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Fresh and hardened properties of self-compacting concrete containing metakaolin

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HIGHLIGHTS

- Satisfactory workability and rheological properties can be achieved for SCC with MK.
- Workability maintain till about 60 min of hauling time for SCC containing up to 15% MK.
- MK significantly enhanced the compressive strength of SCC within the first 14 days.
- MK inclusion leads to lower absorption, better tensile strength and more electrical resistivity.
- 10% MK in SCC can be regarded as a suitable replacement.

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ABSTRACT

This paper presents the fresh and hardened properties of self-compacting concrete (SCC) containing metakaolin (MK). Totally, fifteen mixes including different MK contents (0–20% by weight of cement) with three water/binder (W/B) ratios of 0.32, 0.38 and 0.45 were designed. The fresh properties were investigated by slump flow, visual stability index, T_{50}, V-funnel and L-box. The slump flow changes with hauling time were also considered. The hardened properties were tested for compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), initial and final absorption and electrical resistivity.

The fresh concrete test results revealed that by substituting optimum levels of MK in SCC, satisfactory workability and rheological properties can be achieved, even though no viscosity modifying agent was needed. MK inclusion significantly enhanced the compressive strength of SCC within the first 14 days up to 27%. Moreover, the compressive strength of SCC with MK can be predicted in terms of UPV by using multiple regression analysis. The tensile strength and electrical resistivity of the SCC containing MK were higher than those of the control SCC by maximum of 11.1% and 26%, respectively. A low absorption (below 3% at 30 min) can be achieved for MK mixes classified as "good" concrete quality. In general, it seems that 10% MK can be considered as a suitable replacement regarding to the economic efficiency, fresh and hardened properties of MK concrete.

1. Introduction

Self-compacting concrete (SCC) is a high flowable concrete, which can be placed and compacted without any vibration in complex or dense reinforced formworks. In order to achieve such behavior, the main requirements of fresh SCC are filling ability, passing ability and very high segregation resistance. The first two properties can be achieved by using a high-range water reducer (HRWR) admixture. To secure stability/cohesion of the mix, a large quantity of powder materials and/or viscosity-modifying admixture (VMA) is required.

According to EFNARC [1], the term powder is defined for materials of particle size smaller than 0.125 mm which includes fraction of aggregate, additions and cement. Portland cement is a highly energy-intensive product. On the other hand, about 7% of total CO_{2eq} emanations are produced by the cement industry [2]. In addition, some disadvantages in the properties of concrete have been reported as the cement content exceeded a specified value [3]. To minimize these negative effects, the requirement to increase powder content in SCC is usually met by the use of additions. For this purpose, substantial studies have been performed on the usage of different additions for partially replacement of cement in SCC or self-compacted mortar such as marble powder [4,5], limestone powder [6], basalt powder [5,6], fly ash [7–9] and slag [10,11].

Previous studies have shown that the use of some additions could result in a lower compressive strength than that of control mixes, especially at early ages. A study by Khatib [7] exploring the effect of different fly ash content on the performance of SCC. The results show that, generally, there is strength reduction for concretes containing fly ash compared with that of the control

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concrete. Similar conclusion has been reported by other researchers for SCC containing fly ash [8,9]. Compressive strength reduction were reported by Boukendakdji et al. [10] for SCC mixtures with increasing slag content up to 15% at all ages. Khatib and Hibbert [11] studied the strength development of concrete with slag and showed there is a systematic decrease in compressive strength as the slag content increases during the early stages of hydration. Uysal and Sumer [5] measured the effect of different mineral admixtures such as granulated blast furnace slag, fly ash, limestone powder, marble powder and basalt powder on the properties of SCC. From the results, it can be concluded all mixtures had the lower compressive strength at 7 days when compared to control mixture. Brick powder, fly ash, limestone powder and Kaolinite were considered as partial replacement of cement by Sahmaran et al. [12]. Their results on compressive strength show that the use of mineral additives in the self-compacting mortar mostly resulted in a decrease in strength and ultrasonic pulse velocity (UPV) values. The lower compressive strength of self-compacting mortar containing marble powder was also reported by Guneyisi et al. [4]. Reduction in compressive strength may leads to some disadvantages in practical applications. For instance, for fast track construction, early age compressive strength reduction may be unacceptable. The utilization of high pozzolanic activity materials seems to be an efficient choice to overcome this difficulty.

Metakaolin (MK) can also be considered as addition in the production of SCC. MK (commercially available since the mid-1990s [13]) is a thermally activated alumino-silicate material mostly produced by calcination of kaolin clay at temperature ranging from 700 to 850 °C [14] without production of CO_2 [15,16]. MK processing involves lower temperatures than Portland cement which may yield a lower cost on MK production. But, due to the low production of MK, the price will be raised up [16]. Nonetheless, the usage of MK in concrete can be reasonable due to its environmental benefits [15,16] and positive effect on the both short and long terms strength of concrete.

