Effect of silica fume and limestone powder on mechanical properties of ultra-high performance concrete

P Singnio¹, M Sappakittipakorn¹,² and P Sukontasukkul¹

¹ Construction and Building materials research center, Department of Civil Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, Thailand
² Corresponding Author: manote.s@eng.kmutnb.ac.th

Abstract. This research aimed to study the effect of Portland cement replacement with silica fume and limestone powder in Ultra High Performance Concrete (UHPC). Nine mix proportions were designed with a constant amount of binder at 1200 kg per cubic meter of concrete. In these mixes, the cement was replaced with silica fume at 10%, 15% and 20% and limestone powder at 15% and 30% by weight of binder. For all mixes, the ratio of water to binder (W/B) and the steel fiber volume fraction were 0.2 and 2% respectively. After the preparation of test specimens and stream curing for 3 days, compressive strength, flexural strength, and length change due to shrinkage of the UHPC mixes were examined. The results showed that the silica fume increases the compressive and flexural strength (at the first peak load) but the limestone decreases. Without the limestone, the 20% silica fume mix provides the maximum average residual strength. However, when either 15% or 30% limestone is admixed, the optimum residual strength occurs at the 15% silica fume. Moreover, it is worth noting that the reducing amount of cement by replacing either with silica fume or limestone powder effectively reduces the shrinkage.

Keywords: Ultra High Performance Concrete, Silica Fume, Limestone Powder, Flexural Strength, Shrinkage

1. Introduction
Ultra-high performance concrete (UHPC) have been developed to enhance mechanical properties and to overcome the flaw of brittleness [1]. High cement content, very fine aggregate materials, chemical admixtures and fiber addition are the key factors to achieve UHPC. The excellence in its strength and toughness allow it to form thin section members without typical reinforcing steel. It is generally realized that cement manufacture generates the carbon dioxide emission. Since UHPC consumes a lot of cement, the cement replacement shall be engaged to make it more environmentally friendly [2]. Normally, silica fume is used to replace cement because it remarkably refines the UHPC microstructure [3]. Even though silica fume is a by-product collected from silicon refractory, it is not cheap. The amount of silica fume employed then shall be optimized. Limestone powder – a residue from limestone quarry – have recently been utilized as a partial replacement of cement [4-6]. The amount of limestone powder used for a cement replacement is however limited. It is interesting to increase the portion of limestone powder. Therefore, the effect of the silica fume and limestone powder combination on UHPC properties is of interest in this study.
2. Research Methodology

For the controlled mix, Portland cement (ASTM Type I) is used as a main cementitious binder material. The binder content is 1200 kg/m$^3$ and the water to binder ratio is kept constant at 0.20. Fine aggregates are graded #50, #100, and #200 quartz sand (i.e. passing a No.50, No.100 and No.200 sieve, respectively) [7]. The toughness of cementitious matrix is enhanced by adding hooked-end steel fiber (length of 35 mm, aspect ratio of 65, and tensile strength of 1100 MPa) at 2% by volume fraction. Polycarboxylate ether (PCE) based high range water reducing admixture is also added to achieve sufficient workability [7,8]. The proportion of controlled UHPC mix is tabulated in Table 1.

| Mix   | Binder | Quartz Sand #50 | Quartz Sand #100 | Quartz Sand #200 | Water | Fiber (2%) |
|-------|--------|-----------------|-----------------|-----------------|-------|------------|
| UHPC  | 1200   | 660             | 200             | 100             | 240   | 156        |

The Portland cement is partially replaced with two industrial by-products, which are limestone powder (at 0, 15, and 30% wt. of binder) and silica fume (at 10, 15, and 20% wt. of binder). Totally, there are nine mixes (UHPC1 to UHPC9 as shown in Table 2) investigated in this study. The limestone powder is an industrial grade refined from residues of limestone quarries. It is a very fine white powder passing a No.600 sieve. The silica fume is an ultrafine solid sphere of silicon dioxide collected as from silicon and ferrosilicon alloy furnaces. Its diameter is ranged from 0.03 to 0.3 micron. The chemical compositions of these two binders and cement are listed in Table 3. In addition, the physical properties and the particle size distribution of all binders and aggregates are shown in Table 4 and Figure 1.

