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Fiber-reinforced alkali-activated cement concrete

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ABSTRACT

Ordinary Portland cement (OPC) concrete is the most commonly used construction material. Although OPC concrete has an irreplaceable role in today's world, it is also responsible for about 8% of the global CO_2 emission (Andrew 2018). Alkali activated cement (AAC) is an emerging binder type that has been proven to be an excellent alternative to OPC (Juenger et al. 2011). Researches are now focused on characterizing the various behaviors of this binder. One such area of interest is the behavior of fiber-reinforced alkali-activated concrete. This study investigates the performance of two alkali-resistant glass fibers and one high-performance polyvinyl alcohol (PVA) microfiber in AAC concrete. Three AAC and two OPC concrete mixes were taken as a control. The influence of different fiber contents on the workability and the compressive and flexural strengths was investigated. Furthermore, the stress-strain relationship and load-deformation curves are studied for the control and 0.5% PVA fiber content specimens. The results showed that the workability of fiber-reinforced AAC decreased with the increase of fiber content. The fibers improved the flexural performance of the concrete and showed some minor improvements on the compressive strength.

1. INTRODUCTION

In the past few decades, with the rapid development of the construction industry, the global production of ordinary Portland cement (OPC) increased rapidly. One tonne of OPC clinker production releases about one tonne of CO_2 to the environment (Garcia-Lodeiro et al. 2015). It is estimated that the CO_2 emitted from the production of OPC accounts for about 8% of the total global emissions (Andrew 2018). Alkali activated cement (AAC) has shown promising potential in curbing this problem. AAC is produced by activating source materials such as fly ash and slag with alkaline solutions. The source materials are usually byproduct materials. The use of such materials saves raw materials and decreases the emission of CO_2 associated with the manufacture of OPC.

High compressive strength and low tensile strength is common behavior for all

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types of concretes. With the increase of compressive strength, concrete becomes brittle, and its toughness and ductility reduce. Such behavior of concrete can be reduced by adding fibers to concrete. Fibers absorb the tensile strain acting on the concrete to overcome its brittleness, improve its toughness, and optimize the performance. A concrete with more toughness or energy-absorbing capability can be used in structures subjected to impacts and earthquake loads (Boulekbache et al. 2010).

Among other factors, fiber and binder types influence the performance of fibers in concrete (Koenig et al. 2019). Fiber can have a different effect in OPC and AAC concretes due to the different binder systems. Furthermore, the effect can also be different even within AAC concrete groups due to the different types of AACs available. Research on the properties of fiber-reinforced AAC concrete is not extensive; hence further research is needed. Therefore, this study aims to explore the effects of different fibers types and dosages on the performance of fiber-reinforced AAC.

2. EXPERIMENTAL PROGRAM

2.1. Materials and mix proportions

FA, GGBS, and SF were used in the preparation of the alkali-activated concretes. The chemical compositions of these source materials are summarized in Table 1. The activator solution used is a mixture of sodium silicate and sodium hydroxide. The sodium silicate solution includes 26.82% silicate, 8.2% sodium oxide, and 64.98% water, while the sodium hydroxide is a 50% by weight solution. Fine aggregates with a maximum aggregate size of 3.15 mm and additional fines (0.1 – 0.35 mm) were used. Three different fiber types: alkali-resistant glass fibers, AR-TEC 950-13X and Cem-FIL 60.3, and polyvinyl alcohol fiber, MasterFiber 401, were used.

