrinkage decrement mediated by SRAs was caused by a coarser pore structure rather than a drop in surface tension in the pore solution. The inclusion of SRAs had minimal effect on the total porosity of AAC mortars, as shown in Fig. 30 [82]; nevertheless, it had a considerable increase on both the average and median pore widths of these mortars. Briefly, the impact of SRAs on the inside of AAC mortars can increase the uniformity of hydrate precipitation and formation, which is a positive outcome. This reduces gel phase collapse and reorganization during curing, maintaining internal structure stability and decreasing micro-crack formation.

It is noticeably discussed by author [4] the concern regarding the modifications to AAC’s mechanical behavior and degree of shrinking brought on by SRA, it has been reported that as SRA content rises, shrinkage reduces; in contrast, compressive strength shows a wide range of variation [362]. It is also found that while some studies have found that higher SRAs reduce AAC compressive strength, others have found the opposite true [49,244]. The matrix type, SRA type, alkaline content, and curing time may all play a role in these variable circumstances. In brief, SRAs are used to prevent concrete shrinkage caused by drying, because the interfacial region at which they must operate expands dramatically during drying [4]. Fig. 31 shows the summary of the influence of SRA admixtures in the relative shrinkage ratio as reported by numerous scholars.

### 4.4. Improving internal curing

Internal curing (IC) involves adding additional water reservoirs within the concrete mixture to provide a consistent and prolonged moisture supply to the cementitious matrix as it cures. In the context of AAC, improving internal curing means optimizing this technique to enhance the distribution of moisture within the concrete, which helps to counteract the shrinkage caused by the drying process. This is typically achieved by incorporating lightweight aggregates, superabsorbent polymers, or pre-soaked fine aggregates into the concrete mixture. These IC agents absorb water and release it gradually during the curing period, maintaining a more favorable moisture content within the concrete to minimize shrinkage and cracking.

In recent years, SAP serving as IC agents to minimize the shrinkage of AACs have attracted extensive research attention due to their superior shrinkage-mitigating impact and reasonable cost compared with other shrinkage decreasing techniques [2,74]. The effects of various SAP concentrations on AS for AAC mortars with various activators have been investigated [62], with results indicating that apart from successfully reducing the natural process of attrition in composites, SAPs can act as an IC agent to help the specimens stay hydrated by releasing the absorbed water, as clearly deliberated in Ref. [3]. As SAP concentration increased, the effect of decreasing shrinking became increasingly evident. The IC action of the SAP compensates for the lost free water and further prevents autogenous shrinkage [364]. Also, it also positively affects the development of strength in the AAC system [181]. Furthermore, SAPs can soak up part of the additional free water in the slurry, and they can subsequently release the water that they have soaked up into the composites during the hydration process [73]. This helps maintain a high level of internal RH in the composites. Moreover, adding 0.3% SAPs decreased the autogenous shrinkages of Na$_2$CO$_3$- and waterglass-activated pastes by roughly up to 70%, respectively. Day reported that the AAC paste porosity and shrinkage are decreased because SAPs can retain water within the paste and permit the further hydration of un-hydrated matrix particles, In contrast, the introduction of SAPs decreased the strength and electrical resistivity of the AACs. Enhanced w/b ratio and large voids are responsible for the lower shrinkage in AAC [181]. It has also been reported that pre-wetting the fibers before using them in an IC lumen structure can boost the efficiency of shrinkage prevention, especially at early ages [3].

Several scientists have investigated ways to reduce drying shrinkage, including adding mineral additions to chemical admixtures, fibers, alternative aggregates and changing external curing systems [214]. It is found that IC can considerably improve the strength, decrease autogenous shrinkage and enhance the final concrete product quality [365]. For moist treatment approaches, it includes IC and two popular types of external curing: fogging, water spraying, saturated coverings, or steam, and sealed curing, such as by coating, plastic sheeting, or membrane/compound curing [223]. The amount of autogenous shrinkage mortar experienced after being activated with Na$_2$CO$_3$ and water glass decreased by about 75% and 86% when 0.6% SAP was added to AAS mixes. The reduced shrinkage can be attributed to the enhanced IRH, which results from the SAP replenishing the slurry’s early water loss. According to a study, Na$_2$CO$_3$-activated mortars show less shrinkage than waterglass-activated mortars, while Na$_2$CO$_3$- and waterglass-activated AAC pastes showed similar autogenous shrinkages [62]. Besides, Na$_2$CO$_3$ activated pastes only shrink by 0.22 times as much as waterglass activated pastes, while AAS length and weight.
variations at 50% RH and 70% RH with varied amounts of gypsum or CaO incorporation were negligible (Fig. 32). [63].