**Table 1. Mix proportion of controlled UHPC (kg/m$^3$)**

**Table 2. Specimen codes and the variation of binder combination**

| Specimen Code* | Portland cement | Silica fume | Limestone powder |
|----------------|-----------------|-------------|------------------|
| 1 SF10 LP0     | 1080            | 120         | 0                |
| 2 SF15 LP0     | 1020            | 180         | 0                |
| 3 SF20 LP0     | 960             | 240         | 0                |
| 4 SF10 LP15    | 900             | 120         | 180              |
| 5 SF15 LP15    | 840             | 180         | 180              |
| 6 SF20 LP15    | 780             | 240         | 180              |
| 7 SF10 LP30    | 720             | 120         | 360              |
| 8 SF15 LP30    | 660             | 180         | 360              |
| 9 SF20 LP30    | 600             | 240         | 360              |

*SF = Silica Fume and LP = Limestone Powder

**Table 3. Chemical compositions of binder materials (% w/w)**

| Composition | Portland cement | Limestone powder | Silica fume |
|-------------|-----------------|------------------|-------------|
| CaO         | 61.33           | 0                | 0.48        |
| CaCO$_3$    |                 | 82.85            |             |
| Al$_2$O$_3$ | 6.40            | 2.39             | 1.17        |
| SiO$_2$     | 21.01           | 8.43             | 88.30       |
| Fe$_2$O$_3$ | 3.12            | 1.41             | 4.76        |
| MgO         | 3.02            | 3.28             | 0.10        |
| SO$_3$      | 2.30            | 0.10             | 1.05        |

The effect of cement replacement with silica fume and limestone powder is experimentally evaluated via compression, bending, and shrinkage tests. Following the ASTM C39, the compressive strength is measured using a 100-mm diameter and 200-mm height cylinder specimen. To examine
flexural performance, the ASTM C1609 is employed on a 100x100x350 mm prism specimen. For the shrinkage, the length change of a 75x75x285 mm prism is measured as per ASTM C596.

The mixing of all mixes is done using a concrete pan mixer. They are filled and consolidated into the cylindrical and prismatic molds. Three replicates are prepared for each test method. After molding, the specimens are warped with plastic sheets to prevent water loss and are allowed to set for 24 hours. For the shrinkage test, the specimens are immediately examined. Their length is measured by using a length comparator apparatus once a day for 60 days. During the test, they are kept in air-dried condition at 55±5% RH and 23±2°C. For the other tests, the specimens are steam cured at 90°C for 72 hours and then allowed to cool down for 6 hours at room temperature prior to the testing.

Table 4. Physical properties of binders and aggregates used for UHPC mixes

| Property                | Specific Surface (cm²/g) | Density (g/cm³) | SMD* (µm) | VMD** (µm) |
|-------------------------|--------------------------|-----------------|-----------|------------|
| Portland cement         | 3801                     | 3.15            | 5.26      | 19.75      |
| Limestone powder        | 6051                     | 2.73            | 3.63      | 9.75       |
| Silica fume             | 11521                    | 2.21            | 2.36      | 4.56       |
| Quartz sand #50         | 274                      | 2.65            | 82.64     | 183.68     |
| Quartz sand #100        | 560                      | 2.65            | 40.46     | 85.99      |
| Quartz sand #200        | 2176                     | 2.65            | 10.4      | 34.51      |

*SMD = Sauter Mean Diameter (µm)  
**VMD = Volume Mean Diameter (µm)

Figure 1. Particle size distribution of all binders and quartz sands used for UHPC mixes