Table 1. Chemical composition of ingredients

Composition	FA (%)	GGBS (%)	SF* (%)
SiO_2	49.79	34.48	93.81
Al_2O_3	26.71	11.48	0.48
Fe_2O_3	8.57	-	1.49
MgO	2.47	7.08	0.46
CaO	4.34	42.43	0.30
K_2O	3.36	0.66	0.77
Na_2O	1.28	0.56	0.42
SO_3	1.49	2.17	0.20
TiO_2	1.23	1.14	-
Specific surface area (m^2/g)	0.45	0.46	19.40
Specific gravity (g/cm^3)	2.28	2.91	2.20

*manufacturer specification

Table 2. type of fibers used

Fiber name	Fiber material	Tensile strength (MPa)	E-modulus (MPa)	Diameter (mm)	Length (mm)	Specific gravity (kg/m³)
AR-TEC 950-13X	AR-glass	1,400	74,000	0.018[a]	13	2,700
Cem-FIL 60.3 82tex	AR-glass	>700	-	0.014[a]	12	2,680
MasterFiber 401	PVA	800	29,000	0.16	12	1,300

[a] filament diameter

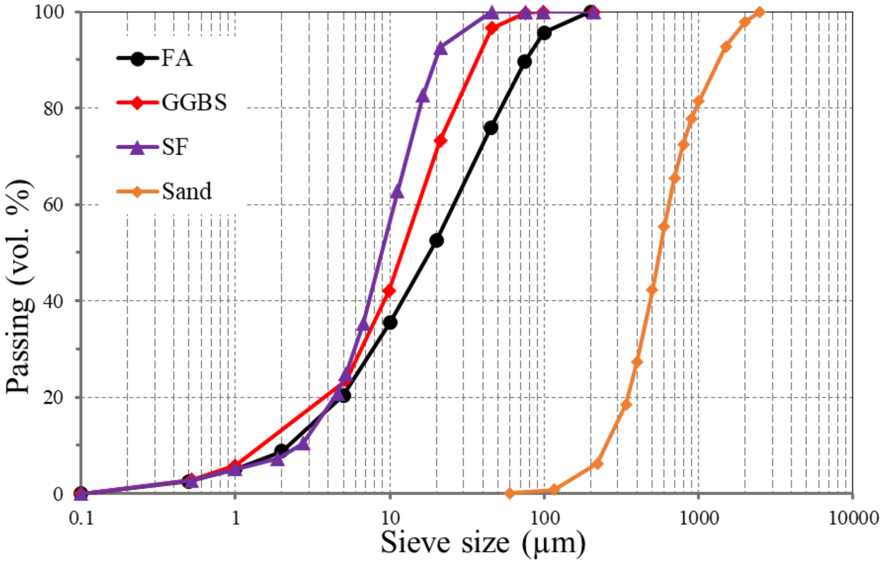

Fig. 1. Particle size distribution

The research is part of an ongoing project on developing a concrete mixture for use in textile-reinforced concrete. Textile reinforcement requires fine-grained concretes due to their smaller openings; hence no coarse aggregate was used. The constituents of the precursor are set at 55% FA, 40% GGBS, and 5% SF based on the authors' previous work (Tekle et al. 2021). Three mixes were designed targeting a medium and two high strength classes (C1, C2 and C3). Two OPC mixes were also used for comparative purposes. These mixes were taken as control mixes to understand the fiber's effect in different strengths. The mix proportions are as shown in Table 3. The influence of different fiber contents and fiber types on the workability and the compressive and flexural strengths was investigated.

Table 3. Mixture proportions of the control mixes

Materials (kg/m³)	C1	C2	C3	OPC1	OPC2
2/4 sand	408	429	444		
0/2 sand	509	537	555	771	774
0.1-0.35	102	107	111	514	516
Cement	-	-	-	550	550
Limestone	-	-	-	160	160
FA	278.8	329.5	380.2	-	-
Slag	202.8	239.6	276.5	-	-

SF	25.3	30	34.6	41	41
SHL	51.6	60.8	70	-	-
SSL	129	152.1	176	-	-
Water	197.7	118.3	44.7	230	230
SP	-	27.6	47	9	16.8

2.2. Specimen preparation and experimental method

The sodium silicate and sodium hydroxide solutions were mixed in the required proportion at least 24 hours before mixing. AAC specimens were prepared by first mixing the dry materials (sand and binder) in a mixer for about two minutes. Afterward, the prepared alkaline solution was mixed with the additional water, added slowly to the dry mixture, and mixed for about two minutes. The fibers were then added in a small amount to avoid fiber balling and produce concrete with uniform materials consistency and mixed for an additional two minutes at low speed to avoid fiber damage.

