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DRYING SHRINKAGE OF ALKALI-ACTIVATED SLAG CONCRETE WITH NATURAL/RECYCLED AGGREGATES

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Abstract

Each year a large amount of construction and demolition waste (CDW) is generated in the European Union. For sustainability development the CDW is recycled and re-used. To promote the use of CDW, recycled aggregates from CDW were incorporated in alkali-activated concrete (AAC), which mainly consisted of secondary materials or industrial by-products. This study investigated the influence of recycled aggregates on workability, compressive strength and drying shrinkage of slag-based AAC. Properties of conventional concrete with natural/recycled aggregates were also tested for comparison. The results showed that the pre-saturated recycled aggregates only slightly affected the workability of conventional concrete or AAC. Recycled aggregates reduced compressive strength of both conventional concrete and AAC due to extra water for pre-saturation of the recycled aggregates. The mass loss of the concrete specimens upon drying was greater for low-strength concrete than for moderate strength concrete. The recycled aggregates increased the mass loss and drying shrinkage of AAC. For conventional concrete, low-strength concrete had a higher drying shrinkage compared with moderate strength concrete. On the contrary, for AAC in this study, low-strength concrete had a lower drying shrinkage compared with moderate strength concrete.

Keywords: recycled aggregates, conventional concrete, alkali-activated concrete, compressive strength, drying shrinkage

1. INTRODUCTION

Concrete is the most essential material for buildings and infrastructure due to its good performance and economical characteristic. Each year a huge amount of concrete is produced worldwide, while the global cement production increased from 1.4 billion tons in 1995 to 4.1 billion tons in 2019 [1]. Depending on applications the designed service life of concrete structures mainly ranges from 50 years to 100 years [2]. After the service life or premature failure, concrete structures need to be demolished. According to Eurostat [3], 345 million tons mineral waste from construction and demolition was generated in the European Union in 2016. For sustainability development, the construction and demolition waste (CDW) is being recycled and reused. The recovery rate of CDW in the EU had reached 89% in 2016 [3]. In the annual review 2018-2019 reported by European Aggregates Association, recycled/re-used aggregates takes up 12% of the total amount of aggregates used in construction [4]. By using recycled aggregates in concrete, the burden of extracting primary natural resources (e.g., gravels) is alleviated. A comprehensive review on recycled aggregate in conventional concrete has been published, in which the fresh properties, mechanical properties, long-term performance and design codes are discussed in detail [5].

To further promote sustainability, secondary materials or industrial by-products need to be used to a large extent in concrete production. For that purpose, alkali-activated concrete (AAC) has emerged as a solution. The AAC is cement free and can be made with industrial by-products, like blast furnace slag (BFS) and fly ash (FA) as precursors, NaOH and water glass as alkali activators, and aggregates [6]. Concerning that 70% - 80% of the volume of concrete is made of aggregates, attempts have also been made to incorporate recycled aggregates from CDW in AAC [7-14]. These studies mainly focused on workability, mechanical properties and durability (e.g., water absorption, chloride resistance, sulfate resistance and freeze-thaw resistance). Investigation on drying shrinkage, which is a common critical issue for AAC [16], is still scarce for AAC with recycled aggregate. This study mainly investigated the influence of recycled aggregates on drying shrinkage of slag-based AAC. Meanwhile, workability and compressive strength of the AAC with natural/recycled aggregates were tested and compared with that of conventional concrete.

2. MATERIALS AND EXPERIMENTS

3.1 Raw materials

Concrete with two strength classes were prepared, namely low strength (i.e., C30) and moderate strength (C50). For each strength class, both conventional concrete and AAC were prepared. Conventional concrete was prepared with cement (CEM III/B 42,5 N), quartz sand, natural/recycled coarse aggregates. AAC was prepared based on RILEM mixtures [17], with BFS as precursor, NaOH pellets (Honewell) and water glass (PQ Corporation) as activators, quartz sand, natural aggregates or recycled aggregates. The chemical compositions of CEM III/B 42.5 N [18] and BFS [19] are listed in Table 1. BFS had a particle size of 0.1 - 50 μm and a d_{50} of 18.3 μm. The quartz sand had a modulus of 3.4. The natural aggregates were pebbles with a size of 4-16 mm. The recycled aggregates from CDW mainly consisted of crushed concrete (77 % by weight) and unbound stone (18% by weight), with a size of 4-16 mm, a saturated surface dry density of 2400 kg/m^3, and a water absorption capacity of 5.2%. The recycled aggregates were pre-saturated with water before use.

