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Performances evaluation of binary concrete designed with silica fume and metakaolin

Mohammed Seddik Meddah [a,*], Mohamed A. Ismail [b], Sherif El-Gamal [a], Heni Fitriani [c]

[a] Dept. of Civil & Architectural Engineering, College of Engineering, Sultan Qaboos University, Al-Khod 123, Oman

[b] Dept. of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia, Miri 98000, Sarawak, Malaysia

[c] Civil Engineering Department, Faculty of Engineering, Universitas Sriwijaya, Palembang, Indonesia

HIGHLIGHTS

- Using SF and MK in concrete industry reduce clinker production and consumption.
- The use of SF and MK also reduce the ECO_2.
- Strength and durability are improved even with low replacement level of 5–10%.
- Overall, SF pozzolana seems to perform better than MK.

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ABSTRACT

The use of various pozzolanic and cementitious materials not only has an environmental and economic impact, by the reduction of Portland cement clinker production, but also could significantly improve the strength and durability performances of concrete. Silica fume (SF) is a well-known and largely used pozzolanic material due to numerous improvements that could provide to concrete while metakaolin (MK) even with quite similar performance is still less popular in concrete industry. The present study investigates and compares the key mechanical properties and durability performances of binary concrete mixes designed with different replacement levels of SF and MK varying from 5% to 25% of Portland cement (PC).

The results indicate that using both SF and MK in a partial substitution of PC could significantly improve strengths and durability performances of blended cement concrete mixes in comparison with the control PC-concrete. Meanwhile, SF-concrete seems to perform better than MK-concrete with regards to strength development and resistance to freezing-thawing while MK-concrete has exhibited a better performance with regard to carbonation and chloride ions ingress. Furthermore, although economical assessment showed an increase in the cost of concrete made with SF/MK due to the fact that SF/MK are more expensive than PC, environmental assessment revealed that significant reduction of the embodied CO_2 (ECO_2) is generated when using MK, and especially SF as a partial substitution of PC. Designing a binary SF and MK concretes may help towards producing clean and environmentally friendly concrete material.

1. Introduction

Silica fume and metakaolin are both considered as ultrafine pozzolanic materials leading to appreciable enhancement of strength properties and durability performances of concrete. Substantial increase in autogenous shrinkage and water/admixtures demand are also recognized when using these two powders in partial substitution of PC in concrete [1–6].

Silica fume is composed mainly of non-crystalline silica generated by electric furnaces as a by-product of the manufacturing process of silicon metal and ferrosilicon alloys. Silica fume is an ultrafine powder consisting mainly of spherical particles with an average diameter of around 0.15 μm and an extremely high specific surface area ranging between 13,000 and 30,000 m^2/kg. Each SF particle is considered to be 100 times smaller than the average cement particle size. It is believed that in a typical 10% SF replacement of Portland cement, there will be from 50,000 to 100,000 SF particles for each cement particle [7].

Silica fume is one of the most used pozzolanic material to improve strength and significantly enhancing impermeability and

* Corresponding author.
E-mail address: seddikm@squ.edu.om (M.S. Meddah).

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durability performances and produce high/ultra-high performance concrete [8]. Throughout the years, both laboratory investigations and field applications have proven the superiority of this material over all other recognized pozzolanic and cementitious materials. The major disadvantages of SF might be summarized into an increased water and chemical admixtures demand, an increased self-desiccation shrinkage and the resulted internal tension stress [2–5,9–11] and a higher cost compared to all other existing conventional pozzolanic materials [12].

Unlike fly ash (FA), SF, slag and other supplementary cementitious materials (SCMs), MK is not a by-product generated by an industrial process; it is a product manufactured under well-controlled conditions. MK is produced by heating kaolin to temperatures of 600–900 °C. This calcination process, leads to change in the structure of kaolin and transform it to an amorphous and highly reactive pozzolanic material, suitable for use in cement-based applications [13,14].

Generally, the average size of MK particles is ranging from 0.5 to 5 μm, which makes them smaller than PC particles but larger than SF particles. Both MK and SF are typically introduced in concrete at 5 to 10% as partial replacement of PC. Standard SF ranges from grey to black in color while MK is white. This makes MK very attractive in architectural applications where white and lighter colors are preferred as well as in the production of high-performance concrete [15,16].

Both MK and SF are known to react with calcium hydroxide (CH) and form additional calcium-silicate-hydrate (C—S—H) thus, a denser hydrated cement paste structure could be achieved. It has been shown that the rate of the pozzolanic reaction and consumption of CH in MK-PC system is higher than in SF-PC system, which indicates a higher initial pozzolanic activity [6]. This rapid and early pozzolanic reaction with CH may contribute to shorten the initial and final setting times of PC-MK system [6,13,14]. In addition, the pore network refinement and densification of the matrix in the interfacial transition zone (ITZ) can lead to an enhancement of the MK-concrete strength [17] and high early autogenous shrinkage [6].