The consistency of the fresh mixture is determined by flow tests with a Haegermann cone according to EN 1015-3. The fresh mixture was then removed from the flow table and added back to the mixing bowl and mixed for an additional 15 seconds. The mixture was then placed into 40 mm × 40 mm × 160 mm prisms for compressive and flexural testing according to EN 1015-11. 100 mm diameter by 200 mm height concrete cylinders were prepared for some of the mixes to study the stress-strain relationship. Three specimens were produced for each mixture. 150 mm × 150 mm × 700 mm beams were also prepared and tested to study the load-deflection curves. After casting, the specimens were covered and placed in the environmental control room (20°C temperature and 65% humidity). The specimens were demolded after 24 hours and kept in the environmental control room until the test day.

3. RESULTS AND DISCUSSIONS

3.1. Results

The flow diameters and the compressive and flexural strengths were used as an evaluation criterion. Table 4 gives a summary of these results. The compressive and flexural strength values are average of 6 and 3 specimens, respectively. The specimens are identified by the concrete class (C1, C2, C3, OPC1 and OPC2), the fiber type and the fiber content.

Table 4. Details of mixes and results

Specimen Name	Fiber type	Flow (cm)	Compressive strength (MPa)	Flexural strength (MPa)
C1-AR	-	30.5	37.3	5.6
C1-AR 0.3	AR-TEC 950-13X	26.6	37.0	5.9
C1-AR 0.5	AR-TEC 950-13X	25.7	40.8	7.1
C1-AR 0.7	AR-TEC 950-13X	24.3	35.5	9.1
C2-AR	-	25.8	72.0	9.0
C2-AR 0.3	AR-TEC 950-13X	25.2	67.6	8.2
C2-AR 0.5	AR-TEC 950-13X	23.7	72.8	9.0
C2-AR 0.7	AR-TEC 950-13X	22.9	73.0	9.4

C3-AR	-	19.6	68.3	7.0
C3-AR 0.3	AR-TEC 950-13X	16.6	73.0	7.7
C3-AR 0.5	AR-TEC 950-13X	15.6	75.0	8.4
C3-AR 0.7	AR-TEC 950-13X	14.6	75.3	8.0
C2-Cem	-	24.6	72.0	9.1
C2-Cem 0.3	Cem-FIL 60	24.4	75.8	9.5
C2-Cem 0.5	Cem-FIL 60	23.8	71.6	9.5
C2-Cem 0.7	Cem-FIL 60	22.6	71.5	9.1
C2-PVA[a]	-	25.7	32.2	3.7
C2-PVA 0.3[a]	MasterFiber 401	25.1	34.7	4.6
C2-PVA 0.5[a]	MasterFiber 401	24.8	35.1	4.4
C2-PVA 0.7[a]	MasterFiber 401	23.6	36.8	4.6
OPC1-AR[b]	-	28.3	66.4	8.3
OPC1-AR 0.7[b]	AR-TEC 950-13X	18.8	69.5	11.7
OPC1-Cem[b]	-	30.8	56.3	8.9
OPC1-Cem 0.7[b]	Cem-FIL 60.3	24.3	63.7	16.2
OPC2-Cem	-	32	87.7	10.6
OPC2-Cem 0.25	Cem-FIL 60.3	24.5	90.6	10.2