Table 1: Chemical compositions of cement and BFS [wt %]

	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	K_2O	TiO_2	Other	LOI
CEM III/B 42,5 N	30.0	11.0	45.0	7.0	1.3	1.9	0.5	0.9	2.3	0.1
BFS	31.8	13.3	40.5	9.3	0.5	1.5	0.3	1.0	0.5	1.3

3.2 Mix design and methodology

Mix designs of conventional concrete and AAC are listed in Table 2. The natural and recycled aggregates were pre-saturated before mixing. 150 mm × 150 mm × 150 mm specimens and 100 mm × 100 mm × 400 mm specimens were cast for tests on compressive strength and drying shrinkage. All specimens were demoulded after 2 days because 2 days curing was needed for demoulding AAC specimens with recycled aggregates. The specimens were subjected to sealed curing at 20 °C until testing. The compressive strength of the 7-day and 28-day old specimens was determined according to NEN 5988. For drying shrinkage measurements, the specimens were stored at 50% relative humidity and 20 °C. The measurements of drying shrinkage started at 3 days and last for 28 days, according to NEN-EN 12390-16. During the drying process at 50% relative humidity and 20 °C, mass loss of the specimens was also recorded.

Table 2: Mix design of conventional concrete and AAC [kg/m^3]

	Low strength concrete				Moderate strength concrete			
	Conventional concrete		AAC		Conventional concrete		AAC	
	C30	C30-RA	S1b	S1b-RA	C45	C45-RA	S3a	S3a-RA
CEMIII/B 42,5N	335	335	-	-	383	383	-	-
BFS	-	-	357	357	-	-	375	375
NaOH	-	-	10,7	10,7	-	-	15	15
$Na_2O \cdot 2SiO_2$	-	-	4,8	4,8	-	-	10,1	10,1
Sand	826	826	734	734	786	786	729	729
Natural aggregate	1017	-	1101	-	1010	-	1093	-
Recycled aggregate	-	915	-	990	-	908	-	983
Water	184	184	156	156	163	163	153	153
W/B	0,55	0,55	0,42	0,42	0,425	0,425	0,382	0,382

3. RESULTS AND DISCUSSION

3.1 Workability

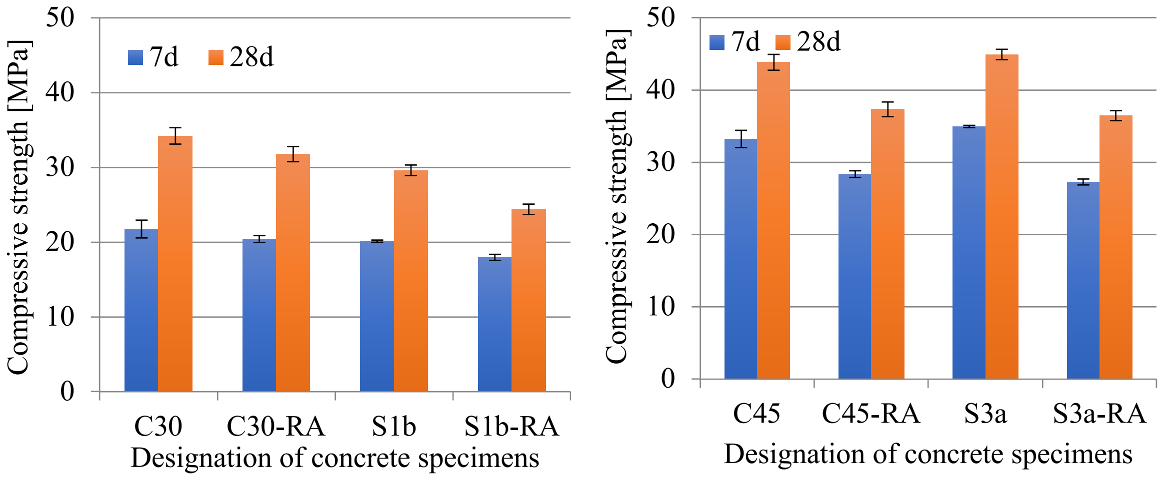
The slump of all mixtures is listed in Table 3. In general, concrete mixtures with recycled aggregates had lower slump values than that with natural aggregates. This can be explained by the angular shape of the recycled aggregates, in comparison with the rounded natural aggregates used in this study. It is known that for a given paste volume, mixtures made with angular coarse aggregate can have lower deformability, thus a smaller slump value [20].

