# EFFECTS OF SILICA POWDER AND CEMENT TYPE ON DURABILITY OF ULTRA HIGH PERFORMANCE CONCRETE (UHPC)

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## 1. ABSTRACT

Ultra-high performance concrete (UHPC) has been shown to achieve exceptionally high strength in compression and high ductility through optimization of the particle packing density of the material's matrix. This dense structure also offers UHPCs the ability to resist deterioration due to other environmental factors, such as freeze-thaw and the penetration of salts and ions from the surface. Robust UHPCs enables structures to last longer, reduces the cost of maintenance and helps achieve a significantly more sustainable infrastructure. To assess these parameters for UHPC, several non-proprietary blends are investigated by assessing the materials' resistance to freeze-thaw cycles, ingress of chlorides as well as the presence and distribution of air voids. The main experimental variables are cement type and the quantity of silica powder, which varies from 0% to 25% of the cement weight. All mixes displayed extremely low levels of chloride ion penetration and high resistance to freeze-thaw with mass loss well below the limit in over 60 cycles of freeze-thaw. Analysis of the test data indicates that the silica powder content has little influence on these performance criteria.

**Keywords:** ultra-high performance concrete **(**UHPC), freeze-thaw, rapid chloride penetration, air-void system, silica powder, durability

## 2. INTRODUCTION AND MOTIVATION

Ultra-high performance concrete (UHPC) is defined as a cementitious material with compressive strength in excess of 150 MPa [Graybeal, 2006, Alkaysi, 2015, 2016, Wille 2011, 2012. It achieves its extraordinary strength characteristics through optimization of the particle packing density of its cementitious matrix [Holschemacher, 2005]. This high particle packing density also leads to high durability [Castro, 2009, de Larrard, 1994]. When properly reinforced with discontinuous fibers, UHPC can develop other beneficial properties, including pseudo-ductile tensile behavior [Wille, 2011] and toughness. Combined with its high durability, pseudo-ductility leads to small crack widths in UHPC structures. The narrow crack widths inhibit the ingress of chlorides, thus potentially creating long-living and, therefore, potentially more sustainable reinforced concrete structures. Various versions of UHPC have been in existence for several decades [Bonneau, 1997]. To date, very little research has been done to investigate the influence of various material parameters on the durability performance of non-proprietary blends of UHPC, including the effects of silica powder and cement type on the freeze-thaw and rapid chloride penetration resistance. To address this gap in knowledge, this study investigates two critical aspects of the durability performance of UHPC: freeze-thaw resistance and chloride ion penetration in different blends of non-proprietary UHPCs. The experimental parameters include cement type and the amount of silica powder.

## 3. BACKGROUND AND PREVIOUS RESEARCH

### 3.1. Freeze-Thaw Resistance

Tests investigating UHPCs resistance to freeze-thaw have been limited. Ahlborn et al. performed freeze-thaw cycling tests in accordance to ASTM C 666, procedure B, showing that after 32 freeze-thaw cycles, ultra-high performance concrete specimens showed no degradation. Acker and Behloul similarly reported that after 300 freeze-thaw cycles, UHPC showed no degradation [2004]. Graybeal performed air void analyses on Ductal©, finding UHPC void numbers to be between 0.008 and 0.30 voids/mm, corresponding to an air content of 5.7% to 7.3% with no vibration [2006]. To date, no research has been done to investigate the durability parameters for a non-proprietary blend of UHPC.

### 3.2. Chloride Ion Penetration Resistance

Performing rapid chloride permeability tests, Ahlborn showed that UHPC was capable of achieving permeability values less than 100 coulombs for both air-cured and steam-cured specimens [2008]. Materials with coulomb values less than 100 are generally considered to have negligible chloride ion penetration. Testing two different types of reactive powder concretes, Bonneau [1997] showed that specimens were able to achieve 6 to 9 coulombs. Graybeal [2006] reported that untreated specimens achieved coulomb values of 360 and 76 at 28 days and 56 days respectively. Most of the existing chloride permeability studies pertain to proprietary materials and data for nonproprietary blends is lacking at present.