In addition, some synthetic activators in alkali-activated binders cause most of its environmental problems. Thus, to evaluate the life cycle of alkali-activated mortar (AAM) made from industrial waste precursors and activators using ReCiPe 2016 [366]. Replacement of fly ash and slag with waste ceramic powder (WCP) and red mud (RM) and traditional activators (sodium silicate (SS)) and sodium hydroxide (SH) with RM, desulfurization dust, and silica fume has environmental consequences. AAM using conventional activators depletes fewer resources due to lower activator dosages and no pretreatment of fly ash. ReCiPe can assess all effect categories except freshwater ecotoxicity and human toxicity, which USEtox recommends. A sensitivity study demonstrates that membrane cell SH generation is eco-efficient. Replacing precursors and activators with industrial leftovers saves up to 14%. AAM with silica fume and sodium hydroxide activators had the lowest impact on ecosystem quality and human health, according to ReCiPe. The M2 and M7 have the lowest resource depletion and environmental impact.

Furthermore, including fiber in concrete can yield positive outcomes in terms of compressive and tensile strength. However, these benefits are typically observed when short fibers with high stiffness are utilized in significant quantities, allowing them to be activated by micro-cracks before reaching the failure load [367]. Moreover, it is crucial to restrict the viscosity and number of compaction voids in the fresh concrete for optimal results. The inclusion of steel fibers or macro-PP fibers did not substantially enhance compressive and tensile strength, likely due to the utilization of specific significant fiber and viscous binder ingredients [368]. An increase in flexural tensile strength may be observed when the fiber content and stiffness reach a sufficiently high level and when the fracture behavior at the matrix peak permits micro-cracks development. The presence of overlapping factors posed a challenge in the characterization of the fracture-mechanical behavior. Nevertheless, the steel fibers with low contents have a flat surface, resulting in diminished bond strength. When micro-cracks occur, little fibers with high stiffness and an optimum cross-sectional shape (such as being coiled, thicker, or having hooked ends) can be effectively engaged [368]. In brief, the SAP method is a beneficial strategy for reducing the autogenous shrinkage of the AAC system because it helps improve the interaction between different materials used to learn more about how drying shrinkage works.

4.5. Reduction of pore solution’s surface tension

Reduction of pore solution’s surface tension is a strategy used to mitigate shrinkage and cracking in concrete, including alkali-activated concrete. Pore solution refers to the liquid phase present within the pores of the cementitious material, which consists of water, dissolved ions, and various chemicals produced during the hydration process. Surface tension is a property of liquids that causes their surfaces to behave like a stretched elastic membrane. In the context of concrete, high surface tension of the pore solution can contribute to shrinkage and cracking. It is found that when the surface tension is high, the liquid at the surface tends to pull inward, leading to the development of capillary forces. These capillary forces can cause the concrete to contract as it dries, resulting in the formation of cracks. By reducing the surface tension of the pore solution, these capillary forces are weakened, and the tendency for the concrete to shrink and crack is diminished. This can be achieved by introducing certain chemical admixtures, surfactants, or additives into the concrete mix. These substances work by altering the molecular properties of the pore solution, reducing its surface tension and improving its ability to maintain a more uniform distribution within the concrete matrix.

Given that the majority of SRAs greatly diminish the as a result of their effect on the surface tension of the pore solution in cement paste, they affect all other aspects of physical variables, such as internal RH, capillary stress, and freezing point depression, depending on surface tension [369]. Most of the SRA comprises amphiphilic molecules, which are known to reduce the amount of shrinkage-related deformation and cracks in AACs [212]. It is found that reducing early shrinkage was achieved through a combination of slower cement hydration due to the adsorption of SRA molecules onto portlandite and the resulting slowing of crystal formation [129]. SRA may reduce shrinkage through the
following mechanisms: 1) maintaining high internal RH and decreasing self-desiccation [370], and 2) increasing Ca\(^{2+}\) concentration and over-saturating ettringite and portlandite [214]. It firstly was hypothesized that the addition of SRA slowed hydration by decreasing the alkalinity of the pore solution [64]. SRA and the pore solution in cement paste can impact AACs. Capillary stress is alleviated in part because the surface tension of the pore solution is lowered [212].

Meanwhile, the combined use of SRA and SAP is typically advised due to the negative effects on becoming hydrated and building muscle rapidly [371] and additional entrainment loss in the case of single-user SRAs [59,370]. Therefore, it is suggested that SRA and SAP be used in a hybrid fashion. Particular attention is paid to combining 2% SRA and 0.3% SAP in high-strength concrete as the most effective approach for minimizing drying shrinkage [212,246]. It is reported that the decrease of shrinkage achieved by utilizing SRA in high-strength concrete was greater than that achieved using wollastonite and EA [354,372]. However, the fall rate slightly dropped as SRA content increased from 1% to 2% [212]. The effectiveness of SRA was examined at various temperatures, and it was discovered shrinking might be minimized to a greater extent at 40 °C than at 10 °C or 20 °C [358]. At high temperatures, water is consumed at a rapid rate, whereas water released from SRA either persists or is absorbed at a slower pace, showing a higher efficiency in these conditions. Additionally, when the weather went from 40 °C to 0 °C, pure water’s surface tension increased by around 1.09, according to Ref. [373]. Further, the type of application of AAFAC and the percentage of application is depicted in Fig. 33 [374].