[a] specimen tested after 7 days, [b]specimen tested after 14 days

3.2. Workability

Mixes with fiber showed lower workability compared to the control mix. The flow diameter always decreased with the increase of the fiber content. Grzesiak et al. (2021) investigated the effect of polypropylene (PP) and polyvinyl alcohol (PVA) fibers on the workability of high performance concrete. The PP fiber improved the slump flow while the PVA showed an opposite effect. The PP fiber has a diameter of 0.7 mm and length of 30 mm, while the PVA has a diameter of 0.16 mm and a length of 12 mm. Hence the difference observed can be due to the smaller size of the PVA fibers. Similarly, in the current study, the lower flow diameter in the fiber-reinforced mixes can be due to the smaller diameter of the glass and PVA fibers. The smaller diameters result in a high specific surface area and, hence, higher absorption of the mixing water and lower workability. Fig. 2 shows the relative flow diameters. C3's workability is more significantly affected by the addition of fiber compared to C1 and C2 mixes. This could be due to the lower water content of this mixture. At the same fiber dosage, OPC's flow diameter reduced more than any of the AAC mixes, showing the lower effect of the fibers on the workability of AAC mixtures. This could be due to the different chemical compositions of the two binders. The lower effect of fibers on AAC's workability can be an advantage, especially in areas that call for higher workabilities, such as textile-reinforced concretes.

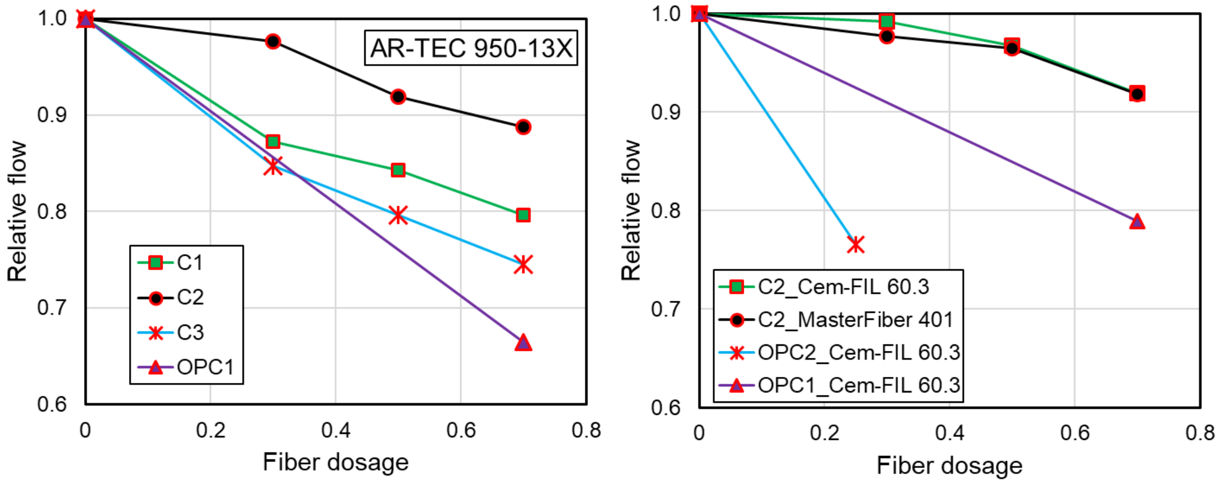

Fig. 2. Relative flow vs. fiber dosage

3.3. Compressive and flexural strengths

Fig. 3 shows the relative compressive and flexural strengths at different AR-TEC 950-13X fiber contents. The compressive strength did not show an obvious increasing or decreasing trend with the fiber content. However, on average, it slightly improved with the addition of fiber. For instance, for C3-AR mixes, the control showed a strength of 68.3 MPa, while the mix with 0.7% fiber showed a strength of 75.3 MPa. Fiber often results in a slight decrease in compressive strength (Koenig et al. 2019; Grzesiak et al. 2021). This is due to the increase in viscosity of the concrete with the addition of fiber, making compaction difficult and leading to a high void in the hardened concrete. The positive effect of the fibers in the current study could be due to the high workability of the control mixes.

