Strategies of Cement Replacement and Cement Paste Replacement to Produce High-strength and Low-cement Content Concrete

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ABSTRACT

To produce high-strength and low-cement content concrete, the authors advocate the strategy of adding silica fume as cement replacement and the strategy of adding limestone fine as cement paste replacement. To study the effectiveness of these two strategies, a comprehensive study with 33 concrete mixes with silica fume or limestone fine produced for strength measurement has been carried out. Test results proved that both the two strategies could increase the strength at the same W/CM ratio and at the same cement content.

INTRODUCTION

Since production of one ton of cement would generate roughly 0.75 ton of CO₂ and consume up to 4.5 megajoule (MJ) of energy [1] when calcinating the limestone, the production of concrete for new buildings generate a large carbon footprint that causes global warming. It is estimated that 7-8% of global greenhouse gas emission comes from cement production and the situation is going to become worse because the demand for concrete is predicted to increase substantially in the years to come [2]. On the other hand, to reduce the volume of concrete needed in new buildings, high strength concrete is required. For example, adopting a Grade 100 concrete (achieved by adding pulverized fuel ash and CSF rather than increasing the cement content) instead of the originally planned Grade 45 concrete for the 70-storey One Island East building in Hong Kong had reduced the volume of concrete needed for the vertical elements by 30% [3]. To minimize the ecological impact of concrete, producing high-strength and low-cement content concrete is the way to go.

To produce high-strength and low-cement content concrete, the effectiveness of two strategies, i.e. use of silica fume (SF) as cement replacement and the strategy...
of adding limestone fine (LF) as cement paste replacement was verified in this study. These two strategies are elaborated and their effectiveness investigated by examining the strength of 33 concrete mixtures containing various amounts of SF and LF on the same strength W/CM ratio basis and the same cement content basis.

MATERIALS

An ordinary portland cement of strength class 52.5N complying with British Standard BS 12: 1996 (equivalent to ASTM Type I), a SF complying with ASTM C 1240-05, a finely ground LF and crushed granite rock aggregates were used in this study. The coarse and fine aggregate were obtained from crushed granite rock, and have a maximum size of 20 and 5 mm, respectively. Sieve analysis verified that the grading curves of these aggregates were within the allowable limits stipulated in British Standard BS 882: 1992.

EXPERIMENTAL PROGRAM

In this study, a total of 33 concrete mixes were produced for 28-day cube strength measurement. To evaluate the effect of addition of SF as cement replacement, 15 concrete mixes with W/CM ratio varying from 0.24 to 0.40 and SF replacement ratio varying from 0% to 15% were produced. To evaluate the effect of addition of LF as cement paste replacement, 18 concrete mixes with W/CM ratio varying from 0.35 to 0.60 and LF replacement ratio varying from 0% to 8% were produced. For all the concrete mix in this study, the fine to total aggregate ratio and paste volume to concrete volume ratio were fixed at 0.40 and 0.34, respectively.

TEST METHOD

The 28-day cube strengths were measured by casting three 150 mm cubes from the concrete, removing the moulds one day after casting, applying water curing at a temperature of $27 \pm 2 ^\circ C$, and testing three of the cubes at the age of 28 days.

EXPERIMENTAL RESULTS

Cement Replacement

The effect of addition of SF as cement replacement on 28-day cube strength is shown in Fig. 1.
As can be shown in the Fig. 1, the cube strength increased as the SF replacement ratio increased. This is because the addition of SF as cement replacement had significantly increased the 28-day cube strengths at the same W/C ratio. This is can be attributed to the filling effect of SF.

To reveal the effectiveness of addition of SF as cement replacement on producing high-strength and low-cement content concrete, the 28-day cube strength was plotted against the cement content at different SF replacement ratio in Fig. 2. It showed that addition of SF as cement replacement shifted the 28-day cube strength-cement content curves upward and to the left. This illustrated that the addition of SF could at the same cement content improve the strength, or at the same strength lower the cement content. Using SF as cement replacement is an effective strategy to produce high-strength and low-cement content concrete.

Cement Paste Replacement

The effect of addition of LF as cement paste replacement on 28-day cube strength is shown in Fig. 3. From the strength results, it is apparent that the addition of LF as cement paste replacement had significantly increased the 28-day cube strengths, even though the W/C ratio was kept constant. As the LF added is chemically inert and therefore not cementitious, the increase in strength should not
be attributed to any increase in the cementitious materials content or lowering of the W/CM ratio. The increase in strength due to addition of LF as cement paste replacement may be 1) the addition of LF acted as nuclei for precipitation of calcium hydroxide and thus increased the degree of cement hydration [4]; 2) the addition of LF reduced the bleeding of the concrete mix through lowering the water/powder ratio, and therefore improved the bond strength of the interfacial transition zones at the surfaces of the aggregate particles [5].

![Figure 3. Variation of 28-day cube strength with W/CM ratio for limestone fine concrete.](image)

To reveal the effectiveness of addition of LF as cement paste replacement on producing high-strength and low-cement content concrete, the 28-day cube strength was plotted against the cement content at different LF replacement ratio in Fig. 4. It showed that, similar to the addition of SF, addition of LF shifted the 28-day cube strength-cement content curves upward and to the left. This illustrated that the addition of LF could at the same cement content improve the strength, or at the same strength lower the cement content. Using LF as cement paste replacement is an effective strategy to produce high-strength and low-cement content concrete.

![Figure 4. Variation of 28-day cube strength with cement content for limestone fine concrete.](image)
DISCUSSIONS

According to the positive results obtained in this study, both the strategy of adding SF as cement replacement and the strategy of adding LF as cement paste replacement are highly effective to produce high-strength and low-cement content concrete. It is noteworthy to point out that both strategies require a higher superplasticizer dosage to compensate the workability loss due to the use of SF or LF. Since SF is rather expensive while LF is relatively cheap, the latter strategy may be more economic one. It is the authors’ belief that a combination of these two strategies may provide an even better effect for production of high-strength and low-cement content concrete. Further research along this line is recommended.

CONCLUSION

To evaluate the strategies of addition of SF as cement replacement and addition of LF as cement paste replacement on producing high-strength and low-cement content concrete, a total of 33 concrete mixes were produced for strength measurement. Test results proved that both the two strategies could increase the strength at the same W/CM ratio. What is more, both the two strategies could significantly improve the strength at the same cement content.

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