5. Conclusions

Shrinkage occurs when concrete lacks moisture content. It is considered an inherent characteristic of composite materials that could cause unequal distortion and result in dangerous fissure formations. The serviceability and durability of reinforced concrete structures are negatively impacted by these cracks, which also compromise the completeness of the structures’ reinforced concrete components and make the composite material susceptible to the seepage of dangerous chemicals. It is reported that sustainable alkali-activated materials (AAM) such as fly ash, rice husk ash metaakolin, silica fume, slag, and red mud are prospective replacements for ordinary Portland cement (OPC) in the development of the sustainable alkali-activated concrete (AAC), which is utilized in a wide range of construction applications. Although these sustainable composites have evolved over time, their significant shrinkage still limits their applicability. In particular, shrinkage deformation caused by moisture migration is a key problem in cementitious materials. It can increase the likelihood of cracking, resulting in a reduction in long-term efficiency and service life. However, the main objective of this article is to perform a robust evaluation of shrinkage behavior and shrinkage alleviation strategies of sustainable alkali-activated concrete. Based on the major findings of this up-to-date critical review of the developments trends of sustainable AACs research over the past 20 years. Several points as conclusions were highlighted as follows:

5.1. General conclusion for shrinkage

- AAS’s drying and plastic shrinkage is much greater than OPC binders. Increasing drying shrinkage is possible when using finer slag aggregate. Denser gels are produced when more reactive SCMs, such as silica fume, lead to higher capillary tension due to the water meniscus and, in the end, more significant dry shrinkage due to the increased hydration products and gel pores.
- Compared to the OPC control mortar, the mechanical performance of the AAS mortars was superior, and the drying shrinkage of the AAS mortars decreased with increasing fibre dosages. Integrating deformed-shaped fibres, such as those with corrugated and hooked-end morphologies, significantly decreased shrinkage due to a strong anchoring effect compared to the other fibres. Also, the lower stiffness of PPF and the marginally poorer bond between the PPF and matrix can be blamed for the inferior performance of composites with high PPF content compared to SF composites.
- Due to its high aspect ratio and low water absorption rate, broken glass is a highly effective replacement for conventional aggregate in reducing drying shrinkage. However, including glass exacerbated the negative impact on the growth of the alkali-silica reaction. On the other note, submerging the part in HCl acid, washing it with distilled water, and coating it with CaSiO\(_3\) all help improve the quality of RCA by lowering the drying shrinkage.
- Much more autogenous shrinkage occurs in AAM systems than in OPC ones. However, the well-known self-desiccation approach may not apply to the autogenous shrinkage mechanism in AAFS systems within the first 24 h because of a potentially unique chemical reaction after casting.
- Compared to OPC, which exhibits monotonic chemical shrinkage after casting, metakaolin-based AAC (MK-AAC) exhibits a drastically different chemical deformation history. The increasing stiffness of the microstructure is likely responsible for the chemical shrinkage of MK-AAC in the late stages of polymerization, since it leads to greater tensile stresses on the capillary network of the pores.
- After being exposed to 7% carbon dioxide for 240 h, the carbonation depths in alkali silicate-activated slag concretes ranged from 4 to 25 mm. As NaOH-activated slag is less reactive and has a denser C–S–H gel composition, it is hypothesized that it is more amenable to carbonation than Na\(_2\)SiO\(_3\)-activated slag. The carbonation rate in AAS systems appears higher than in OPC systems due to the lack of calcium hydroxide.
- Reducing the sodium silicate concentration in the alkali activator helps lessen the drying shrinkage of FA-AAC. Also, adding different fibres to conventional AAFA reduces dry shrinking. Since broken glass has a high aspect ratio and a low water absorption rate, it can replace coarse aggregate to prevent drying shrinkage. The best results were seen with PEG having molecular weights between 2000 and 10,000, with a possible 25% reduction in drying shrinkage at a PEG inclusion of 2%.
- Since SRA molecules adsorb onto portlandite, cement hydration slows crystal formation, resulting in less early shrinkage. When comparing the efficacy of different methods for reducing shrinkage, using magnesium oxide and calcium oxide as EAs is preferred over adding gypsum. MgO mitigated the drying shrinkage to a much greater extent than autogenous shrinkage, but the modulus of sodium silicate also had a role in this.