Table 3: Slump of fresh conventional concrete and AAC [mm]

C30	C30-RA	S1b	S1b-RA	C45	C45-RA	S3a	S3a-RA
160	100	175	155	65	60	165	160

3.2 Compressive strength

Fig. 1 shows the 7 days and 28 days compressive strength of conventional concrete (i.e., low-strength: C30 and C30-RA, moderate-strength: C45 and C45-RA) and AAC (i.e., low-strength: S1b and S1b-RA, moderate-strength: S3a and S3a-RA). The low-strength concrete C30 and S1b had a 28 days compressive strength of 34 MPa and 30 MPa, respectively. The moderate-strength concrete C45 and S3a had a 28 days compressive strength of 44 MPa and 45 MPa, respectively. The incorporation of recycled aggregates reduced compressive strength of both conventional and AAC, which was in accordance with reported work [7]. Porous and cracked structure of recycled aggregates were believed to be one of the causes of reduction of concrete strength. Besides, the extra water for pre-saturation of recycled aggregates diluted the alkali solution, and thus reduced the concrete strength. Note that the negative effect of recycled aggregates on compressive strength was smaller for low-strength concrete than for moderate-strength concrete. It is known that the mortar matrix plays a greater role for low-strength concrete, while the influence of coarse aggregates becomes bigger for high-strength concrete [21, 22].



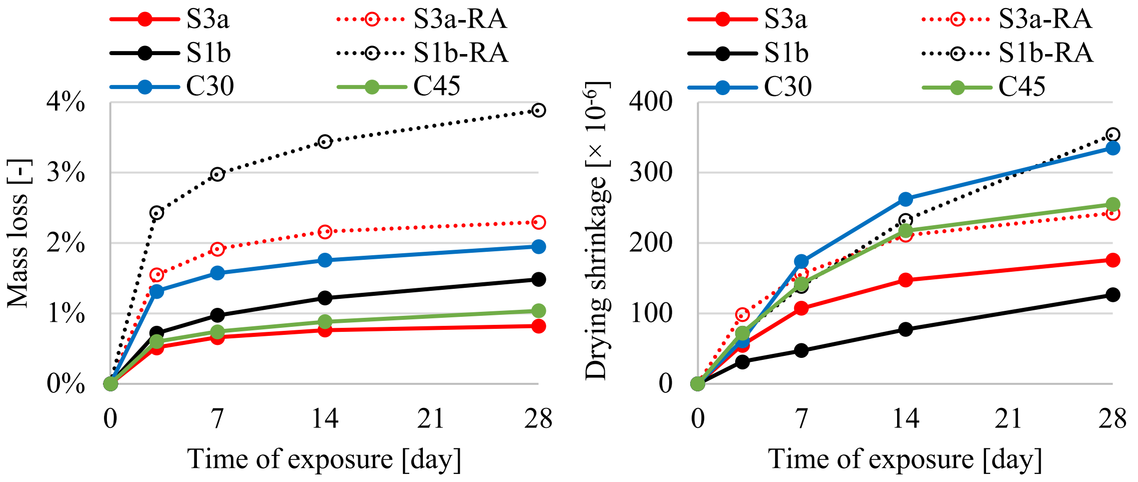
(a) Low-strength concrete (b) Moderate-strength concrete

Figure 1: Compressive strength of conventional concrete and AAC

3.3 Drying shrinkage and mass loss

Fig. 2 shows the mass loss and drying shrinkage of conventional concrete and AAC. In general, the mass loss of the specimens upon drying was greater for low-strength concrete (e.g., C30 and S1b) than for moderate strength concrete (e.g., C45 and S3a). The mass loss of the specimens was also greater for concrete with recycled aggregates (e.g., S1b-RA and S3a-RA) than for concrete with natural aggregates (e.g., S1b and S3a).

The incorporation of recycled aggregate in AAC increased the drying shrinkage, in accordance with the findings by Alonso et al. [23] who applied recycled fine aggregates from CDW in alkali-activated slag mortar. The increase in paste content in concrete due to the incorporation of recycled aggregate was identified as the main reason for the increase of drying shrinkage [24, 25]. For conventional concrete, low-strength concrete had a higher drying shrinkage compared with moderate strength concrete. It can be explained by the fact that low-strength concrete had a higher porosity and a coarser pore structure, leading to a faster moisture loss compared with moderate-strength concrete. On the contrary, for AAC, low-strength concrete had a lower drying shrinkage compared with moderate strength concrete. The causes are more complicated than that for conventional concrete. One possible reason can be related to the alkali activators of the AAC. In this study, moderate-strength AAC was prepared with a higher concentration (i.e., NaOH and $Na_2O{\cdot}2SiO_2$) and a higher modulus (i.e., SiO_2/Na_2O) of the alkali solution. The higher concentration of alkali activator was reported to increase the drying shrinkage of AAC [26]. Besides, a higher modulus of alkali solution resulted in finer pore structure. The finer pores increase the tensile stresses imposed by pore solution to capillary pores under drying, and consequently the drying shrinkage rates increase [27].



