Article
Mitigating Autogenous Shrinkage of Alkali-Activated Slag Mortar by Using Porous Fine Aggregates as Internal Curing Agents

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Abstract: Alkali-activated slag (AAS) is beneficial for resource conservation in that it consumes little primary industrial energy, and it also performs well in terms of its mechanical properties and durability. However, its higher autogenous shrinkage compared to OPC mortars is a serious issue impeding AAS-based binder development for practical applications. This study investigated the feasibility and performance of active recycled aggregates when applied as man-made internal curing agents (MAs) for AAS mortars. They were applied as aggregate replacements for sand in this study to investigate the effects on the autogenous shrinkage, internal relative humidity (IRH), compressive strength, hydration properties and pore structure of AAS mortars. Three MAs with the sizes of 0.63–1.25 mm (MA 0.63), 1.25–2.5 mm (MA 1.25) and 2.5–4.75 mm (MA 2.5) were used. The results showed that MAs have potential as internal curing agents to mitigate the autogenous shrinkage of AAS mortars. When using saturated MAs, the autogenous shrinkage of AAS mortars was reduced by 87.68%. The addition of MAs also significantly prolonged the critical time taken for the IRH to start decreasing from 100%.

Keywords: alkali-activated slag; internal curing; recycled fine aggregates; autogenous shrinkage; internal relative humidity

1. Introduction
Nowadays, alkali-activated slag (AAS) is one of the hottest topics surrounding greener binders in concrete research, not only because the production of AAS releases 25–50% less greenhouse gas than that of ordinary Portland cement (OPC) [1,2] but also based on a common view that AAS can achieve a similar or even superior performance to OPC concrete [3–5]. It is generally reported that AAS concrete possesses better resistance to acids, and has quicker setting times and a low hydration heat [3–5], which makes it suitable to be applied in extreme environments, such as for rapid repair, severe cold conditions, and in ocean engineering. However, substantial autogenous shrinkage occurs during the AAS hardening process. It was reported that the autogenous shrinkage of AAS concrete was as much as four to six times higher than that of OPC concrete [6]. The recorded autogenous shrinkage commonly passes thousands of micro-strains, depending on the mixing proportions and ages. In one instance, Vafaei et al. [7] found that the 28 d autogenous shrinkage of AAS activated by NaOH and Na2CO3 reached 2500 µε and 2700 µε, respectively. Tu et al. [8] recorded an excessive autogenous shrinkage of 7000 µε in 2 d for AAS activated by 10 M of NaOH/water glass solution. Non-uniform deformation occurs in the mortar due to autogenous shrinkage, then tensile stresses are formed and those induce harmful cracking. Not only does this reduce a structure’s durability but it also provides a path for...
various deleterious substances to penetrate the mortar and corrode the material inside the structure [9,10].

One of the fundamental theories is that the autogenous shrinkage of AAS is caused by the unsaturated capillary pores due to internal water loss during hydration (self-desiccation), forming tensile capillary stress [11]. The tensile capillary stresses in the capillary pores in microstructures arise when water is consumed during the reaction and partially replaced by empty pores, leading to the formation of menisci in the pores and pulling the solid skeleton of the material inward. Replenishing the microstructure of AAS with additional water to maintain a high relative humidity within the capillary pores has been regarded as the best choice to combat excessive autogenous shrinkage [3,7,8]. Using such a route to provide additional water is known as internal curing. For this process, water is either previously loaded or carried by water reservoirs. When the internal relative humidity of AAS drops, the internal curing water is released from the larger pores of water reservoirs into smaller capillary pores, driven by the relative humidity differences of large and small pores. In such a way, the self-desiccation of cementing materials can be mitigated, with water reservoirs acting as a key to implementing the expected internal curing of cement materials. Over the past decade, lightweight aggregates (LWAs) and superabsorbent polymers (SAPs) have been extensively studied as internal curing agents [12,13]. Beyond them, there have also been other attempts to use materials such as perforated cenospheres (PCs), crushed returned concrete aggregates, wood pulp, rice husk ash, and biochar as internal curing agents [14–18]. Sakulich and Bentz [19] proved that the autogenous shrinkage of AAS mortars activated by water glass or sodium carbonate can be mitigated by saturated LWAs. Song et al. [6–8] found that the addition of SAPs significantly mitigated the autogenous shrinkage of AAS mortars, nevertheless leading to decreased compressive strength. Chen et al. [2] confirmed that the autogenous shrinkage of AAS mortars can be eliminated by using water-filled materials. Van et al. [15] reported that the water carried by rice husk ash improved the compressive strength and mitigated the autogenous shrinkage of ultra-high performance concrete.

