# Use of recycled aggregates as internal curing agent for alkali-activated slag system

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## HIGHLIGHTS

- RA could be used as an internal curing agent for an AAS.
- RA could reduce autogenous shrinkage.
- Pore structure of RA influenced to internal curing efficiency.
- Strength of AAS was not degraded by RA.

## ARTICLE INFO

## ABSTRACT

This study aims to investigate the feasibility of recycled aggregates (RA) as an internal curing agent for an alkali activated slag (AAS) system. The physical and chemical characteristics of the aggregates were studied through various analytical techniques including X-ray diffraction, thermogravimetry, mercury intrusion porosimetry, and indirect alkalinity measurements. The compressive strength, degree of hydration, and autogenous and dry shrinkages of AAS generated with RA were measured and compared with those of AAS made using artificial lightweight aggregates. The use of RA can reduce the autogenous shrinkage of an AAS system without a decrease in compressive strength. The degree of hydration for AAS mortar was not increased by the addition of RA owing to the dilution effect of the alkali activator, which was caused by the additional water supplied from internal curing materials.

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## 1. Introduction

Although ordinary Portland cement (OPC) is an optimized inorganic binder for modern construction, some limitations and disadvantages still remain in terms of its technical, environmental, and economical standpoints. Alkali activated slag (AAS), a synthetic alkali aluminosilicate material made from solid aluminosilicate with a highly concentrated alkali activator, can be an alternative OPC binder [13]. Compared with OPC, AAS requires less energy for the manufacturing process, which is associated with carbon emissions [38]. Moreover, it has many advantages including a low hydration heat evolution and high acid resistance, which cannot be achieved using OPC [34,3,43].

However, one of the major disadvantages preventing the utilization of an AAS binder system is autogenous and dry shrinkages that are considerably greater than those of OPC [24]. Although the mechanism of this phenomenon is not fully understood to date, it has been considered to be attributed to the following characteristics of an AAS system: finer micropore structures, a lower stiffness, and lack of shrinkage-sustainable hydration products, i.e., ettringite and portlandite [36,11,7,8,22,40,41]. Most of all, the theoretical chemical shrinkage of AAS was shown to be about twice that of OPC [35]. The larger chemical shrinkage associated with AAS hydration is likely related to the glassy nature of the slag itself, which results in a relatively low atomic packing density of an unhydrated material [35]. In addition, owing to a rearrangement and reorganization of layered sheets of a calcium-aluminasilicate-hydrate (C-A-S-H) gel under capillary stress, the dry shrinkage of an AAS matrix is irreversible and permanent, i.e., a viscous behavior occurs, whereas that of an OPC matrix is semi-reversible through re-saturation, i.e., with an elastoplastic behavior [41,40].

Although the shrinkage mechanism of AAS slightly differs with that of OPC, researchers have attempted to utilize various methods

to mitigate the shrinkage of OPC for an AAS system. One promising method is applying saturated materials in the mixtures as a water reservoir, a so-called 'internal curing' [30]. This method is generally used to reduce autogenous shrinkage of high-strength OPC concrete because it can prevent the self-desiccation of the cement system with a low water-to-binder w/b) ratio [19]. Sakulich and Bentz [30] reported that the autogenous shrinkage of AAS mortar activated with water glass (liquid sodium silicate) or sodium carbonate can be mitigated through the addition of a saturated artificial lightweight aggregate, although the dry shrinkage is not reduced even through this mechanism. Song et al. [32] presented similar results using a super absorption polymer SAP). The water in saturated internal reservoirs can be transferred to the layered C-A-S-H sheets of an AAS system, which might reduce the capillary stress resulting in lower shrinkage [11]. It is worth mentioning that the chemical admixtures including a shrinkage reducing and expanding agent can also reduce the dry and autogenous shrinkage of an AAS matrix during an early age. However, some of the characteristics, such as the setting time, long-term strength, durability, and even the expansion potential of AAS with chemical admixtures can sensitively fluctuate based on their dosage and curing conditions [9,26,42,44].

Recycled aggregates (RA), i.e., crushed residue from old concrete structures, could be an alternative internal curing agent for an AAS system owing to its high water absorption. RA possesses many advantages in terms of availability, waste management, and economy compared with a conventional internal curing agent including artificial lightweight aggregates and an SAP. In a study by Kim and Bentz [21], crushed returned fine aggregates, i.e., artificial RA crushed from newly manufactured concrete, were applied for high-strength OPC concrete with a 28-day compressive strength of about 80 MPa. It was found that the aggregates can reduce the autogenous shrinkage by about one-half of the original OPC concrete, although this yields a decrease in the compressive strength to 50–66 MPa, i.e., a 63–82% reduction from the original concrete. Only in the case of a blended use of crushed returned fine aggregates and artificial lightweight aggregates, the autogenous shrinkage of the original concrete can be mitigated completely without any reduction in strength.

