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Synergistic effects of micro-silica and nano-silica on strength and microstructure of mortar

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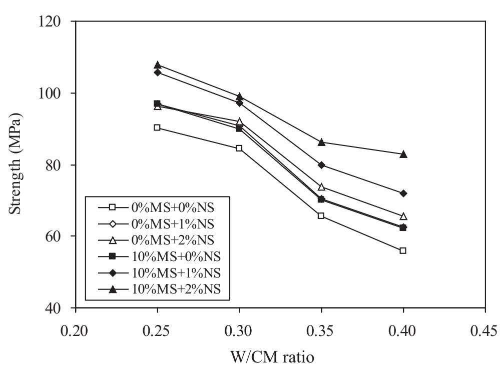
HIGHLIGHTS

- NS is more effective than MS in increasing the strength of mortar.
- At same strength, use of NS would lead to lower SP demand than MS.
- Addition of both MS and NS has synergistic effects on strength and microstructure.
- NS should be added together with MS for maximum performance.

GRAPHICAL ABSTRACT

As shown in the figure below, it is found that each of MS and NS is more effective in the presence of the other, or in other words, they have significant synergistic effects on strength when used together.



28-day strength versus W/CM ratio for different MS + NS contents

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ABSTRACT

Micro-silica (MS), of much finer size than cement, has been proven to be effective in improving the strength and durability of concrete. With the advent of nanotechnology, nano-silica (NS), of even finer size than MS, is now available for production of concrete, especially high-performance concrete (HPC). To investigate the combined effects of MS and NS on the strength and microstructure of mortar or the mortar portion of HPC, an experimental program was launched, in which mortar mixes with various water, MS and NS contents but a constant workability were produced for cube strength measurement and microstructure imaging. From the test results, it was found that even a very small NS content of only 1–2% has substantial positive effects on the cube strength and microstructure, but a very high superplasticizer demand. More importantly, the combined addition of MS and NS has significant synergistic effects on strength and microstructure. These results suggest that NS should not be added alone but should be added together with MS to exploit their synergistic effects for maximum performance.

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1. Introduction

During the past decades, more and more materials with cementitious and/or pozzolanic properties have been used as cement replacement in concrete production. Some of these materials are industrial wastes or by-products such as fly ash, slag and silica fume [1–3], some are manufactured materials such as metakaolin [4,5], and some are natural materials such as zeolite and volcanic tuff [6,7]. Among these materials, silica fume, which is also called micro-silica (MS) because of its fine particle size of generally smaller than 1 μm, is one of the most popular supplementary cementitious materials used in production of high-strength concrete (HSC) and high-performance concrete (HPC) [8–11]. Due to the filling effect of MS and the pozzolanic reaction of MS with $Ca(OH)_2$ generated by cement hydration, the addition of MS can effectively improve the microstructure, mechanical properties and durability of the concrete produced [12,13].

More recently, the advent of nanotechnology has brought in various types of nano-materials, which may have good applications in civil engineering, especially concrete production, due to their four major effects: size effect, surface effect, quantum effect and interface effect [14–17]. These nano-materials have attracted great research interest. For instance, it has been found that nano-$CaCO_3$ can accelerate cement hydration and improve strength of concrete [18,19]. Nano-Al_2O_3, nano-Fe_2O_3, nano-Fe_3O_4 and nano-clay have been demonstrated to have great effects on microstructure, workability, mechanical properties and durability of cementitious products [20–26]. And, nano-TiO_2 has already been used in road pavement and cement-based facade finishing to remove air pollutants due to its photocatalytic effect [27,28]. Moreover, carbon nanotubes and nanofibers have also attracted great attention due to their reinforcing and self-sensing properties [29–31]. Among these nano-materials, nano-silica (NS), with a high purity of SiO_2 and an ultrahigh fineness [32], has become one of the most popular research objects for further advancement of concrete technology [33–36].