## 4. EXPERIMENTAL PARAMETERS

### 4.1. UHPC Mix Designs

The UHPC employed in this research was originally developed by Wille and Naaman [2011], and consisted of white cement, silica powder, silica fume, fine sands, high range water reducer and very low water-binder (w/b) ratio (W - 25, Table 1). Using this original mix as a basis, nine different blends were created by changing the type of cement and content of silica powder. Three different types of cements were identified and used. The first is a Portland type I, white cement. Though UHPC with this cement has been the subject of much research focusing on tensile and compressive strength properties and strain rate effects associated with, data on durability for UHPCs with white cement does not exist. The second cement chosen is regular Portland type V cement. This cement was chosen for both its lower cost, and good sulphate resisting properties. The third cement chosen is a 50:50 blend of Portland Type I with ground granulated blast furnace slag (GGBFS). The quantity of cement and silica fume was held constant for all of the mixes, but the amount of silica powder was changed from 0% (none) to 25% of the total amount of cement. The water to cement ratio was held constant for all mixes, at 0.22 w/c. All of the blends contain 1.5% smooth steel fibers by volume fraction. To facilitate the following discussion, each mix is designated by its variables as C - X, where C is the cement type and X is the amount of silica powder. For example, V - 25 is Portland Type V with 25% silica powder to cement by weight.

**Table 1: Mixes Proportions for UHPCs tested**

| Name | White Cement Type I | Silica Fume | Silica Powder | Fiber (%) | Fine Sand | Course Sand |
|---|---|---|---|---|---|---|
| W - 25 | 1.00 | 0.25 | 0.25 | 1.50% | 0.26 | 1.06 |
| W - 15 | 1.00 | 0.25 | 0.15 | 1.50% | 0.29 | 1.14 |
| W - 00 | 1.00 | 0.25 | 0.00 | 1.50% | 0.31 | 1.26 |
| | **Portland Type V** | | | | | |
| V - 25 | 1.00 | 0.25 | 0.25 | 1.50% | 0.26 | 1.05 |
| V - 15 | 1.00 | 0.25 | 0.15 | 1.50% | 0.28 | 1.14 |
| V - 00 | 1.00 | 0.25 | 0.00 | 1.50% | 0.31 | 1.26 |
| | **Type I / GGBS** | | | | | |
| IG - 25 | 1.00 | 0.25 | 0.25 | 1.50% | 0.26 | 1.06 |
| IG - 15 | 1.00 | 0.25 | 0.15 | 1.50% | 0.28 | 1.14 |
| IG - 00 | 1.00 | 0.25 | 0.00 | 1.50% | 0.31 | 1.26 |

### 4.2. Steel Fiber Reinforcement

Steel fiber reinforced concretes resist post-cracking tensile stress through the composite action between the concrete and fibers, including chemical and mechanical bonding at the interface between the two. In this study, all UHPC mixes contain 1.5% steel fibers by volume of the wet concrete. The steel fibers used are brass coated, smooth fibers. Each fiber is 19 mm long with a diameter of 0.2 mm and has a minimum tensile strength of 1965 MPa.

## 4.3. Experimental Procedure

### 4.3.1. Freeze-Thaw Resistance

The resistance of concrete to the combined attack of de-icing salt and frost is evaluated by a modified CIF (Capillary suction, Internal damage and Freeze-thaw) test [RILEM], where the surface scaling, moisture uptake and the internal damage were measured simultaneously. Cylindrical specimens of 150 mm in diameter and 300 mm in height were made. After 24±2 hours of curing the specimens were removed from the mold and submerged in tap water at 20 °C for 28 days. After storage in the water, the specimens were cut into rectangular prisms of 120 mm by 110 mm by 70±2 mm. The cut section was away from the two ends of the cylinder to avoid surface in-homogeneity associated with a cast surface and is parallel to the finishing surface. After air drying at 20 °C and 65% relative humidity for 24 hours, the lateral surfaces of the specimens were sealed by the aluminum foil with butyl rubber. The freeze-thaw machine contains fifteen stainless steel bowls, each containing one specimen. The specimen sits on four spacers so that the bottom test surface is in contact with the test liquid. A freeze-thaw cycle duration is 12 hours. The temperature profile starts with a temperature of 20°C; the temperature of the stainless steel bath with liquid (3% NaCl solution in this case) is lowered at a linear rate of 10 °C/hour for 4 hours; the specimens are kept at -20 °C for 3 hours, then brought back up to room temperature at the same constant rate of 10 °C/hour as used for cooling; the temperature is maintained for 1 hour at 20 °C before the commencement of the next freeze-thaw cycle. During the one-hour isothermal period at 20 °C, the amount of surface scaling, the moisture uptake and the internal damage were measured after a specific number of freeze-thaw cycles. A total of two specimens were tested for each of the material parameters.