The addition of fiber improved the flexural strength of the concretes except for C2-AR 0.3 (Fig. 3). The improvement was more pronounced in the case of the lower compressive strength concrete (C1). In general, the mechanical properties of concrete with a lower compressive strength will be improved through the addition of fibers (Grzesiak et al. 2021). C3-AR specimens with fiber showed a better flexural strength improvement than C2-AR specimens. This could be due to the higher binder content of the C3-AR resulting in better bonding of the fibers.

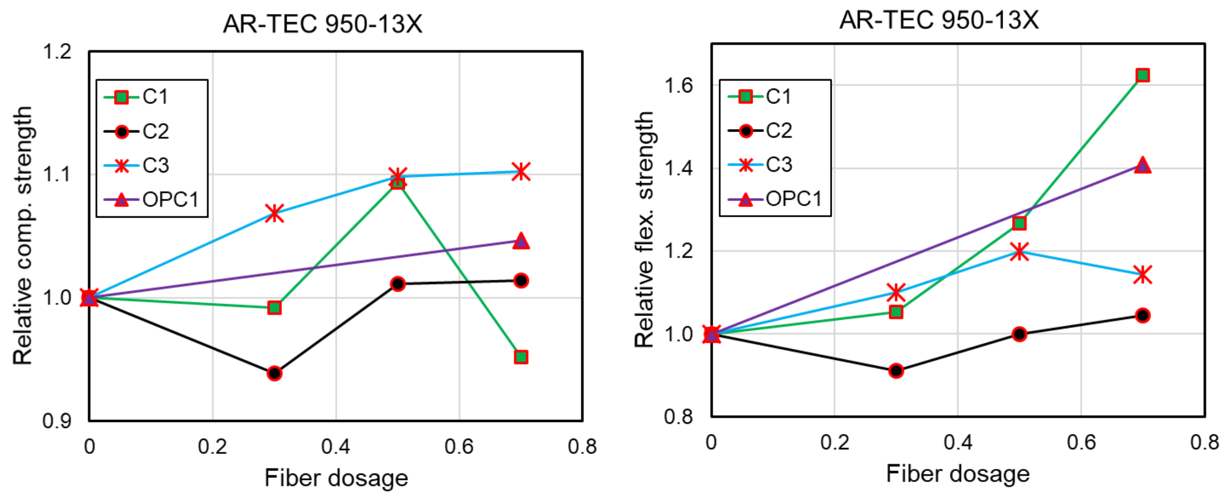

Fig. 3. Relative compressive and flexural strengths

3.4. Compressive stress-strain relationship

The compressive stress-strain relationship for the control and 0.5% MasterFiber 401 reinforced AAC are as shown in Fig. 4. At this fiber dosage, no significant difference was observed in the stress-strain behavior. The average strain at the peak stress is 0.004 for both control and fiber-reinforced concretes. The addition of fibers often increases the strain at the peak stress, as observed in previous researches (Nataraja et al. 1999). The lower fiber content could be the reason for the absence of effect observed in the current study.