NS is finer in size than MS and therefore has a greater specific surface area. Hence, the pozzolanic reactivity of NS should be even higher than that of MS. Being much finer in size than cement, both MS and NS should be effective in filling into the voids between cement grains to increase the packing density of the cementitious materials so as to improve the microstructure and performance of the paste, mortar and concrete produced. However, whilst MS may be used up to 10% or even 20% of the total cementitious materials, NS is suitable for use only up to at most 3% because of the expensive cost, great difficulty in mixing and high superplasticizer demand when a higher NS content is used. Due to the relatively small NS content, the filling effect of just adding NS directly to cement is quite limited. For this reason, the authors are of the view that the combined addition of MS and NS may be better than just adding MS or NS alone. By first adding MS, which is finer than cement, to fill into the voids between the cement grains and then adding NS, which is even finer, to fill into the voids between the MS, the packing density of the cementitious materials and the microstructure of the cementitious paste could be improved to beyond those possible with only MS or only NS added.

It is therefore anticipated that the combined addition of MS and NS might give certain synergistic effects on the performance of concrete, and thus could be a promising way to produce even better HPC than what we are producing today. In fact, some studies have already been conducted along this line. For instance, Jalal et al. [35] found that the blended addition of both MS and NS can further improve the compressive and splitting tensile strengths, water and capillary absorptions, resistivity and chloride penetration resistance. Nili and Ehsani [37] observed that the simultaneous addition of 5% MS and 5% NS could provide the greatest beneficial effect on the strength development of cementitious paste and concrete. Shaikh et al. [38] studied the bond-slip behaviour of steel fiber and polypropylene fiber in high volume fly ash mortar containing MS, NS or (MS + NS), and revealed that the combined usage of 10% MS + 2% NS could increase the pull-out force to higher than those with only 10% MS added or only 2% NS added. Nevertheless, systemic and comprehensive research is still needed to fully exploit the synergistic effects of MS and NS.

However, due to their high specific surface areas and tendency to form agglomerates, there is the difficulty of dispersing the MS and NS particles when mixed with water. One effective dispersion method is to use colloidal NS instead of NS in dry powder form [39–41]. Another effective dispersion method is to add a superplasticizer (SP) [42,43]. These two dispersion methods are not exclusive and can be used together. Somehow, the SP dosage needed for a given workability cannot be theoretically predicted and up to now has to be determined by trials. While performing studies on the uses of MS and NS, different ways have been adopted to set the SP dosage. For instance, Senff et al. [44] fixed the SP dosage in all the paste and mortar samples tested and Yu et al. [45] maintained the SP dosage at 4.5% for producing ultra-high-performance concrete, whereas Jo et al. [46] adjusted the SP dosage for each mortar mix to ensure that no segregation would occur. In this regard, the authors are of the view that good workability should be achieved first to ensure proper mixing and compaction, especially when added with MS and NS, which would substantially decrease the workability [47,48]. It is suggested that the effects of MS and NS should be studied with the workability fixed by adjusting the SP dosage until the required workability is achieved.

In the study presented herein, in order to investigate the synergistic effects of MS and NS on strength and microstructure of mortar, a number of mortar mixes with various water, MS and NS contents were produced for workability and cube strength measurements and microstructure observation. For each mortar mix, the SP dosage was adjusted to achieve the required workability. Based on the experimental results so obtained, the advantages and disadvantages of adding MS alone, NS alone, and MS and NS together are evaluated, and the synergistic effects of MS and NS on strength and microstructure are studied.

2. Experimental methodology

2.1. Selection of materials

The cementitious materials comprised of cement, MS and NS. An ordinary Portland cement (OPC) of strength class 52.5N, which had been tested to comply with BS 812: 1996, was used as the cement. A condensed silica fume imported from Europe and tested by the supplier to comply with ASTM C 1240-03 was used as the MS. A dry powder form nano-silica manufactured in China with particle size ranging from 5 to 20 nm (as can be seen from the transmission electron microscopy images presented in Fig. 1) and high purity of silica (>99.6%) was used as the NS. Regarding the fine aggregate, natural river sand with maximum size of 1.18 mm, moisture content of 0.21% and water absorption of 1.10% was used. The relative densities of the OPC, MS, NS and fine aggregate were measured as 3.11, 2.20, 1.94 and 2.58, respectively. On the other hand, the SP added was a polycarboxylate-based SP with a solid mass content of 20%. It was a commonly used SP in the construction industry for the production of HSC and HPC.

A laser diffraction particle size analyzer was used to measure the particle size distributions of the OPC and MS, while the mechanical sieving method was used to measure the particle size