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Influence of limestone size and content on transport properties of self-consolidating concrete

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HIGHLIGHTS

- Provide valuable information on the use of limestone powder in self-consolidating concrete (SCC).
- Effect of limestone powder size on transport properties of SCC.
- Influence of limestone powder content on transport properties of SCC.

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ABSTRACT

This study assessed influences of limestone powder' size and content on compressive strength and transport properties of self-consolidating concrete (SCC). Several SCC mixtures were prepared with uniform water-to-cementitious materials ratio and powder content (cement + fly ash + limestone) of 0.45 and 475 kg/m^3, respectively. Class F fly ash substituted 20% by weight of cement and 10, 15 and 20% of total cementitious materials was replaced with limestone powder having average particle size of 3 or 8 μm. Slump flow of 635 ± 25 mm, visual stability index of 0 or 1, and maximum passing ability (difference of slump and J-Ring flow) of 37.5 mm were used for all studied mixtures. The devised experimental program included compressive strength, absorption, rapid chloride penetration (RCPT), rapid chloride migration (RCMT), and water penetration depth. The results of this study revealed that inclusion of limestone powder and reduction in its size were both effective in improving compressive strength and transport properties of SCC. While absorption, volume of permeable voids, water penetration depth, and RCPT improved significantly through use of limestone powder, the improvements were marginal for compressive strength and RCMT. Reduction of limestone powder size had more effect in improving performance of 28-day cured concrete as compared to that of 90 days mixtures.

1. Introduction

In the 1980s, Japan reduced the number of skilled workers in their construction industry which adversely affected concrete construction, producing many under- and over-consolidated structures. While under-consolidation caused increases in entrapped air and surface flaws, excessive vibration resulted in segregation, external and internal bleeding, and the damage of the air void system, which in turn, reduced strength and durability of concretes [2]. To solve these challenges, self-consolidating concrete (SCC) was proposed with the idea of durable concrete structures independent of the quality of the construction work, which compacted into every angle of the formwork under its own weight without requiring mechanical vibrating compaction. SCC not only solved the above-mentioned challenges, but also offered several advantages when compared with vibratory-placed concrete including higher flow ability, lesser screeding and better self-leveling, shorter construction period, lower labor costs, higher construction quality and productivity, and a better work environment through reduction in construction site noise [2,15]. After SCC's development and rapid spread in Japan and Europe, recently it has become considered for precast/prestressed implementation in the United States [2]. State Departments of Transportation have also become more active in SCC for research and applications [36].

Use of SCC, however, has its own challenges. It is susceptible to more drying and autogenous shrinkage, and creep than vibratory-placed concrete due to its high cementitious materials content. SCC induces additional formwork pressure when compared to traditional concrete [20,30]. The need for a higher cementious

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materials content and consideration for extra formwork pressure may result in a higher production cost for SCC [8].

One way to address the afore-mentioned concerns and to reduce production cost of SCC is to utilize mineral admixtures, including inert materials, natural or industrial Pozzolans, and cementitious materials, to account for a portion of the paste volume. Of inert or low-reactive mineral admixtures, limestone powder has the potential to improve economy of SCC through reduction in Portland cement, ultimately leading to environmental benefits and improving concrete durability through better paste quality. It was shown that usage of limestone powder can improve workability of SCC because of its enhanced particle size distribution, resulting in reduction of water and HRWR demands [24]. This enhanced workability allows for a decrease in the water content which may improve the overall strength of the SCC [16]. The static stability and reductions in bleeding, yield stress and plastic viscosity can occur with the addition of limestone powder, as well [16,22]. Incorporation of limestone powder can decrease autogenous shrinkage of SCC [29]. Limestone powder can act as nucleation sites for hydration products, especially the C_3S phase, which leads to accelerated cement hydration [14]. It can also act as a filler between cement's coarser particles, thus optimizing the packing density and improving mechanical and durability properties [13]. Due to its mostly inactive role in hydration, it can provide a dilution effect which allows most of the water to be used for cement hydration [13]. Lastly, though for the most part chemically inert, limestone powder has the potential to slightly modify hydration phases [13]. It was reported that limestone powder altered Portland cement's hydration due to the transformation of monosulphoaluminate hydrates and formation of mono- or hemi-carboaluminate, along with additional ettringite [9]. Addition of these products may lead to slight increases in hydration products' volume [18,21,23], and a potential increase and decrease in strength and permeability of concrete, respectively [14]. Da Silva and De Brito [11] showed viability of producing SCC using fly ash and limestone filler.

