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Mechanical and microstructural properties of self-compacting concrete blended with metakaolin, ground granulated blast-furnace slag and fly ash

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HIGHLIGHTS

- The amount of SP increased with the increase of MK and GGBS in SCC to achieve the same consistency as PC.
- MK gave the most enhancing effect as an SCM on mechanical and microstructural properties of SCC.
- MK and GGBS were able to enhance modulus of elasticity which was correlated well with strength of SCC.
- MK has a greater effect on the microstructural strength of the transition zone than GGBS.
- Lower Ca/Si ratios indicate the improvement of compressive strength.

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ABSTRACT

The aim of this study is to investigate the mechanical and microstructural properties of self-compacting concrete (SCC) mixtures containing three supplementary cementitious materials (SCMs), namely metakaolin, ground granulated blast-furnace slag and fly ash. For the mixtures, cement was replaced by SCMs at different levels. The mechanical properties were evaluated against a control mixture (without SCM). The microstructural properties were examined using SEM and EDS on mixtures with high volume of SCMs. The utilisation of SCMs enhanced compressive strengths. Metakaolin gave the most enhancing effect as a replacement material to cement on mechanical and microstructural properties of SCC at all ages.

1. Introduction

Self-compacting concrete (SCC) is a new type of high-performance concrete characterized by its ability to flow and compact under its own weight without the need of any external vibrations and also fill the formwork whilst maintaining homogeneity without any migration or separation of its large components even in the presence of congested reinforcement [1,2]. Researchers [3–6] have defined SCC in almost the same terms as a highly flowable concrete that should meet the requirements of flow-ability, passing ability and segregation resistance.

In the last two decades, SCC has been developed further, utilising various supplementary cementitious materials (SCMs) such as metakaolin (MK) [7–14], fly ash (FA) [9,11–14] and ground granulated blast-furnace slag (GGBS) [9]. The incorporation of different SCMs in concrete can have a considerable effect on both fresh and hardened phases [7–14]. All SCMs have two common features; their particle sizes are smaller than or the same as Portland cement (PC) and they exhibit pozzolanic behaviour involving in the hydration reactions. Pozzolans, which contain silica (SiO_2) in a reactive form, have little or no cementitious value by themselves. However, in a finely divided form and in the presence of moisture they chem-

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ically react with calcium hydroxide (CH) at ordinary temperatures to form cementitious compounds [15,16].

GGBS is a by-product from the blast-furnaces used to make iron. It has been successfully utilised in many countries around the world achieving many technical benefits in construction industries [17,18]. Adding GGBS to self-compacting concrete offers many advantages related to increasing its compactability, consistency and retaining it for a longer time, while protecting cement against both sulphate and chloride attack [19]. Because GGBS has about 10% lower density than PC, replacing an equal mass of cement by GGBS will result in a larger paste volume, which extensively increases the segregation resistance and flow ability. A study was carried out by Oner and Akyuz [20] on 32 different mixtures of SCC containing GGBS, indicated that as GGBS content increases, water to binder ratio decreases for the same consistency and thus GGBS has a positive effect on the consistency. They specified further that the compressive strength of concrete mixes containing GGBS increases with increase of GGBS replacement level.

Metakaolin is produced by heat-treating kaolin, one of the most abundant natural minerals at ascetically high temperatures, ranging from 650 to 800 °C [21,22]. MK normally contains 50–55 percent SiO_2 and 40–45 percent Al_2O_3 [23,24]. Other oxide particles exist in small quantities including Fe_2O_3, TiO_2, CaO, and MgO. MK particles are generally finer than cement and coarser than silica fume particles in an order of scale. Due to the controlled nature of the processing, MK powders are very consistent in appearance and performance [25]. Regardless of the reactivity of an SCM, if it is extremely fine, it will generally impart some benefit to mortars and concrete. Small particles, which can fit between cement grains, allow for more efficient paste packing, which in turn reduces bleeding, lowers the mean size of capillary pores, and may reduce water requirements due to a ball bearing effect (if the particles are round) [26]. Improved particle packing at the aggregate/paste interface results in a thinner transition zone with a denser, more homogeneous microstructure [27]. In addition, acting together, many small particles have a large total surface area, leading to an increase in reactivity. Typically, SCMs such as MK with higher volume of alumina substances, incline to have higher pozzolanic capacities. This is because of the formation of C-A-H which has a high CH demand. This is actually critical, as CH does not affect concrete strength significantly and can be disadvantageous to durability. The removal or reduction of CH particles can be satisfied by secondary reaction with MK. Therefore, MK can greatly enhance concrete performance [26,28]. There is little existing literature regarding the effect of metakaolin on the modulus of elasticity. As it has been shown to increase compressive strength and to densify the microstructure, it follows that MK might also lead to increased elastic modulus, or stiffer concrete. From the literature, modulus of elasticity generally seems to increase with increasing MK content, although the rate of increase is lower than that for compressive strength [29].