Recently, researchers found that coarse recycled aggregates (CRAs) are another potential internal curing agent. Saturated CRAs have been applied to reduce the autogenous shrinkage and prevent the early cracking of OPC or AAS materials [20]. Kim and Bentz [14] investigated and found that 75% of the internal curing water was released from CRAs at an 80% RH, contributing to mitigated autogenous shrinkage. Lee et al. [3,21] reported that CRAs were effective at mitigating the autogenous shrinkage of both AAS and OPC high-performance concrete.

In addition to CRAs, recycled fine aggregates (RFAs) have occasionally been mentioned as internal curing agents for AAS mortars. These may be more suitable than CRAs to internally cure AAS mortars due to their smaller particle sizes and higher water absorption rates of between 13.1 and 14.05% [22,23]. Li et al. [24] reported that 27.78–35.22% of absorbed water was released from RFAs at a 93% RH, greatly reducing the autogenous shrinkage of OPC mortars. Jesus et al. [25] found that the addition of RFAs was beneficial for the development of the compressive strength of OPC mortars.

In this study, in view of the unstable characteristics of SAP desorption (which leads to great strength reduction [26]), the wide sources of LWA with different properties, and the complex PC manufacturing process, cement was used to prepare standard man-made internal curing agents (MAs) in order to produce active internal curing technology with controllable absorption and desorption, low costs, and easy standardization. We sought to examine the effects of MAs on the autogenous shrinkage, internal relative humidity (IRH), compressive strength, hydration properties, and pore structure of AAS mortars. Three MAs with different particle sizes (0.63–1.25 mm, 1.25–2.5 mm and 2.5–4.75 mm) were prepared and compared. Characterization analysis of those MAs was initially conducted on their chemical compositions and water absorption and desorption properties. Scanning electron microscope (SEM), mercury intrusion porosimetry (MIP) and X-ray diffraction (XRD) analyses were then conducted to reveal the mechanisms of internal curing.
2. Materials and Methods

2.1. Raw Materials

We used ground granulated blast furnace slag (GGBS) corresponding to grade S105 [27]. Table 1 lists its density, BET area, and chemical composition. Figure 1 presents its particle size distribution, indicating that the average particle size is around 18 μm. The activator used in this study was NaOH solution; the sodium oxide equivalent (Na₂O-E) is 10%. Cement mortar was the raw material used for preparing MA. The cement mortar was cured for 7 days at 23 ± 2 °C and >95% relative humidity. The mix proportion and compressive strength of the cement mortar are shown in Table 2. The hardened cement mortar was crushed to particles of less than 4.75 mm. The fineness modulus of MA is 2.57, and its gradation belongs to Grade II, while the apparent density and crushing index are 2390 kg/m³ and 23, respectively. Then, the MA was simply dried in the laboratory at 20 °C. Those dried particles were screened for three ranges: 0.63–1.25 mm (noted as “MA 0.63”), 1.25–2.5 mm (noted as “MA 1.25”) and 2.5–4.75 mm (noted as “MA 2.5”). Figure 2 presents their digital images. Table 3 shows the 24 h water absorption rates of the three MAs. The data suggest that MAs with smaller particle sizes possess larger water absorption rates, which are beneficial for providing additional water to internally cure AAS pastes. Figure 3 gives the MIP results for the MAs to characterize their pore structures. It can be seen from this figure that the pore sizes of MAs depend on their particle sizes. Normally, the pore sizes of the three MAs are distributed <100 nm, and smaller MA particle sizes present a higher total porosity. Sand was collected from the Huaihe River, with a fineness modulus and apparent density of 2.56 and 2650 kg/m³, respectively.

