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Combined effect of steel fiber and metakaolin incorporation on mechanical properties of concrete

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ABSTRACT

This study reports the results of an experimental study on mechanical properties of plain and metakaolin (MK) concretes with and without steel fiber. To develop the metakaolin included steel fiber reinforced concrete mixtures, Portland cement was partially replaced with MK as 10% by weight of the total binder content. Two types of hook ended steel fibers with length/aspect ratios of 60/80 and 30/40 were utilized to produce fiber reinforced concretes. Two series of concrete groups were designed with water to binder ratios (w/b) of 0.35 and 0.50. The effectiveness of MK and different types of steel reinforcement on the compressive, flexural, splitting, and bonding strength of the concretes were investigated. All tests were conducted at the end of 28 days of curing period. Analyses of variance on the experimental results were carried out and the levels of the significance of the variables on the mechanical characteristics of the concretes were determined. Moreover, correlation between the measured parameters was carried out to better understand the interaction between mechanical properties of the concretes. The results revealed that incorporation of MK and utilization of different types of steel fibers significantly affected the mechanical properties of the concretes, irrespective of w/b ratio.

1. Introduction

Concrete is the most commonly used building material all over the world because of its versatility and availability. Especially reinforced concrete structural elements have been indispensable parts of construction works due to the ease in erection and relatively lower cost than the other structural materials. The proper adherence between reinforcing bars and concrete is the most desired property due to the fact that structural performance of reinforced concrete members depends on the monolithic behavior. The prominent component controlling the competence of the bond is mostly the quality of concrete. Because, the reinforcing steel bars are obtained from a fixed manufacturing process and the properties do not significantly fluctuate compared to concrete. However, structural concretes have many different characteristics depending mainly on the amount and type of the ingredients [1]. It is reported that concrete with improved mechanical property has superior adherence with reinforcing steel bars [2].

Apart from its excellent properties, concrete shows a rather low performance when subjected to tensile stress. For this reason, utilization of fibers to provide enhancement in tensile strength behavior of concrete has attracted the interest of the researchers [3–9]. Mechanical properties of concrete can be improved by exploitation of reinforcement with randomly oriented short separated fibers, which obstruct and/or control initiation and propagation of cracks. Fiber reinforced concrete (FRC) can keep on resisting much amount of loads even at deflections. The characteristics and performance of FRC varies depending on matrix properties as well as the fiber material, fiber concentration, fiber geometry, fiber orientation, and fiber distribution [8].

In order to improve the mechanical properties, particularly compressive strength, use of some pozzolanic materials has been reported by researchers for many years [10–16]. Pozzolans, such as silica fume and fly ash, are the most commonly known mineral admixtures used in production of high-strength concrete. These materials impart additional performance to the concrete through reacting with Portland cement hydration products to form secondary C–S–H gel, the part of the paste mainly responsible for concrete strength [17].

For the last two decades, there has been a growing attraction in the beneficiation of metakaolin (MK) as a supplementary cementing material in concrete to enhance its properties. MK is an ultrafine pozzolana, manufactured by calcination of purified kaolin clay at a temperature ranging from 650 to 900 °C to drive off the chemically bound water and destroy the crystalline structure [18–19]. Unlike other industrial by-product materials, MK needs a thorough process of manufacturing. It has to be carefully refined to remove inert impurity and ground to particles of micron size. Research has demonstrated that concrete mixtures incorporating

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Table 1
Properties of Portland cement and metakaolin.

	Item	Portland Cement	Metakaolin
Chemical properties	CaO (%)	61.60	0.5
	SiO_2 (%)	19.43	53
	Al_2O_3 (%)	5.64	43
	Fe_2O_3 (%)	4.00	1.2
	MgO (%)	2.41	0.4
	SO_3 (%)	2.94	–
	K_2O	0.78	–
	Na_2O	0.11	–
	LOI (%)	1.85	0.4
Physical properties	Specific gravity	3.19	2.60
	Fineness (m^2/kg)	328[a]	18,000[b]

[a] Blaine specific surface area.
[b] BET specific surface area.

high-reactivity MK present comparable performance to the ones with other mineral admixtures in terms of mechanical properties as well as permeability and durability properties [20–28]. Moreover, the utilization of this material is also environmentally friendly due to the reduction of CO_2 emission to the atmosphere by decreasing Portland cement consumption.