Limestone powder has been used commonly in regions of Europe as a mineral filler, whereas it has not been as greatly incorporated in the United States' concrete production [35,17]. There has not been enough research on the use of limestone powder in the US to provide adequate data for cement and concrete plants. In particular, limited studies have been conducted on effects of limestone powder on transport properties and durability of self-consolidating concrete. This work aimed to address this concern by replacing up to 20% of total cementitious material with two types of limestone powder having similar physico-chemical properties but different average particle sizes of 3 and 8 μm. The studied transport properties included absorption, water permeability, rapid chloride penetration, and rapid chloride migration.

2. Research significance

The findings obtained under this investigation can offer valuable information on the transport properties of SCC as affected by the use of limestone powder, its particle size and replacement level. It also highlights the economical advantage of limestone as a mineral admixture in producing a more sustainable concrete. In particular, this study uses a constant water-to-cementitious materials ratio, as opposed to a uniform water-to-powder ratio used by previous researchers, in order to properly reflect the role and contribution of cementitious materials to hydration activities. A qualitative classification to reflect the influence of limestone powder on transport properties of SCCs is also presented.

3. Experimental program

3.1. Materials

The materials used in this study included Type V Portland cement as a primary binder, class F fly ash as a secondary binder, limestone powder as an inert mineral admixture, fine and coarse aggregates, and high range water reducer (HRWR). The chemical and physical properties of cement and fly ash are presented in Table 1. Two types of limestone powder were used in this study having average particle size of 3 and 8 μm. Fig. 1 shows the particle size distributions of limestone powders, cement and fly ash. It can be seen that particles of both limestone powders were finer than those of Portland cement and fly ash, acting as a filler between cement particles to potentially improve paste quality. The chemical and physical properties of limestone powders are documented in Table 2. With the exception of the size difference, both limestone powders had similar physico-chemical properties.

The used fine aggregate was natural siliceous sand with a specific gravity of 2.76, absorption of 0.81%, and fineness modulus of 2.78. The coarse aggregate was crushed limestone aggregate with a maximum size of 12.5 mm, a bulk specific gravity of 2.75, absorption of 0.79%, and dry-rodded unit weight of 1567.25 kg/m^3.

3.2. Mixture proportions

The mixture proportions of the SCCs are presented in Table 3. As can be seen, a control SCC was designed by using a water-to-cementitious materials ratio (w/cm) of 0.45 and cementitious materials content of 475 kg/m^3 having Class F-fly ash substituting 20% by weight of cement. The limestone powder contained SCCs were made by replacing 10, 15, and 20% of cementitious materials with 3-μm or 8-μm limestone powder. The total powder content (cement + fly ash + limestone powder) and w/cm were kept constant at 475 kg/m^3 and 0.45, respectively. The similarity in powder content and water-to-cementitious materials ratio resulted in the use of lower amount of water. Using various dosages of HRWR, all studied SCCs maintained the target slump flow of 635 ± 25 mm, a dynamic stability of 1 or less (stable to highly stable), and a maximum passing ability (difference of slump and J-Ring flow) of 37.5 mm.

All SCCs were batched in an electric counter-current pan mixer with a rotating rate of 14.5 rpm and a capacity of 0.0283 m^3. Upon batching, flow property tests of slump flow, visual stability index (VSI), and J-Ring were conducted to ensure that target flow ability, passing ability, and segregation resistance were met. These tests were performed immediately, usually within two minutes after mixing, to guarantee there was no discrepancy with time. After casting, all samples were cured in air tight molds for 24 h. The samples were then de-molded and placed in a moist curing room until testing at the ages of 28 and 90 days.

Table 1
Chemical properties of cementitious materials.

Chemical composition, %	Type V Portland cement	Class F fly ash
SiO_2	20.42	59.93
Al_2O_3	4.25	22.22
Fe_2O_3	4.05	5.16
CaO	63.31	4.67
MgO	2	–
SO_3	2.98	0.38
Na_2O	0.04	1.29[a]
K_2O	0.69	–
Loss on ignition	2.5	0.32
Insoluble residue	0.44	

[a] Total alkali, as Na_2O.