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Influence of fiber inclination angle on bond-slip behavior of different alkali-activated composites under dynamic and quasi-static loadings

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ABSTRACT

This study investigates the influence of inclination angle (0° and 45°) on the interfacial bond-slip behavior of macro steel fibers (straight, hooked end-deformed and length-deformed) and length-deformed polypropylene fibers reinforced in fly-ash and metakaolin based alkali-activated composites (AACs) under quasi-static and dynamic loadings. AACs demonstrate superior peak bond strength and toughness compared to cement composites regardless of fiber type and loading rate. Results also show that straight steel fiber exhibits a complete pullout in AACs. The amount of deformation of the fibers (deformation ratio) determined the failure type at different inclination angle and loading rate, thus governing the peak load and energy absorption. Depending on the fiber orientation, premature fiber rupture or matrix cracking is observed under dynamic loading in AACs due to matrix brittleness. The fiber failure modes in dynamic pullout are no different from those observed in the quasi-static pullout in AACs.

1. Introduction

Alkali-activated composites (AACs) have attracted a great attention and are still increasing their popularity in construction industry and building engineering because of their capability to restrain CO_2 emissions, together with their early strength development, low shrinkage and excellent corrosion and fire resistance. They are considered to be highly sustainable materials since they can be manufactured from agro-industrial waste materials that are rich in silica (Si) and alumina (Al), like fly ash, blast-furnace slag, rice husk ash and palm oil fuel ash. A number of studies have shown that alkali-activated concrete has properties making it suitable as a construction material [1–5]. However, AACs are ceramic-like materials, so they present a typical brittle mechanical behavior with the consequent low ductility and low fracture toughness. This behavior may represent several limitations in structural applications. Due to their brittleness, enhanced ductility and toughness become key priorities for construction applications of alkali-activated materials, as catastrophic failure during service can result in significant damage. This would also open a window to a variety of applications where metals or polymer composites are being used. Fiber reinforcement is an effective and economical way to transform brittle alkali-activated concrete into a ductile material. Different types of fiber reinforcements have been employed in various alkali-activated matrices to improve their flexural strength, impact behavior and ductility [6–14]. It has been reported that reinforcing fibers in these brittle matrices (i) help to control micro and macro-cracks diffusion through the material by generating a bridging effect [6–18], and (ii) changes the post-cracking behavior of the material.

It is well known that the inclination angle of a fiber in a cementitious matrix has a strong influence on the pullout resistance and may potentially change the mechanism of reinforcement [19–21]. Inclined fiber pullout function to predict the flexural behavior of fiber reinforced concrete has been vastly researched [22–24]. A considerable amount of research has gone into investigating the influence of fiber inclination on their pullout from cementitious matrices. Li et al. [19] observed a general increase in pullout load for polymeric micro fibers up to an inclination of 45°, beyond which the load may start to decrease due to matrix cracking. Similar trends were noted for flexible polymeric macro fibers by Leung and Ybanez [25]. For steel fibers, similar trends of increase in pullout load at low inclinations (37° in Ouyang et al. [20], 45° Lee et al.) followed by reduction in pullout load at higher inclinations and 60° in Lee et al. [26] is reported. The mechanism for deformed fibers on the other hand, is more complicated. A similar or slightly higher pullout response at low inclinations (15°) compared to aligned fibers, but at 30° and beyond, much larger reduction pullout load resulting from a severe matrix cracking was reported by Banthia et al. [22,27]. The effect of fiber deformations was found to be profound on the inclined fiber pullout in their study [22]. Albeit this disagreement, it is generally known that the effect of fiber inclination angle on the pullout load and pullout energy is dependent on the fiber material (i.e.

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Table 1
Chemical compositions of OPC, FA and MK.

Chemical compound	Content (%)		
	OPC	FA	MK
SiO_2	19.20	46.8	54.54
Al_2O_3	5.12	23.7	44.16
Fe_2O_3	2.27	13.2	0.51
SO_3	4.08	1.2	–
MgO	2.41	1.0	–
CaO	62.27	3.1	–
Moisture	–	0.1	–
LOI	–	7.9	1.02
Specific gravity	3.15	2.34	2.5
Blaine specific surface area (m^2/kg)	395	–	
Mean particle size		45 μm	4.5 μm

metallic or synthetic); aspect ratio, shape (straight, hooked, corrugated etc.), and properties such as yield strength. Toughness is derived from a combination of debonding fiber pullout action along the direction of the fiber, and bending forces perpendicular to the fiber [21,27,28].