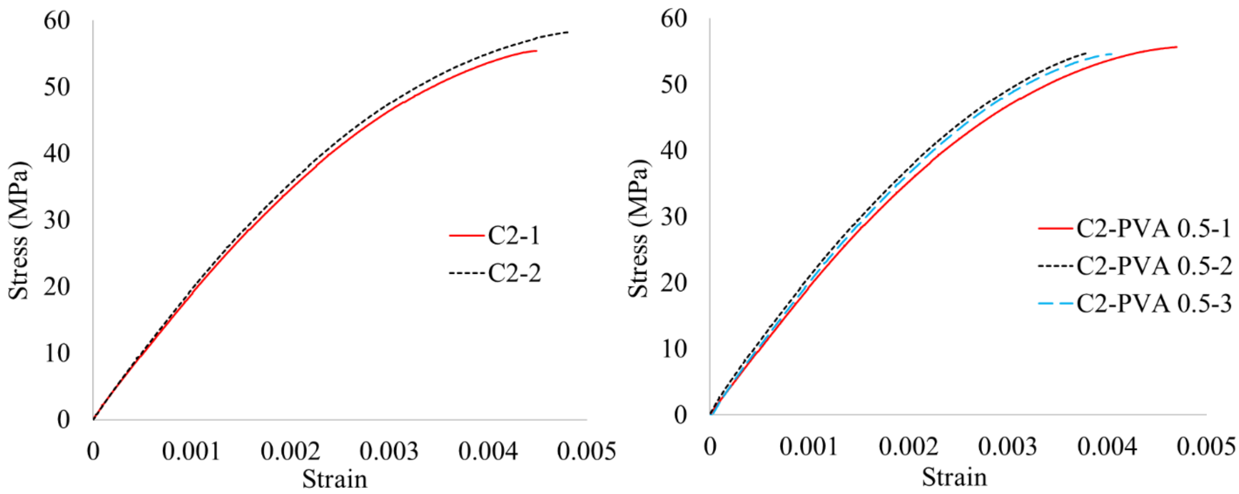

Fig. 4. Compressive stress-strain curve

3.5. Post-cracking behavior

Fibers in concrete absorb the post-cracking energy and improve the ductility of concrete. Fig. 5 shows the force-deflection curve for control concrete and 0.5 % MasterFiber 401 concrete specimens. The concrete without fiber showed a sudden failure, as expected.

The addition of the fiber resulted in a softening behavior of the concrete, as can be observed from Fig. 5.

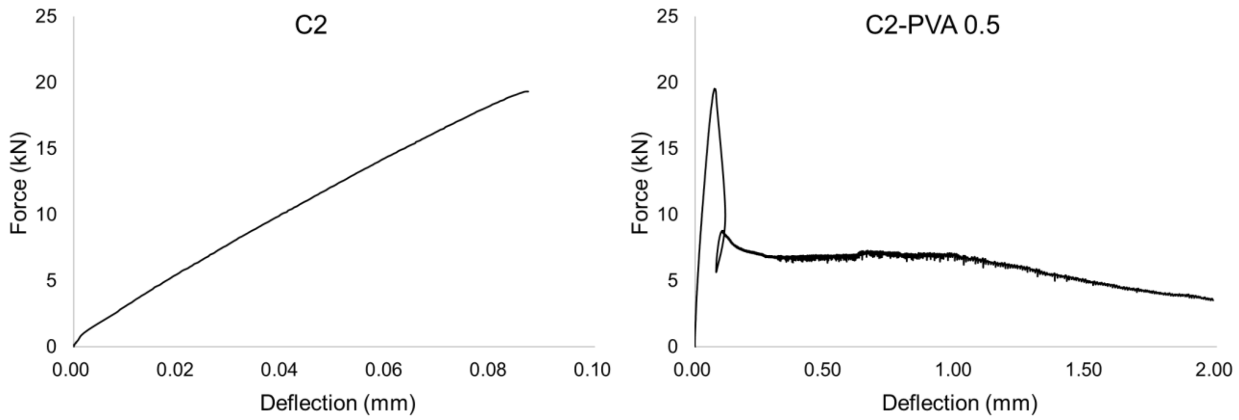

Fig. 5. Force deflection curve

4. Concluding remarks

Based on the experimental study, the following concluding remarks are given:

- The workability of the AAC mixes decreased with the increase of fiber dosages.
- At the same fiber dosage, OPC's flow diameter reduced more than AAC mixes, showing the lower effect of the fibers on the workability of AAC mixtures.
- Despite not showing a consistent increase or decrease with the fiber addition and dosages, the compressive strength slightly improved with the addition of the fibers.
- The flexural strength was improved with the addition of fibers. The most significant improvement was observed for the lower strength concrete.
- At 0.5% MasterFiber 401 fiber content, the stress-strain relationship did not show any significant difference from the control.

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