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Research paper

Microstructural studies on eco-friendly and durable Self-compacting concrete blended with metakaolin

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ABSTRACT

The study focusses on to reduce the carbon dioxide (CO_2) emission into atmosphere and energy consumption through use of pozzolanic materials that improve the structural properties by using vibration free concrete. In this concern, self-compacting concrete (SCC) was prepared with metakaolin (MK) as a partial replacement of ordinary Portland cement (OPC). The positive environmental effect of MK has studied by calculating the CO_2 emission during the OPC and MK production. The durability properties of SCC were investigated through the measurement of water absorption, sulphate attack and chloride permeation to study the environmental benefits indirectly. The effects of MK on internal characteristics of concrete samples were observed by scanning electron microscope (SEM). To evaluate the intensity of the elements in paste compositions, X-ray diffraction analysis (XRD) and energy dispersive X-ray analysis (EDX) were accomplished. The results indicated that a SCC specimen with 10% of MK by weight of cement has resistance to magnesium sulphate solution, chloride diffusion and water absorption. In addition, microstructural analysis confirmed that SCC specimen with 10% MK has reduced intensity of gypsum, ettringite and brucite which were responsible for expansion and cracking of concrete due to the sulphate attack. Hence based on the durability parameters 10% replacement of MK was optimized. Further, MK reduces the use of OPC with less thermal energy and CO_2 emission.

1. Introduction

The concepts of sustainable development and service life are increasingly used in the construction industry. Cement is the most commonly used construction material in the construction industry. This is an energy exhaustive material and responsible for more CO_2 emission. Hendriks et al. (2004) reported that the amount of CO_2 emission in cement manufacture depends on production technique, process and clinker/cement ratio and fuel used. They concluded that use of alternative fossil fuel and blended cements may reduce CO_2 emissions by 20–40% and 20% respectively. Hwang et al. (2015) estimated that the amount of limestone, fossil fuel and use of electricity to produce 1 t of cement ranged from 1.19 to 1.47 t, 68.1 to 97.3 kg and 96.3–119.6 kWh respectively. Adopting the optimized energy sources, alternative raw materials and cements with reduced clinkers will reduce the CO_2 emission from cement industries (Damtoft et al., 2008). Increasing the usage of pozzolanic materials enhance the durability of concrete and reducing the CO_2 emission, because durable structures require less repair and maintenance in this manner service life of structures is also increased (Guneyisi et al., 2008).

The utilization of pozzolans is a trend getting much greater attention and increase with increasing awareness of the environmental protection and sustainable construction (Papadakis and Tsimas, 2002). Therefore there are compelling reasons in the long - term, to extend the practice of partially replacing cement in mortar and concrete with any by- product or pozzolanic materials. It was generally accepted that pozzolans significantly improve the resistance to chloride attack through chloride binding and pore filling effects (Rafik et al., 2010). The incorporation of pozzolanic materials in SCC can improve the strength, durability, reduce the cost and also avoid the ill effects due to improper compaction (Eva et al., 2011). The durability of concrete containing pozzolans is enhanced due to the pozzolanic reaction of various compounds present in the cement during the hydration process (Poon et al., 2001). The most commonly used pozzolanic materials are Silica Fume (SF), fly ash, blast furnace slag, MK and rice husk ash. During the hydration of cement calcium hydroxide (CH) and calcium silicate hydrate (C–S–H) are formed. CH is the most soluble hydration product, and this is a weak link in cement and concrete from durability point of view. When the concrete is exposed to water, the CH will dissolve, increasing the porosity and thus making the concrete more vulnerable to further leaching and chemical attack. Pozzolanic reaction of MK forms additional cementitious C–S–H gel, together with crystalline products, which include calcium aluminate hydrates and alumino-silicate hydrates (C_2ASH_8, C_4AH_{13} and C_3AH_6). These pozzolanic

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Table 1
Chemical and physical properties of OPC and MK.

Chemical constituent %	OPC	MK
SiO_2	21.04	52.24
Al_2O_3	5.02	43.18
Fe_2O_3	3.12	0.6
CaO	62.11	1.03
MgO	2.44	0.61
K_2O	0.56	–
Na_2O	0.28	–
Physical properties		
Specific gravity	3.16	2.54

products contribute to a total pore refinement (Badogiannis and Tsivilis, 2009). Wild et al. (1996) reported that the refined pore system results in more compact concrete, through which transportation of the water and other aggressive chemicals is significantly impeded and therefore a decrease in the diffusion rate of harmful ions.

Hwang et al. (2015) estimated the CO_2 emission during the cement manufacturing process of cement. Ordinary Portland cement results from calcination of limestone and silica in the following reaction (at 1500 °C) produces CO_2

$$5CaCO_3 + 2\ SiO_2 \overset{\Delta}{\rightarrow} (3CaO \cdot\ SiO_2)(2CaO \cdot SiO_2) + 5CO_2. \quad (1)$$

One ton of cement produce 822 kg of CO_2 during extraction and burning process of limestone as well as calcination produces 495 kg CO_2 (Hwang et al., 2015).

