Cement & Concrete Composites 60 (2015) 17–24

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Adding limestone fines as cementitious paste replacement to improve tensile strength, stiffness and durability of concrete

Leo G. Li [a], Albert K.H. Kwan [b,*]

[a] School of Civil and Transportation Engineering, Guangdong University of Technology, Guangdong, China
[b] Department of Civil Engineering, The University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 15 August 2013
Received in revised form 29 January 2015
Accepted 7 February 2015
Available online 10 April 2015

Keywords:
Durability
Filler
Limestone fines
Permeability
Stiffness
Tensile strength

ABSTRACT

The addition of a filler such as limestone fines (LF) to fill into the voids between aggregate particles can reduce the cementitious paste volume needed to produce concrete. In previous studies, it has been found that the addition of LF to reduce the cementitious paste volume would substantially increase the cube strength, and reduce the heat generation and shrinkage of the concrete produced. In this study, the authors aimed to evaluate the effects of adding LF as cementitious paste replacement on the tensile strength, stiffness and durability of concrete. For the evaluation, a series of concrete mixes with LF added to replace an equal volume of cementitious paste were tested for their workability, cube strength, tensile splitting strength, modulus of elasticity, water penetration depth and chloride permeability. The results showed that the addition of LF as cementitious paste replacement would at the same water/cement ratio, and even at the same cube strength, improve the tensile strength, stiffness and durability of concrete.

1. Introduction

Generally, concrete is composed of cementitious paste (cementitious materials and water) and aggregate (fine and coarse aggregates). The packing density of the aggregate in concrete (ratio of solid volume to bulk volume of the aggregate particles) is typically about 0.70–0.80. With this typical packing density, the volume of voids between aggregate particles to be filled with cementitious paste is about 20–30%. In the concrete mix design, the cementitious paste volume must be large enough to first fill up the voids between aggregate particles and then provide excess cementitious paste to form paste films coating the aggregate particles. The filling up of the voids between aggregate particles with cementitious paste is for avoiding entrapment of air inside the concrete mixture, which would impair the strength and durability, whereas the provision of excess cementitious paste to form paste films is for lubricating the concrete mixture and attaining the required workability. For these reasons, to achieve good strength, durability and workability, the cementitious paste volume should not be too small.

However, to improve dimensional stability and reduce risk of cracking, the cementitious paste volume should be reduced to as small as possible. During curing of fresh concrete, heat is generated from the chemical reactions of the cementitious materials in concrete [1–4]. Such heat generation, which causes thermal expansion and contraction, could be decreased by reducing the cementitious materials content. Since the water/cementitious materials (W/CM) ratio is governed by the strength and durability requirements and therefore has to be kept constant, the cementitious materials content should be reduced by reducing the cementitious paste volume without changing the W/CM ratio. At later age, as the concrete dries after hardening, drying shrinkage occurs [5–7]. Since the shrinkage of the hardened cementitious paste constitutes the major part of concrete shrinkage, such drying shrinkage could be decreased by reducing the cementitious paste volume. Hence, whilst on one hand, generous cementitious paste volume needs to be provided to achieve good strength, durability and workability, on the other hand, the cementitious paste volume needs to be minimized to improve dimensional stability and reduce risk of cracking. Such a dilemma in concrete mix design is not easy to resolve [8].

One possible way of resolving the above dilemma is to add an inert filler to fill into the voids between aggregate particles so that the amount of cementitious paste needed to fill up the remaining voids is decreased. If the filler is a powder as fine as the cementitious materials, this may be taken as adding the filler to the cementitious paste so as to increase the volume of the powder paste (with a filler added, the paste contains not only the cementitious materials and water, but also the filler, and therefore should better be called powder paste) for filling the voids between aggregate

* Corresponding author.
E-mail addresses: ligu@gdut.edu.cn (L.G. Li), khkwan@hku.hk (A.K.H. Kwan).

http://dx.doi.org/10.1016/j.cemconcomp.2015.02.006
0958-9465/

particles. So long that the powder paste volume is more than sufficient to fill up the voids between aggregate particles and provide excess paste to form paste films coating the aggregate particles, the cementitious paste volume may be reduced to improve dimensional stability and reduce risk of cracking without causing any adverse effects on the strength, durability and workability. Such reduction in cementitious paste volume can also reduce the cement consumption and carbon footprint of the concrete production.

Among the various inert fillers, limestone fines (LF) may be a good choice. LF is a by-product of the limestone quarry industry, which, if not used, has to be disposed of as waste causing environmental problems. In fact, LF has been used in concrete for many years. Early in 1977, Soroka and Setter [9] showed that LF in concrete could act as nuclei for precipitation of CSH and thus speed up the hydration of cement and early strength development. Subsequently, many studies on the use of LF as fine aggregate replacement have been conducted to evaluate the effects of such usage of LF on the workability [10], strength [11–13], dimensional stability [14,15] and durability [16,17] of concrete. Investigations have also been carried out to explore the use of LF as cement replacement and assess the effects of such usage of LF on the various properties of concrete [8,18–25].