Strength properties, including compressive, splitting tensile, and flexural as well as modulus of elasticity have been found to increase in MK-concrete as compared to control concrete while setting time was found to be shorter in MK-mixtures [18,6]. The use of MK also decreases the permeability of concrete and hence, increases its resistance to harmful substances such as chloride ions ingress and sulfate attack [15,19–21] and improve the overall concrete durability. Wild and Khatib [14] also found that MK-mixtures reduced expansion due to alkali-silica reaction (ASR) and chloride ions penetrations when compared to PC and PC-SF mixtures. In fact, the reduction in the ASR expansion in MK-mixtures is mainly due to the formation of additional C—S—H by the pozzolanic reaction with MK due to a lower Ca/Si ratio compared to that in conventional C—S—H. This secondary C—S—H resulted from the pozzolanic reaction of MK-CH is believed to bind alkalis ions available in the system, and hence, reduce risk of ASR in MK-concrete [13,22].

Therefore, using MK and SF as a partial substitution of PC could improve both the engineering properties and durability performances of concrete, and also significantly reduce the ECO_2 generated by concrete. Several research works dealing with the effect of SF or MK on fresh and hardened properties of concrete have already been carried out and published. However, very limited studies have focused on comparing the mechanical, durability, economic and environmental performances of these two ultrafine powder on concrete material.

In the current study, the key fresh properties, mechanical and durability performances of concrete mixes designed with various replacement levels of PC by both SF and MK were examined. A comparison of concrete made with the same replacement content of SF/MK was considered. In addition and due to the environmental impact of concrete industry, an environmental assessment in terms of ECO_2 and an economical estimation were also carried out.

2. Experimental methods

2.1. Materials

An ordinary Portland cement CEM I 42.5N conforms to EN 197-1:2000 [23] was used in all control concrete and mixes with various replacement levels (by weight) of PC by SF and MK were adopted to form binary binders. In these binary binders, PC was partially substituted by SF at ranges from 0 to 20% and MK replacement was from 0 to 25%. The physical properties, chemical and mineralogical compositions of the PC and the two pozzolanic admixtures (SF and MK) used are presented in Table 1. Both SF and MK used could be considered as high siliceous materials and are in line with the key requirements of ASTM C1240 and ASTM C618-12a standards, respectively [24,25]. The particle size distributions of PC, MK and SF are presented in Fig. 1.

Fine aggregate used consists of river sand of 0–5 mm with a fineness of 2.4 while coarse aggregate (CA) consists of two granular fractions of 5–10 mm and 10–20 mm of crushed granite. A required amount (expressed as% of cement weight) of polynaphthalene sulfonate superplasticizer (SP) conforming to BS 5075: Part 3 and ASTM C494 [26] was introduced to reach an average targeted slump of 75 ± 5 mm, and an air-entraining agent compliant to BS 5075: Part 2 was used to enhance the freeze-thaw resistance of air-entrained concrete.

2.2. Concrete mixes and specimen preparation

Concrete mixes (PC and binary) were prepared with five different water-to-cementitious materials ratios (*w/cm*) of 0.45, 0.52, 0.60, 0.65 and 0.79. This wide range of *w/cm* was selected to investigate the effect of using various contents of SF and MK on the overall performance of binary concretes. To maintain the yield, the fine aggregate content was slightly adjusted while the total amount of coarse aggregate (1200 kg/m^3) was kept constant. The detailed mix design of both PC-concrete and binary cements concretes tested is given in Table 2. Concrete mixes were properly labelled as given in Table 2 and produced using a pan mixer concrete. Both SF and MK were introduced in the mixer immediately following cement and after aggregates, but prior to water. The dry ingredients were mixed for 1 min for homogenization. Superplasticizer was mixed and homogenized with water and then added gradually to the mix while the mixer is operating. The wet mixing was operated for 3 min. Slump test was carried out on all mixes immediately after the end of the mixing sequence and before concrete was cast in the moulds.

Three specimens at each testing age of the control mix and binary concrete mixes with SF or MK referred to as PC, PC-SF and PC-MK respectively, were investigated in terms of their mechanical and durability performances as described below in the testing procedures section. Binary mixes SF and MK label are followed by a number indicating the replacement level of PC by SF and MK. All specimens tested were cast in metallic moulds (cylinders, cubes and prisms) in three layers and compacted with a vibrating table as indicated in BS 1881: Part 108: 1983 [27]. Immediately after casting and for the first 24 h, all concrete samples were kept in their moulds in a laboratory environment and covered with plastic membrane.

Table 1
Main physical properties and chemical composition of PC, MK and SF used.

Constituents	PC	SF	MK
Chemical composition, %			
SiO_2	21.4	95.3	55.1
Al_2O_3	4.7	0.65	40.4
Fe_2O_3	2.7	0.28	0.64
CaO	65.2	0.27	0.03
MgO	1.0	0.41	0.36
SO_3	2.9	0.25	–
TiO_2	–	–	0.01
Total Alkali, Na_2Oe	0.55	0.767	1.39
LOI	0.9	–	1.2
Bogue composition, %			
C_3S	67.3	–	–
C_2S	10.6	–	–
C_3A	7.9	–	–
C_4AF	8.2	–	–
Physical properties			
Density, kg/m^3	3140	2200	2590
Fineness, m^2/kg	381	15,750	12,474
Residue on 45 μm,%	6.2	0.2	0.4