In this respect, it has been reported that the use of MK in concrete can increase the compressive strength of mixtures especially during early ages of hydration. Poon et al. [17] showed that at early ages, the higher pozzolanic activity of MK results in a higher rate of strength development and pore structure refinement when compared to silica fume -or fly ash- blended cement pastes. However, at the same level of replacement, MK concrete had similar strength after 28 days with respect to silica fume concrete [18]. Kim et al. [19] measured the concrete strength with Korean MK and suggested that 10% replacement of MK is an appropriate replacement. Considering durability aspects, the positive effect of MK was reported in literature. Zhang and Malhotra [18] reported that 10% MK concrete shows excellent performance under freezing and thawing. It is generally accepted that incorporation of MK improves the resistance to chloride penetration. From the chloride penetration test results presented by Poon et al. [20], it can be observed that the MK concrete shows lower total charges passed up to 87% compared with control concrete. More recently, Shekarchi et al. [21] reported that at 15% replacement of MK, transport properties of concrete measured in terms of water penetration, gas permeability, water absorption, electrical resistivity and ionic diffusion were improved up to 50%, 37%, 28%, 450%, and 47%, respectively. The positive effect of MK addition on the corrosion resistance property of specimens was reported by researchers [22,23]. For instance, Batis et al. [23] shows the usage of MK, either as a sand replacement or as a cement replacement, could improve the corrosion behavior of mortar specimens.

However, different aspects of normal concrete containing MK have been reported in literature but to the authors' knowledge, the performance of MK in SCC is not well documented, particularly over a wide range of water/binder (W/B) ratios. In particular, the effects of MK as a high surface area mineral addition on the workability as well as mechanical properties of SCC need to be fully recognized. So, the present study is an effort to characterize the fresh and hardened properties of SCC containing MK. For this purpose, several tests concerning slump flow, T_{50}, visual segregation index (VSI), V-funnel and L-box were conducted to assess the workability of the matrix. To simulate the real-world applications, the slump flow values were measured at different hauling times. Furthermore, hardened properties were evaluated by compressive strength, splitting tensile strength, UPV, initial (30 min) and final water absorption and electrical resistivity.

2. Experimental plan

2.1. Materials

Type I Portland cement conforming to ASTM C150 and MK were used as binder materials in the production of concrete mixes. The chemical compositions and physical characteristics of binders are given in Table 1. Also, the particle size distribution curves of binders are shown in Fig. 1. The fine aggregate was natural river sand. Limestone gravel with water absorption of 0.73 and a nominal maximum size of 12.5 mm was used as coarse aggregate. Polycarboxylic ether based high range water reducer (HRWR) namely *Glenium51* with density between 1.06 and 1.08 g/cm^3 (at 20 °C) was used to enhance the flowability of the mixtures. In addition, a polysaccharide based VMA in an aqueous solution with a concentration of 20% was used.

2.2. Mixture proportion

Based on the W/B ratios of 0.32, 0.38 and 0.45, SCC mixtures were designed in three groups which defined as G1, G2 and G3, respectively. In each group, the reference concrete was prepared by only Portland cement while in the remaining mixtures Portland cement was partially replaced with the MK. The amount of MK in

Table 1
Chemical composition of Portland cement and MK.

	Cement	MK
Chemical composition (%)		
SiO_2	21.46	52.1
Al_2O_3	5.55	42.8
Fe_2O_3	3.46	1.6
CaO	63.95	0.2
MgO	1.86	0.21
SO_3	1.42	0.00
K_2O	0.54	0.32
Na_2O	0.26	0.11
Physical properties		
Specific surface (m^2/g)	0.33	2.54
Specific gravity	3.15	2.6

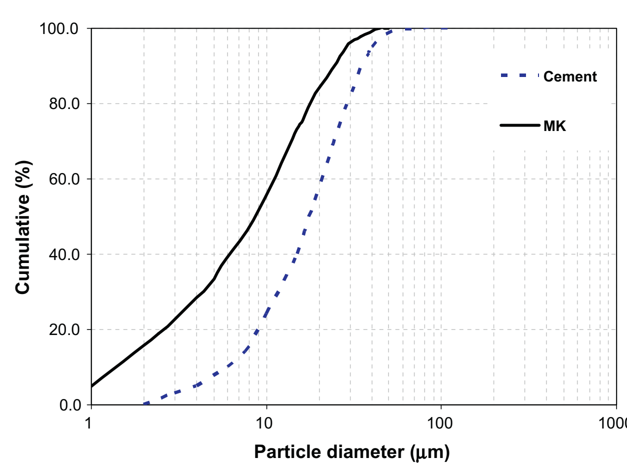

Fig. 1. Particle size distribution for binders.