The effects of RA on an AAS system were expected to differ from those of an OPC system. The unhydrated cement portion in RA may stimulate the hydration of AAS system and densify the interface microstructures. On the contrary, the concentration of alkali activator in the AAS system may become diluted owing to the water absorbed in the RA, resulting in a decrease in the degree of hydration. Owing to this contradiction, it is not easy to expect the effects of RA on an AAS system without conducting proper experiments. Kathirvel and Kaliyaperumal [17] reported that a slight increase, i.e., less than 10%, of the compressive and flexural strengths of AAS concrete was found when 50 wt% of natural gravel was replaced with recycled coarse aggregates. To the best of the authors' knowledge, it is difficult to find published results on the effects of recycled aggregates for internal curing on the reduction of autogenous and dry shrinkages of an AAS system, which is the primary motivation of the present work.

In the present study, the feasibility of RA as an internal curing agent for an AAS system was experimentally investigated. Untreated RA having a particle size of 2–9.5 mm, obtained from a local construction waste disposal facility, was selected for this purpose. To understand the mechanistic effects of using RA on the performance of an AAS system, the physical and chemical characteristics of the aggregates were evaluated using various analysis methods including X-ray diffraction (XRD), thermogravimetry, mercury intrusion porosimetry (MIP), and indirect alkalinity measurements. By measuring the various properties of an AAS mortar including the compressive strength, degree of

hydration, autogenous and dry shrinkages, and drying mass loss, the effects of RA were evaluated and compared with those of artificial lightweight aggregates, i.e., a conventional internal curing agent.

## 2. Materials and experimental procedures

### 2.1. Materials

#### 2.1.1. AAS binder

Blast furnace slag (BFS) activated using powder-type sodium silicate was utilized as a binder in the present study. The BFS and sodium silicate used were supplied by the steel works of POSCO C&C, Inc. (Gwyangyang, South Korea) and Honam Chemical, Inc. (Seoul, South Korea), respectively. The weight proportions of BFS and sodium silicate were fixed to 90% and 10%, respectively, throughout the present work, and were determined based on a study by Yang et al. [39]. It should be noted that the powder-type sodium silicate could prevent an unwanted rapid setting which occasionally led by the liquid-type sodium silicate under high temperature [39]. The specific gravity and specific surface area of BFS were 2.90 and 4204 $cm^2/g$, respectively. The BFS used satisfied both the Korea Standard (KS) F 2563 Type 3 and ASTM C 989 Grade 100. The chemical composition of the BFS analyzed using XRF spectroscopy is presented in Table 1. The weight composition of the sodium silicate powder was 50.2% $Na_2O$ and 45% $SiO_2$ ($SiO_2/Na_2O$ with a molar ratio of 0.9. In addition, weight composition of sulfate ($SO_3$) was measured to be 2.8%, but some of it might be sulfide ($S^{2-}$) in actual [37]. The specific gravity and maximum particle size of the sodium silicate powder were 1.2 and 425 μm, respectively.

Fig. 1 shows the chemical shrinkage for three samples of both AAS paste and type I OPC paste. The binders of AAS paste were composed of 90% slag and 10% sodium silicate, and the w/b of the paste was 0.40. Type I ordinary Portland cement (OPC) paste, which satisfied both KS L 5201 and ASTM C 150–17, was also used with the same w/b as a reference. For this test, the slag and sodium silicate powder were dry-mixed first and then mixed with water. The measurements were conducted according to ASTM C 1608–12. Chemical shrinkage is calculated as the measured weight of sorbed water (mL) per gram of cement (slag in case of AAS paste). The chemical shrinkage per unit mass of cement at time t is computed as (ASTM C1608):

$$CS(t) = \frac{[h(t) - h(60\,min)]}{M_{cement}} \qquad (1)$$

Here, $CS(t)$ is the chemical shrinkage at time $t$ (mL/g cement) and $h(t)$ is the water level in the capillary tube at time $t$ (mL). The results indicate that, whereas the chemical shrinkage of the OPC paste with a w/b of 0.4 was converged to 0.05–0.10 mL $H_2O$/g binder after 1 week (170 h), the chemical shrinkage of AAS was about 0.24–0.33 mL in a $H_2O$/g binder at 5 weeks (900 h) and continuously increased even after that. It is worth mentioning that other papers have reported that the chemical shrinkage of AAS until 200 h reaches a level equivalent to or even lower than that of OPC [30,8,22]; however, this is not always true for a longer period. The atomic packing densities of slag particles and the sodium silicate are smaller than that of OPC particles, but C-S-H produced in the AAS is similar in proportion to that produced in OPC [35]. Therefore, in order to produce the same amount of CSH, a larger volume of the source materials should be consumed in the AAS, which led to greater chemical shrinkage. Moreover, the polymerization of C-S-H in the AAS results in further increase in the atomic packing density of the hydration products [36,12]. In addition, the