Construction and Building Materials 55 (2014) 158–167

Contents lists available at ScienceDirect

Construction and Building Materials

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

Early-age deformation and autogenous cracking risk of slag–limestone filler-cement blended binders

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HIGHLIGHTS

- Early-age behavior of binary and ternary cementitious matrices.
- Materials: Portland cement, blast furnace slag and limestone filler.
- Influence of various blended binders on their physico-chemical properties.
- Effect of various blended binders on early-age autogenous cracking risk.

ARTICLE INFO

Article history:
Received 10 October 2013
Received in revised form 30 December 2013
Accepted 5 January 2014
Available online 6 February 2014

Keywords:
Autogenous cracking
Blast furnace slag
Chemical shrinkage
Autogenous shrinkage
Early-age
Hydration
Limestone filler

ABSTRACT

This article presents an experimental comparative study of the early-age behavior of binary and ternary cementitious matrices, combining Portland cement (PC), ground granulated blast furnace slag (BFS) and limestone filler (LF). The objective of this work was to quantify the influence of the composition of various blended binders on their physico-chemical evolution and early-age autogenous cracking risk. For this purpose, measurements of the rate of reactions, chemical shrinkage, autogenous shrinkage in free and restrained conditions and mechanical performances were performed on 12 binders prepared with the same water-to-cementitious materials ratio (w/cm = 0.32) and various dosages of PC, BFS and LF. The result analysis showed that the dilution effect reduced the early-age chemical shrinkage while the filler effect and the slag reactions tended to accelerate its development after a few hours of hydration. The substitution of PC with BFS and LF also led to both refining the 28-days pore size distribution measured by mercury intrusion and increasing the magnitude of early-age free autogenous shrinkage. However, in spite of their higher autogenous shrinkage potential, the binary and ternary binders very often exhibited later autogenous cracking ages than the control Portland cement paste.

1. Introduction and scientific background

In recent years, multi-component cementitious binders have received a renewed growing interest from the concrete science community [1–26]. These binders are composed of a binary, ternary or even quaternary combination of Portland cement (PC) and supplementary cementitious materials (SCM) such as filler (quartzite filler – QF; limestone filler – LF) and industrial byproducts/pozzolanic materials (fly ash – FA; calcined clay – CC; microsilica – µS; ground granulated blast furnace slag – BFS; silica fume – SF; metakaolin – MK; etc.). The interest for these alternate binders to ordinary PC is usually explained or justified by three principal reasons:

- A reduction of the environmental impacts. The production of cement-based binders incorporating high volumes of recycled industrial waste or byproducts in substitution of ordinary PC is seen as one of the most promising way for the cement and concrete industry to decrease its CO_2 emissions [7,9,27,28]. This will allow the development of concrete compositions with lower environmental impact [29] and also the reduction of landfill disposal.
- An improvement of long-term performances. Numerous studies showed that the combination of cements with SCM exhibited significant advantages over binary binders and plain PC [5]. Indeed, multi-component cement-based

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http://dx.doi.org/10.1016/j.conbuildmat.2014.01.037
0950-0618/

binders are well known for their improved long-term strength [5,12,14–20,22–24] and durability [4,5,10,13,16,19,24,26].

- A higher potential cost/benefit ratio. The costs of BFS, FA and LF are significantly lower than that of PC and, when considering the material costs, price differences between the individual components may allow, in some cases, the ternary blended cement binders to compete with ordinary PC [5]. However, the use of expensive mineral admixtures (SF for example) to increase the early-age mechanical properties of ternary binders can rapidly reverse this positive cost/benefit ratio [9].

The mix-design principle of multi-component blended cement binders exploits the synergy that may exist between different types of SCM. This synergy, attributed to both chemical and physical phenomena [15,22,24,25], is reflected in two main effects:

- A complementary effect of mutual compensation of the shortcomings of each mineral addition (for example, in PC–SF-–FA blended binder, SF improves the early-age performances of concrete while the later pozzolanic reactions of FA contribute to enhance the properties of the hardened concrete [5,24]).
- And an interactive effect between PC and SCM which enables to obtain greater performances than those obtained with the individual effects of each addition used separately [10,24].

Several studies have been conducted to optimize the composition of ternary binders and various combinations of cement with SCMcm have been investigated (PC + BFS + SF [3,4,9,18,19,26]; PC + FA + SF [4,5,9–11,18,19,24]; PC + FA + LF [8,13,21–23,25]; PC + BFS + LF [12,14,21]; PC + FA + BFS [1,2,19,30]; PC + FA + MK [13,17,20]; PC + SF + LF [16]).