In this study, effectiveness of MK and steel fiber on mechanical properties of concretes with and without steel fiber was examined through an experimental program. The concretes dealt with this study were produced by two different water/binder (w/b) ratios. For steel fiber reinforced concretes, two different types of steel fiber with length/aspect ratios of 60/80 and 30/40 were used. The steel fibers were added to concrete with 0.25% and 0.75% of the volume of the concrete. The mechanical properties of the concretes were measured through compressive, flexural and splitting tensile strength testing at the end of 28 days of curing. Moreover, adherence between reinforcing steel bar and concrete were evaluated by means of bonding strength test at the same age. The statistical analysis and calculation of the contributions of the independent factors on mechanical behavior of concretes were realized by general linear model analysis of variance (GLM-ANOVA). Additionally, the relation between mechanical properties and the bonding strength of the concretes were evaluated through correlating the experimental data.

2. Experimental study

2.1. Materials

CEM I 42.5 R type Portland cement having specific gravity of 3.14 and Blaine fineness of 328 m^2/kg was utilized for preparing the concrete test specimens used in determination of mechanical properties. The chemical composition of the cement is shown in Table 1. The metakaolin used in this study is a white powder with a Dr. Lange whiteness value of 87. It has a specific gravity of about 2.60, and specific surface area (Nitrogen BET Surface Area) of 18,000 m^2/kg. Physical and chemical properties of MK used in this study are also given in Table 1. The origin of the MK is from Czech Republic. Fine aggregate was a mix of river sand and crushed sand whereas the coarse aggregate was river gravel with a maximum particle size of 22 mm. Aggregates were obtained from local sources. Properties of the aggregates are presented in Table 2. Grading of the aggregate mixture was kept constant for all concretes. Sulphonated naphthalene formaldehyde based high range water-reducing admixture with specific gravity of 1.19 was employed to achieve slump value of 14 ± 2 cm for the ease of handling, placing, and consolidation in all concrete mixtures. The superplasticizer was adjusted at the time of mixing to achieve the specified slump.

Table 3
Properties of steel fibers.

Designation of the steel fiber	Diameter *D* (mm)	Length *L* (mm)	Aspect ratio (*L*/*D*)
SF1	0.75	60	80
SF2	0.75	30	40

Two types of commercially available hooked end steel fibers (Dramix 60/80 and Kemerix 30/40) were used for production of steel fiber reinforced concretes. The geometrical properties and aspect ratios of the steel fibers are given in Table 3.

Reinforcing ribbed steel bars having 16 mm diameter and minimum yield strength of 420 MPa were utilized for preparing the reinforced concrete specimens to be used for testing the bonding strength.

2.2. Mix proportions

Two series of concrete mixtures with water-to-binder ratios of 0.35 and 0.50 were designed to produce plain and MK incorporated concretes. MK modified concretes were produced by 10% replacement of the cement with MK by the weight. For production of steel fiber (SF) reinforced concretes, each type of SF (SF1 and SF2) were added to the concrete by 0.25% and 0.75% of the total concrete volume. Therefore, 20 different types of concrete mixtures were produced for examining the mechanical properties of the concretes. The details of the concrete mixtures are given in Table 4.

The designations of each mix were made according to MK incorporation, type of steel fiber, and volume fraction of steel fiber. For

Table 2
Sieve analysis and physical properties of aggregates.

	Sieve size, (mm)	Passing (%)			
		Fine aggregate		Coarse aggregate	
		River sand	Crushed sand	No. I (4–16 mm)	No. II (16–22 mm)
Sieve analysis	31.5	100	100	100	100
	16.0	100	100	100	27.7
	8.0	99.7	100	31.5	0.6
	4.0	94.5	99.2	1.0	0.1
	2.0	58.7	63.3	0.5	0.0
	1.0	38.2	43.7	0.5	0.0
	0.50	24.9	28.4	0.5	0.0
	0.25	5.4	16.4	0.4	0.0
	Fineness modulus	2.87	2.57	5.66	6.72
Physical properties	Specific gravity	2.79	2.42	2.72	2.73
	Absorption,%	0.55	0.92	0.45	0.42