\(<\text{Reduction in shrinkage}>\)

- Matrix type, SRA type, alkaline content, and curing circumstances may reduce shrinkage, which is the volume loss of binders at constant temperature and with no external pressures. Alkali-activated binders have substantial shrinkage due to pastes’ high mesopore content and reaction products’ absence of crystalline phases (e.g., AFt, AFm, and CH). Many pozzolans can be utilized to minimize the shrinkage of AAC composites. This is because AAC’s compressive strength showed that the pozzolanic reactions of pozzolan caused it. During pozzolanic processes, the gel compacts the adhesive’s porous structure, increasing compressive strength.

\(<\text{The general conclusion for using fibers}>\)

- Fiber insertion improves drying shrinkage resistance due to its high modulus of elasticity and strong binding. AACs soaked with calcium water shriveled considerably after drying, whereas other waters did not. Palm oil fuel ash and steel slag reduce AAC shrinkage by 50%. In summary, corrugated and hooked-end fibers decreased shrinking due to a significant anchoring effect. This phenomenon is caused by interlocking particles that resist deformation.
- PPFs accelerated the moisture loss by convection because their hydrophobic properties, in conjunction with their smooth surface, deflected interior moisture outward. Evaporation accelerated. Fiber
6. Recommendation for the future work

Based on the findings of this extensive review, the following hotspot research areas have been identified and suggested for additional studies by scientists and scholars worldwide:

- The comprehensive overview discusses autogenous shrinkage, which can occur days after castings due to different internal structures of concrete, such as drying shrinkage, and why AAC shrinkage should be treated separately from early age cracking.
- A wider industry sector has not adopted the AASC due to its unreliable long-term durability and inadequate resistance to shrinkage and microcracking, corrosion and carbonation, and probable alkali-aggregate reactions.
- There is no relevant research to counteract the AASC’s shrinkage brought on by the hydrophobic alteration. Additionally, research on the CO₂ diffusion channel rarely touched on the impact of the AASC bulk paste’s pore structure on the carbonation rate.
- Learning how the IC mechanism contributes to drying shrinkage is crucial, and more studies are required. Additionally, there is no extensive research on the impact of IC on drying shrinkage when using lightweight or natural fibers.
- AAABs have been employed in numerous studies, although plastic shrinkage and bleeding properties have not yet been investigated.
- There are currently no theoretical reasons proposed for the autogenous shrinkage of AAS-FA on the first day after casting, variations in pore distribution, or possible impacts on the durability of AACs.
- The underlying reason for the size reduction, especially the autogenous reduction in AASC size, remains unclear, demonstrating the paucity of studies on the subject.
- Only a few studies have investigated RCSF, a potential replacement for commercial steel fibers in cement-based composites. Although the current findings are promising, more studies on the efficiency of RCSF-reinforced cementitious composites, particularly on durability performance, are required. Knowledge of the usage of RCSF in AAC is rare and still limited.

Proposed strategies to mitigate shrinkage

The amount of added slag also plays a crucial role, as adding more slag causes AACs to shrink more when dried. For example, drying shrinkage was reduced by up to 42% and 51% upon adding 35% and 60% FA, compared to its control mixes.

- The drying shrinkage of aggregate greatly depends on the material’s size and volume. Using large-size aggregate enhances the confinement’s influence on decreasing the drying shrinkage effects. When plastic granules are used as fine aggregate in AACs, the drying shrinkage may be decreased by as much as 72%. On the other hand, substituting coarse aggregate with plastic filler increases the drying shrinkage to increase.
- SRAs directly minimize drying shrinkage in AACs. This is accomplished by minimizing the growth of menisci and capillary pores during drying shrinkage while simultaneously limiting the deleterious impact on strength.
- As with PC composites, shrinkage in AAC composites may be controlled by internal curing. Lightweight aggregates and similar substances may induce regeneration from the inside out. Internal curing lessens drying shrinkage by adding water to the composites’ chemical reaction and decreasing the composites’ self-desiccation.
- Shrinkage in AACs may also be decreased by including coarse aggregate or increasing the proper coarse aggregate content. Adding coarse material to the AAS composite provides a constraint inside the matrix.
- Adding chemical additives such as magnesium oxide and calcium hydroxide results in drying shrinkage that is less severe. These chemical additions speed up the activation reaction, which causes the creation of products that fill the gaps and perform as restraints within the matrix. As a consequence, the drying shrinkage is reduced, resulting from the decrease in the shrinkage that occurs during the drying process.
- The effectiveness of these activators may be weakened by lowering their concentration. As a result, it is essential to guarantee that sufficient strength performance remains achieved even with a lower activator concentration.

Compliance with ethical standards

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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