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# Adding limestone fines as cement paste replacement to reduce water permeability and sorptivity of concrete

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## HIGHLIGHTS

- Adding limestone fines as cement paste replacement can reduce cement content.
- Such use of limestone fines would reduce carbon footprint and risk of cracking.
- It would also reduce permeable porosity and water resistance.

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## ABSTRACT

The addition of limestone fines to fill into the voids between aggregate particles can reduce the volume of voids to be filled with cement paste and thus reduce the cement paste volume needed to produce concrete. Apart from decreasing the cement clinker consumption and carbon footprint, this may have other benefits too. In previous studies, the authors have found that the addition of limestone fines as cement paste replacement would substantially improve the dimensional stability. In this study, the authors aimed to evaluate the effects on the water resistance of concrete. For the evaluation, a series of concrete mixes with various water/cement ratios and different limestone fines contents were tested for their workability, strength, water permeability, sorptivity and porosity. It was found that within the ranges of concrete mixes studied, the addition of limestone fines as cement paste replacement would significantly increase the strength and substantially improve the water resistance of the concrete produced.

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## 1. Introduction

The use of limestone fines (LF) as cement replacement is a common practice in European countries. In the European Standard BS EN 197-1: 2011 [1], up to 35% LF is allowed in Portland-limestone cement. The effect of LF in cement has been a major research topic for many years [2]. It is now widely known that by replacing part of cement with LF, not only the cement clinker consumption but also the hydration heat [3] would be significantly reduced. Although the addition of LF as cement replacement would decrease the concrete strength, especially at later ages [4], this can be compensated simply by lowering the water/(cement + LF) ratio [5]. However, the effect on durability is fairly complicated. It has been reported that the addition of LF as cement replacement up to 20% would increase the gas permeability and decrease the water permeability, while the addition of LF from 20% to 35% would turn to decrease the gas permeability and increase the water permeability [6].

Apart from cement replacement, LF has also been used as fine aggregate replacement. Basically, the addition of LF to replace part of the fine aggregate has no or little adverse effect on the concrete strength [4,7]. Moreover, the addition of LF as fine aggregate replacement would significantly reduce the shrinkage of the concrete produced [8,9]. It has also been found that the addition of LF as partial replacement of fine aggregate would decrease the water permeability [10]. This may be attributed to the reduction in pore size of the voids between the aggregate particles due to the relatively high fineness of the LF added. However, the use of LF as fine aggregate replacement would not help to reduce the cement clinker consumption and carbon footprint of the concrete. This is a good way of using LF in places where there is shortage of fine aggregate, but the opportunity is not taken to also improve the sustainability of our concrete production.

Since LF is chemically inert, it acts mainly as a filler when added to cement paste, mortar or concrete. Throughout the years, the LF has been used to replace either part of the cement or part of the fine aggregate. However, it is the authors' belief that the LF, being a filler, should better be used to fill into the voids between the

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aggregate particles so as to improve the packing density of the aggregate and reduce the volume of voids to be filled. The voids between the aggregate particles must be completely filled with cement paste or otherwise air will be entrapped in the concrete mix causing reductions in strength and durability. By adding LF to fill into the voids between the aggregate particles, the volume of cement paste needed to fill the voids would be reduced. Hence, with LF added, we may reduce the cement paste volume (volume of cement + volume of water) in the concrete.

For most LF, which has similar fineness as cement, the LF may also be viewed as filling into the cement paste to form part of the paste. With LF added, the paste formed should be called powder paste and its volume should be called powder paste volume (volume of cement + volume of LF + volume of water). The powder paste volume must be sufficient to fill up the voids between the aggregate particles or otherwise air will be entrapped in the concrete mix. Actually, the powder paste volume is equal to cement paste volume plus LF volume. Hence, with LF added, we may reduce the cement paste volume by an amount equal to the LF volume while maintaining the powder paste volume needed to fill up the voids. This is equivalent to adding LF to replace an equal volume of cement paste. Such addition of LF as cement paste replacement without changing the mix proportions of the cement paste should have no adverse effect on concrete strength but would significantly reduce the cement clinker consumption and carbon footprint of the concrete.

The authors have been advocating the above strategy of adding LF to improve the packing density of the aggregate for reducing the volume of voids to be filled, and to replace an equal volume of cement paste for reducing the cement consumption without causing any reduction in strength. Apart from reducing the cement consumption, this use of LF may also improve the overall performance of the concrete produced. In previous studies by the authors [11,12], it has been found that this would allow the cement paste volume to be reduced by up to one-third without causing air entrapment, improve the cohesiveness of the fresh concrete and increase the cube strength of the hardened concrete. More importantly, this would substantially decrease the heat generation at early age [11] and the drying shrinkage at later age [12], or in other words, improve the dimensional stability of the concrete, which is essential for avoiding thermal and shrinkage cracking of the concrete.

However, the possible effect of adding LF as cement paste replacement on the durability performance of concrete has not been studied yet. As for the addition of LF as fine aggregate replacement, the addition of LF as cement paste replacement would increase the amount of very fine particles in the concrete mix because the volume of LF added is larger than the volume of cement replaced. In theory, this should reduce the pore size of the voids between the aggregate particles and for the same quality of cement paste, reduce the water permeability and sorptivity of the concrete. Hence, it is anticipated that the addition of LF as cement paste replacement would also improve the durability performance of the concrete produced.

