Construction and Building Materials 79 (2015) 326–336

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Permeability properties of self-consolidating concrete containing various supplementary cementitious materials

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HIGHLIGHTS

- Several amounts of SCM were used as binary, ternary and quaternary blends in SCC.
- Silica fume, Class C and F fly ash, metakaolin and slag were studied in one paper.
- Good correlation was established between permeable voids and water absorption rate.
- SCM reduced the permeability of almost all mixtures.
- Class C fly ash improved the permeability better than Class F fly ash.

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form 5 January 2015
Accepted 8 January 2015
Available online 28 January 2015

Keywords:
Self-consolidating concrete
Supplementary cementitious materials
Compressive strength
Rapid chloride permeability
Water penetration depth
Water absorption
Sorptivity

ABSTRACT

In this study, permeability properties of 17 self-consolidating concrete (SCC) mixtures containing various supplementary cementitious materials (SCM) were investigated by different experimental approaches. The effects of SCM type and content on the compressive strength, rapid chloride ion permeability (RCPT), water penetration depth, water absorption and sorptivity were studied. For these purposes, various amounts of silica fume (SF), metakaolin (MK), Class F fly ash (FAF), Class C fly ash (FAC) and granulated blast-furnace slag (BFS) were utilized in binary, ternary, and quaternary cementitious blends. Results showed that partial replacement of PC by SCM increased the compressive strength of control mixtures at 28 and 90 days (except for FAF at 28 days). Mixtures containing MK presented a better performance compared to other SCM at 7 days. The utilization of SCM reduced the RCPT results of almost all mixtures compared to the control mixtures and the reduction was more significant with an increase in the SCM content. All of the mixtures containing SCM had lower penetration depths when compared to reference mixtures at 28 and 90 days. Good correlations were established between the percentage of permeable voids and water absorption. Moreover, there was an inverse but almost linear relationship between permeable voids content and compressive strength of the mixtures.

1. Introduction

Self-consolidating concrete (SCC), one of the latest achievements of concrete technology, was first emerged by Japanese researchers in the second half of 1980s. It is considered as a concrete which can flow readily under its own weight to completely fill the formwork and self-consolidate without any mechanical vibration. This kind of concrete must achieve magnificent deformability and great stability to ensure high filling capacity of the formwork with complicated shapes, deep and narrow sections and congested structural members [1,2].

One of the most important differences between SCC and conventional vibrated concrete is the incorporation of supplementary cementitious materials (SCM), such as fly ash (FA), blast-furnace slag (BFS) and silica fume (SF) at higher volumes in SCC. Thus, a number of studies about the effects of SCM on the fresh and hardened properties of SCC have been conducted. It was reported that utilization of SCM in SCC not only improves the rheological properties and stability of the fresh concretes but also can decrease the cost of SCC and the amount of the CO_2 production related to the use of Portland cement (PC) in concrete. On the other hand, utilizing by-products or wastes as alternative cementitious materials in concrete provide a more sustainable concrete technology through the creation of a balance between development and environment.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.01.053
0950-0618/

In addition, the use of SCM in SCC mixtures improves the mechanical, durability and long term properties of concrete [3–10].

FA is one of the most widely used SCM in SCC. The current annual worldwide production of coal ash is estimated about 700 million tones of which at least 70% is fly ash [11,12]. Many studies [13,14] reported that the use of FA in concrete reduces the dosage of HRWR to obtain similar workability compared to concrete made with only PC and improves the rheological and mechanical properties and durability of concrete. Moreover, FA utilization reduces the demand for cement, fine fillers and viscosity-enhancing chemical admixtures in SCC [15,16].

Another important SCM that has more application in production of SCC is BFS. Each year, in spite of 250 million tones production of BFS in the world, just 90 million tones of it has been utilized in the production of concrete [17]. Similar to FA, utilization of BFS in concrete may increase the workability, durability and long-term properties of concrete [17,18].

SF is considered one of the most effective SCM that greatly increases the strength and significantly reduces the permeability of concrete. In spite of its a few disadvantages such as its limited availability, difficulty to obtain the desired workability and the current high price (relative to PC and other SCM) of SF, it is being used increasingly as a property-enhancing material [19,20].

Metakaolin (MK) is a thermally activated aluminosilicate material processed by calcining kaolin clay within the temperature range of 650–800 °C. An important difference between MK and other SCM is that MK is a primary product, while FA, BFS and SF are secondary products or by-products. Thus, MK can be produced with a controlled process to achieve the desired properties [21,22]. In recent years, there has been a growing interest in the use of MK as a SCM to produce concretes with improved properties. However, only a limited number of studies are available about the properties of SCC containing MK. According to the previous studies [5,7,22] it has been reported that the concrete incorporating MK has a higher compressive strength with no detrimental effect on the long-term strength, higher resistance to the transportation of water and diffusion of harmful ions and higher durability aspects than the control PC concrete.

Despite the above-mentioned advantages of SCM in SCC, they may also weaken SCC properties compared to the plain mixture containing no SCM. For instance, SF and MK significantly increase the early strength and considerably reduce the permeability of SCC but may impair the required workability in fresh concrete [5,20–22]. On the contrary, FA and BFS generally decrease early strength but improve workability [5,8,13,16]. These negative effects may be hindered by combined use of the SCM in concrete by providing a synergistic effect [4,5,23]. However, there is only limited work on the use of ternary and quaternary blends of SCM in SCC. Such a lack of information has found significant importance in this investigation.