FA and BFS, which are available in large quantities, are the most used SCM in replacement of cement in concrete [28]. Their low reactivity at early age can be mitigated by the incorporation of a third component, SF or LF, in moderate amount. The use of SF is increasingly limited due to its high cost [9] while LF, as the main raw material of PC, is usually available in abundance near cement plants. Recent studies have shown that LF used in low or moderate amount (5–10%) may improve the early-age reactivity of ternary binders [21–23,25,31] without compromising their mechanical properties [21,22]. The adequate combination of PC, LF and BFS can even lead to higher performances when compared to the binary blended cements and plain PCs [12–14].

The great majority of research works carried out on ternary binders concerned the development of their mechanical properties and durability indicators. Very few studies have been dedicated to their risk of early-age cracking due to the physico-chemical interactions between PC and SCM [32], while this issue is of great importance for a wider use of these types of binders in the concrete building industry. For example, Akkaya et al. found that ternary binder concretes, submitted to drying, cracked earlier than binary binder concretes, due to their lower strength [32].

This study aims to investigate the early-age behavior of binary and ternary binders prepared with PC and various substitution rates of LF and BFS, focusing on the risk of early-age autogenous cracking. The autogenous cracking risk of 12 blended cement pastes prepared with the same water-to-cementitious materials (w/cm) ratio, equal to 0.32, and different dosages of PC, BFS and LF was analyzed using the ring test method. In parallel, the physico-chemical and mechanical evolutions of the matrices were characterized. The results were then used to correlate the early-age performances of the binders investigated and their resistance to early-age cracking.

2. Materials

A CEM I 52.5 N Portland cement (PC) was used (French standard NF EN 197-1 [33]). Its Blaine fineness was 346 m^2/kg and it contained 3.3% by weight of gypsum and 4.8% by weight of limestone filler. The mass fractions of the main phases of cement, as determined with Bogue formulas, were 70% of C_3S; 9% of C_2S; 3% of C_3A and 13% of C_4AF. The main constituents of cement and granulated ground blast furnace slag (BFS) are given in Table 1. The used limestone filler (LF) contained 97.7% of $CaCO_3$ and its density was 2714 kg/m^3. The particle size distributions (PSD) of PC, BFS and LF are given in Fig. 1.

The pastes were prepared in a mixer of 20 L capacity. Solid constituents were first mixed for 30 s. Then, the mixing water was introduced and the mixing sequence was continued for 90 s at low speed and 90 s at high speed.

The compositions of the various binder pastes are given in Table 2. In the following, the term "binder" or "cementitious materials" refers to the binary or ternary combination of two or three solid constituents (PC, BFS and LF), respectively. The water-to-cementitious materials (w/cm) mass ratio was equal to 0.32 for all the studied mixtures. This low w/cm ratio was chosen in order to amplify the self-desiccation phenomenon at early-age and so the risk of autogenous cracking of the matrices.

3. Testing methods

An isothermal microcalorimeter TAM Air was used to measure the heat flow of reaction of the binders at early age. For each binder paste, 4 g specimens were taken at the end of mixing, accurately weighed (±0.01 g) and placed into two cylindrical flasks. The flasks were then sealed and loaded in the apparatus. The first measurement was acquired about 10 min after the first contact between the binder and the mixing water. The tests were conducted over the first 5 days of hydration. The curves reported in the article are average curves computed from the test results obtained on two parallel specimens.

The chemical shrinkage was determined using the hydrostatic weighing method [34]. At the end of mixing, two samples of 4–5 g were introduced into two different cylindrical flasks. The

Table 1
Mass composition (%) and density of cement (PC) and blast furnace slag (BFS) (Data provided by the supplier).

Constituents	PC	BFS
SiO_2	21.39	34.49
Al_2O_3	3.66	13.19
Fe_2O_3	4.25	0.40
CaO	64.58	41.03
MgO	0.96	8.21
MnO	0.13	0.40
TiO_2	0.16	0.88
K_2O	0.28	0.54
Na_2O	0.10	0.43
SO_3	2.63	0.10
Density, kg/m^3	3200	2890

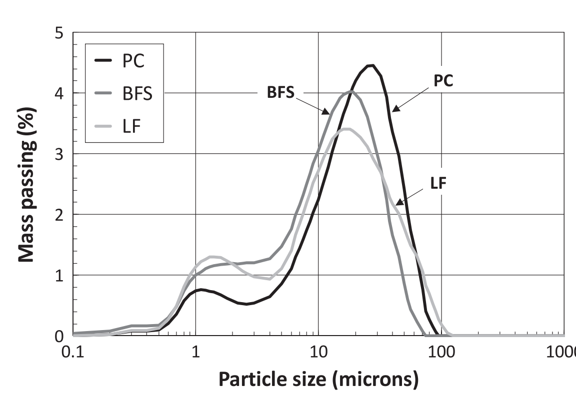

Fig. 1. Particle size distributions for PC, BFS and LF measured by laser granulometry. Results are the average of two individual measurements.