Table 1. Density, BET area and Chemical composition of GGBS.

|        | Density/kg/m³ | BET Area/m²/g | CaO | SiO₂ | Al₂O₃ | MgO | Fe₂O₃ | TiO₂ | K₂O | LOI |
|--------|---------------|---------------|-----|------|-------|-----|-------|------|-----|-----|
| GGBS   | 2800          | 1.535         | 43.7| 26.5 | 18.2  | 4.9 | 1     | 1    | 0.8 | 3.9 |

Figure 1. Particle size distribution of GGBS.
Table 2. Mix, properties of MAs and compressive strength of MAs.

| Mix/kg/m³ | Compressive Strength/MPa |
|-----------|--------------------------|
| Cement    | Water | Sand | 3d  | 7d  | 28d |
| 547       | 275  | 1430 | 23.18| 30.08| 35.12|

Table 3. Properties of MA.

| Sizes/mm | Specific Density/g/cm³ | Water Absorption/% |
|----------|------------------------|--------------------|
| MA 0.63  | 0.63–1.25               | 2.40               | 15.41             |
| MA 1.25  | 1.25–2.5                | 2.42               | 12.16             |
| MA 2.5   | 2.5–4.75                | 2.38               | 11.92             |

Figure 2. Digital image of MAs.

Figure 3. Pore distribution for MAs with different particle sizes: (a) differential distribution curve; (b) cumulative distribution curve.

Figures 4 and 5 show the XRD spectra and TGA of the MA, respectively. These indicate that the MA contains quartz, CH, calcite and margarite as its major constituents, while the CH content is 25.1% by calculation.
2.2. Mix Proportions

To investigate the effect of internal curing by MAs on the autogenous shrinkage and mechanical strength of AAS mortars, two series of mortars were manufactured. Series A added a constant quantity of additional water in all mixtures, where the ratio of extra water to bind (wa/b) was 0.2. In series B, the sand was completely replaced by MA, as shown in Table 4. Internally cured mixtures were coded as A x or B x, with x meaning the kind of MA. Before mixing, MAs were saturated through immersion in tap water for 24 h, then the surface water was wiped off using a wet towel.
Table 4. Mix proportion of AAS mixtures (kg/m$^3$).

| Mixtures | GGBS | Activator | Sand | MA | Additional Water |
|----------|------|-----------|------|----|------------------|
| Control  | 616  | 308       | 1276 | 0  | 0                |
| A 0.63   | 616  | 308       | 396.02 | 800 | 123.20           |
| A 1.25   | 616  | 308       | 170.74 | 1013.16 | 123.20         |
| A 2.5    | 616  | 308       | 234.65 | 1032.69 | 123.20         |
| B 0.63   | 616  | 308       | 0     | 1160.03 | 178.76           |
| B 1.25   | 616  | 308       | 0     | 1169.67 | 142.23           |
| B 2.5    | 616  | 308       | 0     | 1150.38 | 137.13           |

2.3. Test Methods

2.3.1. Absorption and Desorption Rates of RFAs

The water absorption of the MAs was determined according to ASTM C 128-15 [28]. The MAs were first immersed in water for specified times—30 min, 1 h, 3 h, 6 h, 12 h and 24 h—at room temperature (23 °C). At each time point, about 150 ± 10 g wetted RFA was collected and wiped off using a wet towel, to achieve surface-dry MAs. Finally, the surface-dry MAs were oven-dried again until their weight was constant. By calculating the mass changes of the surface-dry and dried MAs, the water absorption rates could be obtained. The water desorption of RFAs can be described by the mass loss with a function of relative humidity (RH). According to ASTM E104 [29], about 20 g of surface-dry RFAs were placed in an environmental chamber for 5 d under different RHs built by saturated salt solutions. The desorption rates were thus calculated by the mass change of the RFA samples. Saturated salt solutions were used to control the RH evolution.