However, there has been limited research on the use of LF as cementitious paste replacement (replacement of an equal volume of cementitious paste without changing the mix composition of the cementitious paste). The authors are of the view that since LF is not a cementitious material, it should better be used as cementitious paste replacement rather than as cement replacement. By using LF as cementitious paste replacement, the cementitious paste may be substantially reduced while maintaining the required powder paste volume to fill the voids between aggregate particles and form paste films coating the aggregate particles. In previous studies, it has been found that this would allow the cementitious paste volume to be reduced to fairly small values without causing air entrapment, improve the cohesiveness and stability of the fresh concrete, increase the cube strength, and more importantly decrease the heat generation [26] and shrinkage [27] of the concrete.

In the study reported herein, a number of trial concrete mixes with different amounts of LF added as cementitious paste replacement were produced for testing of workability, cube strength, tensile splitting strength, modulus of elasticity, water penetration depth and chloride permeability. To evaluate the effects of LF volume (solid volume of LF expressed as a percentage of volume of concrete) at different water/cement (W/C) ratios, the LF volume was varied from 0% to 12% whereas the W/C ratio was varied from 0.35 to 0.60. It will be seen that the addition of LF to reduce the cementitious paste volume would, apart from improving the dimensional stability, also improve the tensile strength, stiffness and durability of concrete.

2. Experimental program

2.1. Materials

An ordinary Portland cement (OPC) of strength class 52.5 N complying with European Standard EN 197-1: 2000 [28] and a limestone fines (LF) containing 95% calcium carbonate and 2% silica were used for all the concrete mixes. The solid densities of the OPC and LF had been measured as 3112 and 2642 kg/m^3, respectively. A laser diffraction particle size analyzer was used to measure their particle size distributions and the results so obtained are plotted in Fig. 1. Based on these particle size distributions, the volumetric mean particle sizes of the OPC and LF were determined as 11.8 and 13.6 μm, respectively. Hence, the OPC and LF used have similar fineness. Nevertheless, the LF has a slightly wider size range than that of the OPC. Regarding the aggregate, both the fine and coarse aggregates were crushed granite rock with a solid density of 2610 kg/m^3. The fine aggregate has maximum size of 5 mm, water absorption of 0.89% and fineness modulus of 2.68, whereas the coarse aggregate has maximum size of 20 mm and water absorption of 0.70%.

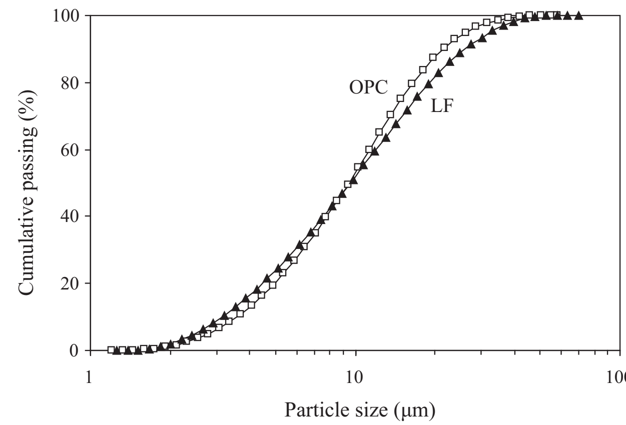

Fig. 1. Particle size distributions of OPC and LF.

2.2. Mix proportions

A total of 20 trial concrete mixes with various water/cement (W/C) ratios and different amounts of LF added as cementitious paste replacement were produced for testing. Their W/C ratio was varied from 0.35 to 0.60 in increments of 0.05 whereas their LF volume was varied among 0%, 4% and 8% for the concrete mixes with W/C $\leqslant$ 0.50 and among 0%, 4%, 8% and 12% for the concrete mixes with W/C $\geqslant$ 0.55 so as to study the effects of LF volume at different W/C ratios. The LF volume was increased only to 8% for the concrete mixes with W/C $\leqslant$ 0.50 because increasing the LF volume to 12% at W/C $\leqslant$ 0.50 would produce very dry concrete mixes.

For every concrete mix, the powder paste volume (volume of cementitious paste plus volume of LF, expressed as a percentage of volume of concrete) was fixed at 34%. In other words, the sum of the cementitious paste volume and the LF volume was set constant. As LF was added, the cementitious paste volume was reduced by the LF volume so that at LF volumes of 4%, 8% and 12%, the cementitious paste volume was reduced to 30%, 26% and 22%, respectively. With the powder paste volume fixed, the aggregate volume was also fixed. In every concrete mix, the fine to total aggregate ratio was set at 0.40 and the 10 mm to 20 mm aggregate ratio was set at 1.0. Hence, in each and every concrete mix, the fine aggregate content, 10 mm aggregate content and 20 mm aggregate content were 689, 517 and 517 kg/m^3, respectively.

Details of the concrete mix proportions are presented in Table 1. Each concrete mix was assigned an identification code of C-X-Y, in which C denotes concrete, X denotes the W/C ratio and Y denotes the LF volume. It should be noted that the LF was added as cementitious paste replacement, not as cement replacement. Hence, when LF was added, both the water content and cement content were reduced but the W/C ratio was kept constant. In terms of quantity per volume of concrete, the water content varied from 135 to 221 kg/m^3, the cement content varied from 238 to 505 kg/m^3 and the LF content varied from 0 to 317 kg/m^3.

As in usual practice for the production of high-performance concrete, a superplasticizer (SP) was added to each concrete mix to disperse the fine particles. The SP added was of polycarboxylate