Franck et al. (2010) studied the effect of mineral admixtures (limestone filler, siliceous filler, SF, MK) on the SCC for precast industry in the economic and environmental aspects. They found that incorporation of MK produced positive effect such as economic and environmental concerns. They reported the environmental values concerning energy consumption and energy balance CO_2 emission. MK is produced from heating kaolin (dehydroxylation) to temperatures of 650–900 °C without CO_2 emission (Sabir et al., 2001). The dehydroxylation of kaolin given in following equation,

$$Al_2\ O_3 \cdot 2SiO_2 \cdot H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + H_2O. \quad (2)$$

Al-Akhras (2006) investigated the resistance of MK on conventional concrete subjected to sulphate attack. He found that sulphate resistance of MK concrete increased with increasing the MK replacement level and he showed that concrete containing 10 and 15% MK replacements showed excellent durability to sulphate attack. Bonda et al. (2014) studied the changes in compressive, expansion and capillary water absorption of geopolymer concrete subjected to sulphate attack. They also investigated the phases by means of XRD. Ramlochan and Thomas (2000) studied the effect of partial replacement of High-Reactivity MK (HRM) with cement on mortar. Their results indicated that HRM had beneficial effects on resistance to sodium sulphate attack. Kiachehr and Omid (2013) examined the effect of pozzolanic binders such as SF, MK and zeolite on SCC in magnesium sulphate environment. They reported that addition of MK and zeolite in concrete specimen exhibit positive effects when compared to SF. This negative effect was due to the formation of brucite (magnesium hydroxide) which is responsible for expansion and cracking of concrete. The intensity of elements evaluated by EDX analysis shows that SF had high intensity for brucite when compared to MK and zeolite. This positive effect occurred in these were due to the least volume expansion and least loss of mass.

The required service life, design requirements and anticipated exposure environments of structures are not only achieved by appropriate materials but also by properly designed, prepared and well compacted concrete (Ahmed and Assem, 2015). The quality and durability of concrete may be affected by unsuitable materials and improper compaction. To overcome such difficulties, vibration free SCC with inclusion of pozzolanic materials was used (Eva et al., 2011). SCC is a highly fluid concrete mixture that can compact under its self-weight without segregation (Rahmat and Yasin, 2012). Bassuoni and Nehdi (2007) investigated the durability of different SCC mixes under sulphate attack. The variables they considered were different types of binders, their combinations, air-entrainment, sand-to-total aggregates mass ratio and hybrid fibre reinforcement. The study revealed that blended binders and hybrid fibres showed more resistance to sulphate attack. Khatib and Wild (1998) found that MK has a beneficial effect on resistance to sodium sulphate attack of mortar at the replacement level of 15%.

The best recognized chemical consequences of magnesium sulphate attack on concrete components are the formation of ettringite (calcium aluminate trisulphate 32 hydrate, $CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$), gypsum (calcium sulphate dihydrate, $CaSO_4 \cdot 2H_2O$) and brucite. The formation of ettringite can result in an increase in solid volume, leading to expansion and cracking. The formation of gypsum can lead to softening and loss of concrete strength. The presence of ettringite, gypsum and brucite are the evidences of sulphate attack and these were verified by petrographic and chemical analyses.

In this study SCC mixes were prepared by partially replacing cement with MK. To assess effect of MK on durability, water absorption, sulphate attack and chloride penetration tests were performed on SCC specimens. The formation of ettringate, gypsum and brucite were also studied by EDX, SEM and XRD analysis. Further environmental balance of MK in SCC based on energy and CO_2 emissions were also studied.

2. Materials and methods

2.1. Materials

Concrete specimens were prepared using 53 grade cement and MK. MK conforming to IS: 12269 (1987) procured from Indian English Clay Limited, Trivandrum, India was used. Table 1., shows the physical and chemical properties of OPC and MK. Locally available well graded coarse aggregate and fine aggregate (conforming to IS: 383 1987) were used. To improve the workability of SCC, newly developed poly-carboxylic ether based Super Plasticizer (SP) was used as a high range water reducer (IS 9103: 1999).

2.2. Mix proportion and preparation of the specimens

Kavitha et al. (2015) carried out tests on the fresh concrete as per EFNARC (2005) guidelines and arrived at a SCC mix proportions incorporating of MK as a replacement material for OPC. They reported that 10% MK replacement offered better micro (micro crack width, Ca: Si ratio and C–S–H formation) and macro (mechanical) level properties. The mix proportions for the present study were taken from Kavitha et al. (2015) and presented in Table 2. The control SCC mix contained 500 kg m^{-3} cement and in the other SCC mixes; cement was replaced with 5, 10 and 15% MK by weight. To obtain the required SCC mix tests were conducted on fresh concrete as per EFNARC (2005) guidelines. The water/binder ratio was taken as 0.38 and SP content was varied between 3 and 5 kg m^{-3} at every MK replacement level. The mixes that satisfied the requirements of passing ability, filling ability

Table 2
Mix proportion for SCC (kg/m^3).

Constituents	Binder		FA	CA	Water	SP
	Cement	MK				
MK0	500	–	900	650	190	3
MK5	475	25	900	650	190	3
MK10	450	50	900	650	190	4
MK15	425	75	900	650	190	5