2.3.2. Flow

The flow of AAS mortars was measured according to ASTM C1437 [30] using a flow table. A circular truncated cone mold was uniformly filled with fresh mortars, and the surface flush with the top of the mold was planes by straight edge before moving the mold, immediately dropping the flow table 25 times at a constant frequency. The flow value of each mixture was measured by the average diameter along two orthogonal directions, thereby evaluating the workability of AAS mortars.

2.3.3. Internal Relative Humidity

To monitor the IRH changes of AAS mortars with and without RFAs, capacitive-type relative humidity sensors provided by Vaisala Oyj Co. were used. In a typical procedure, fresh mixture was cast into a cylinder mold with the sizes of $d \times h = 50 \times 100$ mm. Previously, we placed a plastic sleeve at a depth of 50 mm and the wall was replaced by polyester net fabric. The data collection and recording started at 5 min after mixing.

2.3.4. Compressive Strength

According to ASTM C349 [31], AAS mixtures were cast into 50 mm cubic modules. The mortars were cured under the standard curing environment in a moist curing room at $23 \pm 2$ °C and 95% RH. The compressive strength of the AAS mortar was determined using a hydraulic compression tester at 3, 7, 28 and 56 days, and reported by taking the average of three cubes.

2.3.5. Autogenous Shrinkage

According to ASTM C1698 [32], corrugated plastic tubes with a size of Φ37 × 420 mm were filled with fresh mixtures and sealed at both ends. After a final set, the distance between the two tips was measured as the initial length by a dial indicator, then subsequently placed in a standard curing room, where measurements were taken twice daily for the next
33 days. The autogenous shrinkage at each measurement time was calculated according to Equation (1):

\[ \varepsilon = \frac{(L_T - L_O)}{L_O} \times 10^6 \]  

where \( L_O \) is the initial length at the final setting time of the sample, and \( L_T \) is the length at the measuring time. For each mixture, triplicate samples were obtained and the averaged value was taken to reduce random errors.

2.3.6. Pore Structure Testing and Interfacial Transition Zone (ITZ) Characterization

An AutoPorIV 9510 series pore-size analyzer produced by the Micromeritics Instrument Corporation was used for the MIP test of AAS mortars. The samples collected after further hydration and oven-dried at 105 °C for 24 h before testing. Gemini 300 with an acceleration voltage of 10 kV was employed to provide the microstructure. Before testing, the specimens were wrapped in epoxy resin, and the surfaces were polished with 600-, 1200-, 3000-, 5000- and 7000-grit emery paper.

3. Results and Discussion

3.1. Absorption and Desorption Rates of RFAs

The water absorption rate of a water reservoir is highly related to the internal curing efficiency and the compressive strength of AAS mortars [3,8]. Figure 6 presents the water absorption and desorption rates of different RFAs. As can be seen from Figure 6a, MAs absorbed water quickly, and more than 80% of their saturation occurred during the first hour. The 24 h water absorption rates of MA 2.5, MA 1.25 and MA 0.63 were 11.92, 12.16, and 15.43%, respectively. It can thus be seen that the water absorption rates of MAs differed with their particle sizes. Smaller RFAs with larger porosities exhibited higher water absorption rates.