The current study focuses on the permeability properties of SCC containing various amounts of SF, FA, MK and BFS as a partial replacement of cement. These SCM were used in binary, ternary, and quaternary cementitious blends to investigate the variations of some rheological and hardened properties of SCC. The fresh concrete tests include slump flow, T_{50} time, V-funnel flow time and plastic viscosity while hardened concrete tests were compressive strength, chloride ion permeability, water penetration depth, water absorption rate, volume of permeable voids and sorptivity.

2. Experimental methods

2.1. Materials

In this study an ordinary Portland cement CEM I 42.5 R, was used. Five types of SCM, which are SF, FAC, FAF, MK, and BFS, were also used in the binary, ternary, and quaternary cementitious blends. Table 1 summarizes the physical and chemical properties, and Fig. 1 shows the particle-size distributions of the PC and SCM. As can be seen in Fig. 1, SF is obviously the finest of all SCM. The next finer material is MK which is considerably different from the other SCM. In addition, the particle size distribution of PC, BFS, FAC and FAF are similar to each other. Crushed limestone with a maximum particle size of 15 mm and 4 mm were used as coarse and fine aggregate, respectively. The bulk specific gravity of the coarse and fine aggregates were 2.64 and 2.61, respectively, and their absorption capacities were 0.21% and 0.67%, respectively. A polycarboxylate ether-based HRWR conforming to ASTM C494 Type F [24] with a specific gravity of 1.06 and a solid content of 28% was employed to achieve the desired workability in all of the mixtures.

Table 1
Physical and chemical properties of PC and SCM.

	PC	SF	FAC	FAF	MK	BFS
CaO (%)	64.06	0.25	36.56	3.24	0.3	35.2
SiO_2 (%)	17.74	87.92	31.94	59.5	51.1	40.3
Al_2O_3 (%)	4.76	0.4	13.5	18.5	39.1	10.2
Fe_2O_3 (%)	3.17	0.35	4.09	6.96	2.15	0.67
MgO (%)	1.28	3.97	1.42	2.03	0.7	6.9
SO_3 (%)	2.94	0.21	3.86	0.47	0.08	1.4
K_2O (%)	0.8	0.81	0.94	1.93	1.78	0.97
Na_2O (%)	0.45	1.79	1.1	1.27	0.11	1.12
Free lime (%)	2.21	–	2.69	0.42	–	–
Other minor oxides (%)	0.64	1.43	0.91	1.26	0.88	1.34
Loss on ignition (%)	1.95	2.87	2.99	4.32	3.8	1.9
Specific gravity	3.13	2.29	2.73	2.38	2.54	2.97
Blaine Fineness (cm^2/g)	3310	–	3470	3220	–	3650
Surface area B.E.T. (m^2/kg)	–	24520	–	–	15410	–
Residue on 45 μm sieve (%)	4.2	–	17.4	19.5	0.4	1.3

2.2. Mix proportions

As summarized in Table 2, one control mixture without any SCM and 16 SCC mixtures with SCM were designed to have a constant w/b ratio of 0.44 and a total binder content of 454.5 kg/m^3. For all SCC mixtures the fine aggregate-to-total aggregate ratio, by mass, was set at 0.53. These parameters were not altered in this research to eliminate their effects on the results and to inspect the effect of SCM merely. The HRWR dosages used in the mixtures were adjusted to secure an initial slump flow of 650 ± 10 mm. The control mixture contained only PC whereas other mixtures incorporated binary (PC + SF, PC + FAC, PC + FAF, PC + MK and PC + BFS), ternary (PC + SF + BFS, PC + FAC + BFS, PC + FAF + BFS and PC + MK + BFS) and quaternary (PC + SF + FAC + BFS) cementitious blends in which a portion of PC was replaced with the SCM. The replacement levels for various SCM were different: it was 4%, 8% and 12% for SF, 4%, 8%, 18% and 36% for MK, 18% and 36% for FA and only 18% for BFS (36% BFS was not used since there was some bleeding on the surface when it was utilized by more than 18–25%). All substitutions of the cement by SCM were made on the total mass basis of the binder. In the production of SCC the mixing efficiency, mixer type, mixing sequence, etc. are very important factors affecting the properties of SCC [25,26]. Therefore, the same procedure for batching and mixing was followed to supply the same homogeneity and uniformity in all of the mixtures. The identification of the mixtures was made according to the type and amount of the SCM. For example, (8SF18FAC18BFS) denotes the quaternary mixture containing 8% SF, 18% FAC and 18% BFS.

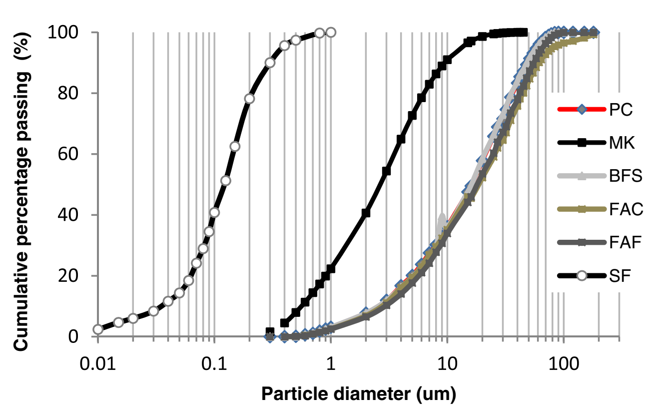

Fig. 1. Particle size distributions of PC and SCM.