To verify the above anticipation, an experimental program aiming to evaluate the effects of adding LF as cement paste replacement on the water permeability and sorptivity of concrete has been conducted, as reported herein. This experimental program is actually part of a comprehensive research program on the use of LF for the production of high-performance concrete with low carbon footprint. Field trials by the second author as a materials consultant have demonstrated that LF is particularly good for the production of self-consolidating concrete and pumpable concrete without using a large cement paste volume. Moreover, the high cohesiveness and low bleeding of concrete mixes containing LF can help to avoid washout of tremie concrete and sedimentation cracks in deep concrete pours. Further research on such beneficial effects is still ongoing and will be reported in later publications.

## 2. Experimental program

### 2.1. Materials

An ordinary Portland cement (OPC) of strength class 52.5N complying with British Standard BS 12: 1996 [13] (equivalent to ASTM Type I) and a finely ground LF were used in all the concrete mixes. The 28-day mortar cube strength of the OPC was measured as 59.0 MPa, whereas the specific gravities of the OPC and LF were measured as 3.11 and 2.64, respectively. By the use of a laser particle size analyzer, the volumetric mean particle sizes of the OPC and LF were determined as 11.4 μm and 14.5 μm, respectively. Since the mean particle sizes of 11.4 μm and 14.5 μm differ from each other by only about 21%, it may be said that the OPC and LF have similar fineness (having similar fineness here means that the size difference between the two materials is not large enough to allow the finer material to fill into the voids of the coarser material).

On the other hand, both the coarse and fine aggregates were obtained from crushed granite rock. They were obtained from the market and are thus representative of typical aggregates being used in commercial production of concrete. The coarse aggregate has a maximum size of 20 mm. Its specific gravity and water absorption were measured to be 2.61 and 1.01%, respectively. The fine aggregate has a maximum size of 5 mm. Its specific gravity, water absorption and fineness modulus were measured to be 2.52, 1.89% and 2.68, respectively. Sieve analysis verified that the grading curves of the coarse and fine aggregates were within the allowable limits stipulated in British Standard BS 882: 1992 [14].

### 2.2. Mix proportions

In total, 9 concrete mixes were produced for testing, as depicted in Table 1. Each concrete mix was assigned an identification code of *C–X–Y*, in which *C* denotes concrete, *X* denotes the water/cement (*W*/*C*) ratio and *Y* denotes the LF volume. The *W*/*C* ratio was varied from 0.40 to 0.60 in increments of 0.10 while the LF volume was varied from 0% to 8% in increments of 4% (note that the LF volume is expressed as a percentage of the concrete volume). In all the concrete mixes, the powder paste volume (cement paste volume + LF volume, expressed as a percentage of the concrete volume) was fixed at 34%. When LF was added, the cement paste volume was reduced by the LF volume. Hence, the LF was added to the concrete mix as cement paste replacement, not as cement replacement. In other words, when LF was added, the cement paste volume was reduced but the *W*/*C* ratio was kept constant.

This relatively large powder paste volume of 34%, which should be large enough for the production of a high-flowability concrete, was adopted because one major goal of the present study was to develop a high-flowability concrete with a low cement content (and thus low carbon footprint) and a high dimensional stability for possible use as a self-consolidating concrete, pumpable concrete or tremie concrete. In the present study, up to a maximum LF volume of 8% had been added and the cement paste volume had been reduced from 34% to 26%. The production of a high-flowability concrete using just a cement paste volume of 26% is not easy. Nevertheless, the authors have dedicated themselves to develop such "green" and high-performance concrete with low carbon footprint.

With the powder paste volume fixed, the aggregate volume was also fixed. Moreover, the fine to total aggregate ratio was fixed at 0.4. In each concrete mix, the fine aggregate content, 10 mm aggregate content and 20 mm aggregate content were calculated as 672, 504 and 504 kg/m$^3$, respectively. As in usual practice for the production of high-flowability concrete, a superplasticizer (SP) was added to each concrete mix. The SP was added to the concrete mix in increments until a slump of at least 200 mm and a flow of at least 500 mm were achieved. The SP dosage and the slump and flow results actually achieved of each concrete mix are listed in the second to fourth columns of Table 2 (these results will be discussed in details later).

### 2.3. Measurement of workability and strength

Each concrete mix was tested for its workability in terms of slump and slump-flow, and its strength in terms of 28-day cube strength. The slump was measured by the slump test as the drop in height of the concrete after filling the concrete into the slump cone and lifting the slump cone in accordance with BS EN 12350-2: 2009 [15], while the slump-flow was measured as the average diameter of the patty formed after the slump test (with the slump-flow measured, the test became the same as the slump-flow test) in accordance with BS EN 12350-8: 2010 [16]. For brevity, the slump-flow is abbreviated hereafter as flow. The cube strengths were measured by casting three 150 mm cubes from the concrete, removing the moulds 1 day after casting, applying water curing at a temperature of 27 ± 2 °C, and testing of the cubes at the age of 28 days, in accordance with BS EN 12390-3: 2009 [17]. The cube strength result is taken as the average cube strength of the three cubes cast from the same batch of concrete and tested at the same time.

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