In addition, in internal curing systems, water loaded in MAs should be released to be readily available to the surrounding pastes even under a high IRH. In this regard, it is necessary to understand the water desorption performance of MAs, as shown in Figure 6b. It can be seen that at a 94% RH, MA 0.63, MA 1.25, and MA 2.5 released 29.14, 34.05, and 39.35% of the absorbed water. Then, at 70% RH, 67.42% (MA 0.63), 56.25% (MA 1.25), and 59.56% (MA 2.5) of the carried water was released. This indicates that MAs with hydrated or unhydrated, as well as mesoporous cement grains, impeded the transportation of absorbed water.
3.2. Flow

Figure 7 shows the flow of fresh AAS mixtures with MAs. It can be seen that the addition of MAs enlarged the flows of mortars, which increased with decreased particle sizes of MAs. This suggests that the additional water entrained within MAs was released into the surrounding pastes after being added. Such released water increased the thickness of the water film, thereby contributing to improved flow values. For series A, the wa/b of each group was the same, but the flowability differed greatly; a larger particle size with an irregular shape negatively affected the flowability.

![Flow of AAS mixtures.](image)

Figure 7. Flow of AAS mixtures.

3.3. Autogenous Shrinkage

Figure 8 shows the autogenous shrinkage of mortars with different MAs over time. For the control without an internal curing agent, the autogenous shrinkage developed rapidly with elapsed time. The recorded value for the control was 1242.85 με at 28 d, and the final value in the measurement range was 1416.67 με. Such autogenous shrinkage of AAS is significantly larger than that of OPC-based materials by six times or more [6]. This means that AAS is more sensitive to cracking due to autogenous shrinkage. As expected, the benefit of internal curing for mitigating the autogenous shrinkage of AAS mortars was confirmed by using MAs. It can be seen from Figure 8 that for the internal curing mixtures of series A and B, the autogenous deformations were expansive in the initial period. This expansion was noted by Bentz [19] and Chen [2] in their studies. The reasons were explained as thermal expansion, the formation of expansive hydration products, and internal curing. Often, the autogenous shrinkage of internal curing groups developed quickly, with an almost linear trend. Compared to the control, the autogenous shrinkages of the experimental group were reduced by 42.85% (A 0.63), 23.11% (A 1.25), 20.95% (A 2.5), 87.68% (B 0.63), 58.32% (B 1.25), and 60.45% (B 2.5), respectively.

In series A, due to the different water absorptions of the MAs, the same wa/b was guaranteed by replacing part of the sand with three kinds of MAs. Mortars incorporated with MAs with smaller sizes exhibited a superior internal curing performance. Since MA 0.63 had more large pores with a lower capillary stress of water, water was more easily desorbed from the MA to relieve self-desiccation of the mortars [24]. Yet, as an active internal curing agent, the MA will have continued to hydrate so that the pathway of water desorption could be plugged by the reaction products [3]. Thus, the water in the larger particles could not be well-desorbed, resulting in a disadvantageous effect on autogenous shrinkage reduction. As shown in Figure 6b, less water was released from larger than smaller particles.
In series B, sand was completely replaced with the same volume of one of three kinds of MA. There was more of an effect on reducing autogenous shrinkage with MAs with higher absorption capacities. Compared to the control, autogenous shrinkage decreased to 12.32% for mortar with MA 0.63 because the water absorption of MA 0.63 was higher, meaning it was adding more water to the mortar. Yet, for another reason, smaller particles were distributed better. As shown in Figure 9, it was more likely that a higher volume of mortar would obtain water from MAs with a smaller distance between aggregates [33], which ensured a better internal curing performance. In previous studies [2,26], the autogenous shrinkage of AAS could be totally eliminated by SAPs and the cenosphere; B 0.63 could not achieve the same effect, even though the wa/b was higher. This was related to the difficulty of releasing all the extra water from MAs.

Figure 8. Autogenous shrinkage of AAS mortars different RFAs.

Figure 9. Schematic diagram of cured zone.