(a) Mass loss (b) Drying shrinkage

Figure 2: Mass loss and drying shrinkage of conventional concrete and AAC. After 3 days sealed curing, the concrete specimens were subjected to drying for 28 days.

Fig. 3 shows the relationship between mass loss and drying shrinkage of conventional concrete and AAC. For concrete with natural aggregates, moderate-strength concrete (i.e., C45, S3a and S3a-RA) exhibited a steeper curve of drying shrinkage with respect to mass loss compared with low-strength concrete (i.e., C30, S1b and S1b-RA). This result is in accordance with the findings for conventional concrete in [28]. At a certain mass loss, the smaller drying shrinkage of low-strength concrete can be explained by the fact that the water loss mainly took place in large capillary pores, thus lower tensile stresses were generated in the pores [29]. It is also interesting to note that the curves of C30 and C45 almost coincided with that of S1b and S3a, respectively. It indicates that for concrete with natural aggregates there existed a correlation between the compressive strength and the drying shrinkage-mass loss relation. For concrete with natural aggregates in this study, it is implied that reaching a certain drying shrinkage was a matter of time, depending on the point when a certain mass was lost. For AAC, the drying shrinkage-mass loss curves of S1b and S3a were steeper than that of S1b-RA and S3a-RA, respectively. This can be explained by the extra water for pre-saturation of recycled aggregates, which diluted the alkali activators and resulted in lower geopolymerization of AAC [7]. The lower geopolymerization indicates a coarser pore structure of AAC. With the coarser pore structure, smaller tensile stress was generated in capillary pores at a certain mass loss, leading to a smaller drying shrinkage of S1b-RA and S3a-RA.

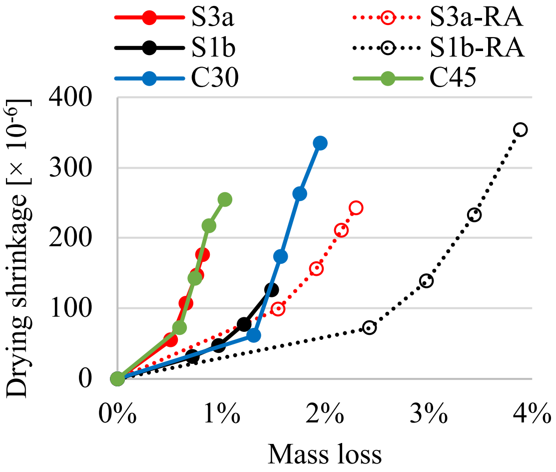


Figure 3: Relationship between mass loss and drying shrinkage of conventional concrete and AAC. After 3 days sealed curing, the concrete specimens were subjected to drying for 28 days.

4. CONCLUSION

This study evaluated the influence of recycled aggregates from construction and demolition waste on workability, compressive strength and drying shrinkage of conventional and alkali-activated concrete (AAC). The following conclusions can be drawn:

- Incorporation of pre-saturated recycled aggregates only slightly affects the workability of conventional concrete or AAC. The slightly reduced workability of concrete with recycled aggregates was due to the angular shape of the recycled aggregates compared with the rounded natural aggregates.
- Recycled aggregates showed a similar effect on compressive strength of both conventional concrete and AAC. The reduction of compressive strength of concrete with recycled aggregates was caused by the extra water for pre-saturation of the recycled aggregates that diluted alkali activators. Porous and cracked structure of recycled aggregates was believed to be another cause of concrete strength reduction.
- The mass loss of the specimens upon drying was greater for low-strength conventional concrete or AAC than for moderate-strength conventional concrete or AAC. The recycled aggregates increased the mass loss of AAC compared with natural aggregates.
- Recycled aggregate increased the drying shrinkage of AAC, explained by the increase in paste content in concrete due to the incorporation of recycled aggregate. For conventional concrete, low-strength concrete had a higher drying shrinkage compared with moderate strength concrete. On the contrary, for AAC in this study, low-strength concrete had a lower drying shrinkage compared with moderate strength concrete. It was explained by the higher concentration and modulus of alkali solution of AAC.

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