Recent research has been carried out to evaluate the behavior of fiber reinforcement cementitious materials under impact loading using different methods [29–32]. Several researchers have reported a general increase in fiber-matrix interfacial bond strength of cementitious materials at high loading rate [27,30,31,33,35]. Since the matrix in AACs is different from that of Ordinary Portland cement (OPC)-based materials, the effect of the interaction between the fibers and the alkali-activated matrix on interfacial properties is significantly changed [36]. Indeed, previous studies on the fracture behavior of alkali-activated materials have shown that these materials behave quite differently when subjected to flexural or tensile loading due to their brittle nature [37–39]. Studies have also shown that the type and nature of source materials used in the production of AACs certainly affect the mechanical and durability properties [40].

Notably, limited research has been carried out towards understanding the behavior of alkali-activated matrix-fiber pullout with fiber inclination angle under dynamic and quasi-static loadings. In contrast to durability or serviceability, the poor absorption of energy under impact loading causes concerns for a brittle alkali-activated material. Therefore, in this study quasi-static and dynamic properties of these materials reinforced with various commercial macro fibers are considered.

A potential alternative to conventional concrete, the understanding, to date, on fiber bond-slip behavior in AACs is lacking. Fly ash (FA) and metakaolin (MK) were used as source materials to activate the alkaline solutions to examine the bond-slip behavior of different AACs under different loadings. Based on the literature survey, where different angle (0, 15, 30, 45, 60 and 75) inclination effect for different fibers in cement matrix have been investigated, 45 inclination was found more critical and appropriate to study the bond-slip behavior of AACs in this study [19–21]. The effects of fiber inclination angle (0° and 45) and rate of loading (quasi-static and low velocity dynamic), on single fiber pullout behavior of those different matrices are investigated. Four types of fibers comprising steel (straight, length-deformed, hooked end-deformed) and polypropylene (length-deformed) have been employed. The results are compared to the bond-slip behavior of the same fibers in OPC composites as control condition.

2. Experimental program

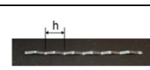
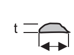
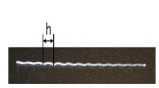
2.1. Materials

Commercially available low calcium class (F) fly ash, conforming to ASTM 618-12a [45] and metakaolin were used as binders. Their chemical compositions as provided by the manufacturer are shown in Table 1. Analytical grade sodium hydroxide in flake form (NaOH with 98% purity) and sodium silicate solutions (Na_2O = 14.7%, SiO_2 = 29.4% and water = 55.9% by mass), were used as the alkaline activators. The fine aggregate was natural river sand with specific gravity of 2.62 and fineness modulus of 2.83 in saturated surface dry condition. Ordinary Portland cement (OPC) was used to produce reference composites. The chemical composition of OPC is also given in Table 1. Commercially available steel and polypropylene (PP) fibers were employed. The properties of the fibers are shown in Table 2.

2.2. Mixture proportions and specimen preparation

The mix proportions (Table 3) of AACs used were based on results from previous studies [5,36]. In order to prepare the alkali solution, sodium silicate and 12 M (M) sodium hydroxide liquids were mixed together (Na_2SiO_3 to NaOH mass ratio of 2.5 resulting in 0.84 and 0.83 Na_2O/SiO_2 ratio in the solution for FA binder and MK activated composites, respectively) at least one day prior to casting. The AACs were prepared with an alkaline solution to binder ratios of 0.4 and 1.1 by mass, respectively for FA and MK; the sand to binder (FA and MK) ratio in AACs was 1.6. MK demanded higher solution compared to FA due to its finer particle size. Further, FA with its spherical shape particles increases workability, when compared to MK with its plates-like structure. The fine aggregate and binder (FA and MK) were dry-mixed in a pan mixer. The liquid component of the mixture was gradually added to the solid particles 3 min later and mixed for additional 3 to 5 min. The fresh FA-based AACs had a stiff consistency and were glossy in appearance, on the other hand, MK-based AACs were sticky and cohesive. The mixtures were cast in dogbone shaped molds for bond-slip test as shown in Fig. 1.

Table 2
Properties of fibers investigated.

Fiber	Shape	Density (g/cm^3)	Geometry	Cross-section*	Geometry*	Tensile strength (MPa)	R_D**
	Length-deformed				l = 50 mm h = 7.5 mm w = 2.5 mm t = 0.65 mm	1242	0.27
Steel	Straight	7.86			l = 50 mm d = 1.0 mm	1100	0
	Hooked end-deformed				l = 50 mm h = 6 mm d = 0.7 mm b = 1.0 mm	1300	0.12
PP	Length-deformed	0.91			l = 50 mm h = 3.3 mm d = 0.88 mm b = 0.5 mm	700	0.27

*l = length, d = equivalent diameter, w = width, t = thickness, h = single deformed portion length, b = transverse depth of the deformed fiber portion; **R_D = deformation ratio.