3.4. IRH of AAS Mortars

IRH is one of the most significant indicators of the working performance of internal curing agents within AAS mortars. Figure 10 presents the IRH curves of the specimens. For the control, the initially recorded IRH was 99.79%, which substantially decreased over time to about 70% at 20 h on account of the rapid rates of hydration and self-desiccation of mortar.
Capillary pores [6]. Such a quick recession of IRH caused significant capillary tension as well as substantial autogenous shrinkage, as can be observed from Figure 8. MAs helped maintain a higher IRH of AAS mortars, and the critical times when IRH started to decrease were delayed. This suggests that the internal curing water entrained in MAs was released into the surrounding pastes. Hence, capillary pores that suffered self-desiccation were replenished. This is important for AAS materials since they normally have finer pore sizes than those of OPC-based materials [34], and the capillary tension induced by the meniscus of fine pores enlarges and leads to excessive autogenous shrinkage [35], as can be seen in Figure 8. By adding MAs, the water loss caused by active hydration between binders and activators in the early stage of the mortars can be effectively compensated for. Therefore, the incorporation of MAs is necessary to combat the material defects of excessive autogenous shrinkage of AAS mortars as well as low IRH. As the hydration process slows, the water absorbed from MAs decreases, resulting in a relatively slow compensation rate of IRH in the later period from the MAs.

![Internal relative humidity of AAS pastes.](image)

The results show that the IRH decreases in A 0.63, A 1.25, and A 2.5 were 12.82, 17.36, and 19.56%, respectively. This indicates that water was more easily released from smaller particles. MA 0.63 had more large pores, meaning the extra water was more likely to be released, driven by the humidity gradient, as shown in Figure 6b. Another possibility is that the pathway of water desorption from large inner particles is longer and easier to plug. Thus, the IRHs of AAS mortars incorporated with larger MAs could not maintain a higher rate. Furthermore, when sand was completely replaced by the same volume of MAs, the IRH dropped by 5.19% (B 0.63), 7.73% (B 1.25), and 7.87% (B 2.5), respectively. This clearly shows that series B maintained a higher IRH than series A, which contributed to there being more water on the MAs, meaning the extra water could fill more capillary pores and better inhibit self-desiccation. In addition, both A 0.63 and B 0.63 maintained a higher IRH on account of MA 0.63 having a higher surface area, which benefits the released water [24].

### 3.5. Compressive Strength

Figure 11 presents the 3, 7, 28, and 56 d compressive strengths of the mixtures. The 3 d compressive strengths of all test groups developed quickly and were as high as about 70% of the 28 d compressive strength. AAS materials are well-known for having high early-age strength [36]. At 3 and 7 d, the compressive strength of AAS mortars decreased accordingly with the addition of MAs, which we attribute to the three following reasons: (1) microcracks
will occur when the MA is broken and screened, resulting in reduced mechanical strength; (2) as an active internal curing agent, the compressive strength of the MA at an early curing age is lower than that of a natural aggregate; (3) the extra water released from the MA may cause a pH value decrease of the alkaline activator and increase the water-to-binder ratio. This phenomenon is more obvious with the increase in the MA replacement rate. As hydration develops, the compressive strengths of some mixtures were comparable to the control at 28 d, such as A 1.25, A 2.5, and B 2.5. The effect of the MA in compressive strength on the 56 d test was better than early age, and even more than the control. In existing studies [7,10,37,38], the compressive strengths of mixtures were reduced by SAPs and LWAs because large voids were generated when water was desorbed, but this was not the case when using MAs. Moreover, the sharp edges and corners of MAs were removed during crushing and screening, with the benefits of alleviating stress concentration in the mortars. Therefore, the problem of compressive strength decrease could be eliminated through internal curing by MAs.

![Compressive Strength of AAS Mortars](image)

**Figure 11.** Compressive strength of AAS mortars.

A more important reason for using MAs as internal curing agents is that unhydrated cement grains are found in MAs, which contribute additional hydration products to hydrate AAS mortars; the grains, as such, may fill the interfacial pores and strengthen the interface [39,40]. The compressive strength increase rates of groups with internal curing were higher than for the control, which suggests that the contribution of MAs to compressive strength was apparent after 28 d. However, the compressive strengths of A 0.63 and B 0.63 decreased significantly, which may have been caused by the particle sizes being too small and the skeleton effect not being obvious.