3. Results and Discussion

3.1. Compressive Strength

For compression test, the cylindrical specimens are axially loaded in a 2000-kN compression machine. The ultimate load applied is converted to compressive strength as shown in Figure 2. From the result of the UHPC1 to 3 (where the cement is replaced with only silica fume at 10%, 15%, and 20% w/w of binder, respectively), it is clearly apparent that the replacing cement with silica fume increases the compressive strength. That is a consequence of the filler effect from its ultrafine particles and of the additional pozzolanic reaction. Similar to the UHPC1 to 3, the group of UHPC4 to 6 and the group of UHPC7 to 9 also replace cement with silica fume at 10%, 15%, and 20% by mass of binder. The compressive strength result of all UHPC mixes is illustrated in Figure 2. The addition of limestone powder decreases the UHPC compressive strength. The decrease is directly proportional to the added amount of the limestone powder. At this high strength level, its chemical bonding (if any) is inferior to the main matrices with silica fume. Therefore, it may be considered that the limestone powder functions like a filling material.
Figure 2. Compressive strength results of all UHPC mixes

3.2. Flexural Performance

The key value of UHPC is not only the high compressive strength but the flexural performance as well. The UHPC generally provides superior flexural strength and toughness because of fiber addition and remarkable interfacial bonding between fibers and matrices. Following ASTM C1609 test method, the load vs net deflection results of all nine mixes are displayed in Figure 3. At the first peak load, the flexural strength of all mixes is in the range of 7.8 to 10.1 MPa as shown in Figure 4. It is apparently that when there is no limestone powder the 20% silica fume (the highest content) provides the maximum flexural strength. However, when the limestone powder is intermixed, the flexural strength is decreased. After the first peak load, it is assumed that the matrix phases start cracking macroscopically. The fibers then bridges the cracks and carries further load applied. The load carrying capacity after this point as shown in Figure 3 exhibits the deflection hardening. The average residual flexural strength (ARS) is presented in Figure 4. When only silica fume is used (in Mix 1 to 3), the ARS is proportional to the silica fume content. It is interesting that, when the limestone powder is introduced (in Mix 4 to 9), the ARS is increased except the 20% silica fume (in Mix 6 and 9).

Figure 3. Load vs net deflection results of the UHPC mixes as per ASTM C1609 test

Figure 4. Results of flexural strength at first peak load and average residual strength

3.3. Shrinkage results for 60 days

During the shrinkage test, all prism specimens are allowed to shrink freely in a temperature and humidity control room. The change of their length is measured once a day for 60 days. Due to shrinkage, the length of all specimens is shortened. Figure 5 shows the specimen’s contraction in term of shrinkage percentage. At the first couple of days, the initial shrinkage of all mixes is very high. The shrinkage continues but at a decreasing rate. During the second month of testing, the shrinkage change is very little. For a comparison among the nine mixes, their shrinkage value at the end of the test is
summarized in Figure 6. It is noticed that while the cement is replaced with silica fume and limestone powder the shrinkage is reduced. The shrinkage is then correlated to cement content as shown in Figure 7.

![Figure 5. Shrinkage result of the nine UHPC mixes for 60 days](image1)

![Figure 6. Shrinkage percentage of the UHPC mixes at the age of 60 days](image2)

![Figure 7. Influence of Portland cement content on the shrinkage of the UHPC mixes](image3)

4. Conclusions
The influence of cement replacement with silica fume and limestone powder on the compressive strength, flexural performance, and shrinkage of UHPC are assessed. According to the experimental result, conclusions can be drawn as follows. Silica fume improves the compressive strength. On the other hand, it is reduced by the addition of the limestone powder. For the flexural strength at the first peak load, the effect is similar to the compressive strength. Without the limestone powder, the 20% silica fume yields the maximum average residual flexural strength. When either 15% or 30% limestone powder is admixed, the average residual strength is optimum with the 15% silica fume (in mix 5 and 8). The cement content significantly affect the shrinkage. As the cement is reduced by the replacement with silica fume and limestone powder, the shrinkage is clearly decreased.

Acknowledgements
The authors would like to thank the Siam Research and Innovation Company Limited for the particle size evaluation of the materials used in this study. We also thank the SR Fiber Company Limited for providing the steel fiber and the Siam City Concrete Company Limited for providing the Portland cement and chemical admixtures.

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