FA or pulverised fuel ash (PFA) in the UK is a by-product of coal fired electricity generating plants. It can be used as a partial replacement of cement in SCC, because of its pozzolanic properties. FA can generally improve both fresh and hardened properties of SCC and can be replaced up to 30 percent of PC by mass. However, FA reacts more slowly than conventional concretes made with PC and therefore the maximum strength needs more time to gain. Adding FA to SCC mixture can improve its rheological characteristics while reducing water demand, because of its small spherical shape [30]. Furthermore, additional studies showed that the effect of FA on the workability of super flowing concrete by replacing 30% of cement with FA can result in outstanding workability [31]. FA can also increase the reactivity of SCC. This effect can lead concrete to increased compressive strength, improved durability and reduced drying [32]. Fly ash can also decrease bleeding and develop constancy [33].

The main aim of this research work was to utilise three types of SCMs: metakaolin, fly ash and GGBS in SCC and to study its effect on hardened and microstructure at different replacement levels of cement (10 and 20 wt% for MK and 10, 20 and 30 wt.% for FA and GGBS) because it was reported in the literature that in major cases concrete blended with SCMs exhibits better performance in strength and improvement in pore structure. The rheological properties were examined by conducting several tests as per The European Guidelines for Self-Compacting Concrete [34] specifications and proper mix proportion was achieved. To assess the mechanical properties of SCC mixes compressive strength and modulus of elasticity were evaluated. For the mixes with higher volume SCMs, the micro-analyses using scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDS) were carried out to assess the Ca/Si ratio.

2. Experimental work

2.1. Constituent materials

Portland cement CEM II/B-V 32.5R, manufactured by Lafarge Company, was used throughout this study. Fly ash used in this experiment is classified as siliceous fly ash (alumino-silicate fly ash) or class F Fly Ash, according to BSI standards [35] where the essential chemical components are silicates and aluminates. The Blaine fineness (specific surface area) of the FA was 35.48 m^2/N (3478 cm^2/g). GGBS in this research comprises mainly of CaO, SiO_2, Al_2O_3 and MgO. It has the same main chemical composition as ordinary Portland cement, but in different proportions. The metakaolin used in this research contained 25% silicon and 20% aluminate. MetaStar 501, obtained from IMERYS Performance Minerals Company, was utilised in this investigation. According to the data sheet provided by IMERYS [36], the specific gravity of the sample used with white colour was 2.5 g/cm^3. The limestone powder used as filler in this study was hydrated lime with 38% calcium and fine particles. Table 1 gives the chemical compositions of cement, MK, FA and GGBS and limestone powder.

The coarse aggregates used in this research were crushed limestone. These aggregates were in one grade size of 10 mm, supplied by a local quarry in the UK in compliance with the requirements of BS EN 12620:2002 + A1: 2008 [37]. The sand used throughout this study was natural sea-dredged from the Bristol Channel in accordance with PD 6682-1:2009 [38] and BS EN 933-1:2012 [39]. ADVA Flow 340 from Grace Company was used as a High Range Water Reducer Admixture (HRWRA) or Superplasticiser (SP). ADVA Flow 340 conforms to BS EN 934-2:2009 + A1:2012 [40].

2.2. Mix design

Mix design method employed in this research was based on the paste volume [34] with appropriate water/powder ratios, which were kept in the range of 0.85 to 1.1 recommended by The European Guidelines for Self-Compacting Concrete [34]. Fig. 1 shows the flowchart of the mix design method used in this study.

In total, 18 SCC mixtures with two water/binder ratios (0.4 and 0.45), including two PC only SCC mixes and two groups of 8 mixtures with different percentage of SCMs, were investigated. In each group, metakaolin replaced at 10 and 20 percent of the normal SCC mixture's cement content by weight. GGBS and FA also replaced at 10, 20 and 30 percent of cement content. Binder content 400 kg/m^3 was kept the same for all mixtures. The mixture proportions are given in Table 2. The amount of superplasticiser was added until satisfying the fixed slump flow target 750 ± 20 mm. The mix codes,