### 3.6. Pore Structure

Existing studies showed that the further hydration of binders around the internal curing agent was facilitated and a denser microstructure was produced due to extra water release [39–41]. Figure 12 describes the pore distribution of mixtures at 28 d. In Figure 12, the volume of pores is increased by internal curing; this makes sense because an MA is a porous structure. It can be seen that MA internal curing had no obvious effect on the macro-pore contents of AAS mortars. Meanwhile, for pores ranging from 10 to 100 nm, the difference began to widen dramatically and observably with an increase in the MA replacement. There may be two reasons for this: (1) as the hydration degree of AAS was...
promoted by the released internal curing water, the volumes of gel pores of less than 10 nm increased, (2) the MA is porous, with pores ranging from 10 to 100 nm (Figure 3).

![Pore volume distribution of mixtures.](image)

Figure 12. Pore volume for mixtures at age of 28d.

The pores could be classified into harmless (smaller than 20 nm), less harmful (20–100 nm), harmful (100–200 nm) and very harmful (larger than 200 nm). Figure 13 summarizes the percentages of four pore-size distributions of pore volume. It clearly shows that the harmful and very harmful pore percentages of internal curing mixtures were lower than those of the control, even though those cumulative pores were higher. The results indicate that MAs increase the porosity while basically being harmless. However, pores smaller than 100 nm did not contribute to the extra water transport in the mortar due to the influence of capillary stress [41,42], which has the downside of mitigating autogenous shrinkage.

![Pore volume distribution of mixtures.](image)

Figure 13. Pore volume distribution of mixtures.

We studied every mixture’s microstructure of the ITZ and found that there were similarities. A typical SEM image was chosen, as shown in Figure 14, the cracks may sample manufacturing process. In early research, the released internal curing water promoted
the hydration of AAS and contributed to more gel production to fill the pores of AAS mortars [40] and enhance the ITZ density [39]. However, it can be noted from Figure 14 that the narrow ITZ of old and new pastes had few continuous pores; this was due to the internal curing water released from MAs, which increased the w/c ratio in this area, resulting in the water film effect, as well as a weak interfacial adhesion. This may explain why the mortar with MA 0.63 had a lower compressive strength. Nevertheless, this phenomenon fell away when the distance of the MA was furthered. In summary, even mixing and appropriate distances of MAs will enhance the interfacial adhesion of old and new pastes.

Figure 13. Pore volume distribution of mixtures.

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4. Conclusions

This study investigated the feasibility and performance of using three particle sizes of man-made internal curing agents (MAs) to mitigate the autogenous shrinkage of alkali-activated slag mortar. We assessed the workability, absorption and desorption rates, internal relative humidity, autogenous shrinkage, and compressive strength. Based on the experimental results, the main conclusions which can be drawn are as follows:

1. MA is an effective internal curing agent to overcome the autogenous shrinkage of alkali-activated slag mortars. Its desorption ranged from 59.56 to 67.42%, depending on the sizes at a 70% relative humidity. The water carried by MAs can be released to be readily available when mixed with alkali-activated slag mixtures or exposed to environments with a higher relative humidity.

2. About 58.32 to 87.68% of the autogenous shrinkage of alkali-activated slag mortars could be reduced by incorporating saturated MAs. The effect became more significant as the MA particle size decreased, as smaller particles will introduce more additional water to the surrounding mortar. The internal curing water that was released helped to maintain the internal relative humidity at higher than 80% within the microstructure of alkali-activated slag mortars and significantly prolonged the critical time when the internal relative humidity started to decrease from 100%. Mortars incorporated with MAs with smaller sizes exhibited a superior mitigation of the autogenous shrinkage.

3. MAs are pozzolanic materials and continue to hydrate with an alkaline activator, which can compensate for the early compressive strength reductions. The pore structure of series A and B became more refined, and the percentages of finer pores increased versus the control. At 56 d, the compressive strengths of alkali-activated slag mortars with MAs were close to those of the reference mortar.
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