### 4.3.2. Rapid Chloride Penetration Test

Evaluation of chloride ingress resistance was tested according to ASTM C1202-12, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration” [19]. A commercially available device, PROOVE’it, was used in order to complete the testing. Specimens of 100 mm in diameter and 50 mm in width were positioned into the measuring cell. Each cell contains a fluid reservoir at each face of the specimen. One reservoir is filled with a sodium chloride solution (3.0% NaCl). The other reservoir is filled with a sodium hydroxide solution (0.3 M NaOH).

## 5. EXPERIMENTAL RESULTS

Table 2 shows a summary of all the test results, which are discussed in more detail in the following sections.

**Table 2: Summary of Test Results**

| UHPC | Rapid Chloride Penetration Total Charge Passed | Air Void Analysis Air Content | Freeze-Thaw Test Total Mass Loss after | f’c MPa |
|---|---|---|---|---|
| W - 25 | 89 | 5.8 | 98.8 | 195.0 |
| W - 15 | 295 | 7.9 | 20.7 | 188.8 |
| W - 00 | 637 | 6.6 | 17.7 | 173.6 |
| V - 25 | 939.5 | 6.1 | 18.2 | 174.3 |
| V - 15 | 488.5 | 6.5 | 18.0 | 187.4 |
| V - 00 | 57 | 4.5 | 42.2 | 177.8 |
| IG - 25 | 137.5 | 5.7 | 20.5 | 172.9 |
| IG - 15 | 229 | 4.8 | 24.2 | 181.2 |
| IG - 00 | 137.5 | 5.8 | 44.7 | 190.9 |

### 5.1. Freeze-Thaw Resistance

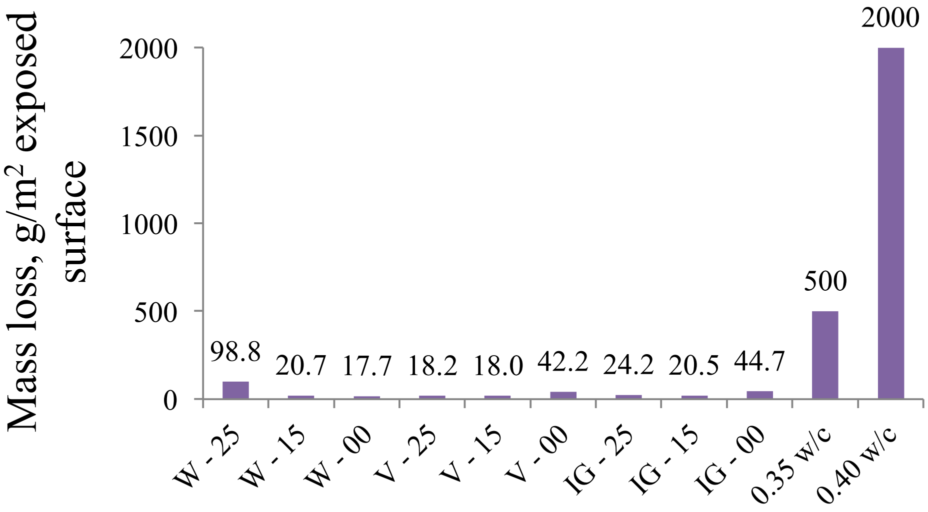

**Figure 1: Mass Loss of UHPC Mixes after at Least 60 Cycles**

From Figure 1, the best performing mix in terms of the least total mass loss was W - 00, with a total loss of 17.7 g/m$^2$. The worst performing mix was W - 25, with a total loss of 98.8 g/m$^2$. Generally, there are no distinct differences in the freeze-thaw resistance of UHPCs with 0% SP, 15% SP and 25% SP. The values are all so low compared to the acceptable mass loss limits for concretes that the differences exhibited by W - 25 are considered to be within statistical tolerances. Figure 1shows that, with the exception of W - 25, all of the mixes are within 15% of each other, and less than 3.3% of the acceptable mass losses limit for concrete, despite varying the level of silica powder and cement type.

### 5.2. Rapid Chloride Permeability

A summary of results is shown in Figure 2 for the nine mixes. The chloride permeability rating is illustrated based on Table 3. Also shown are some typical results for regular concrete.

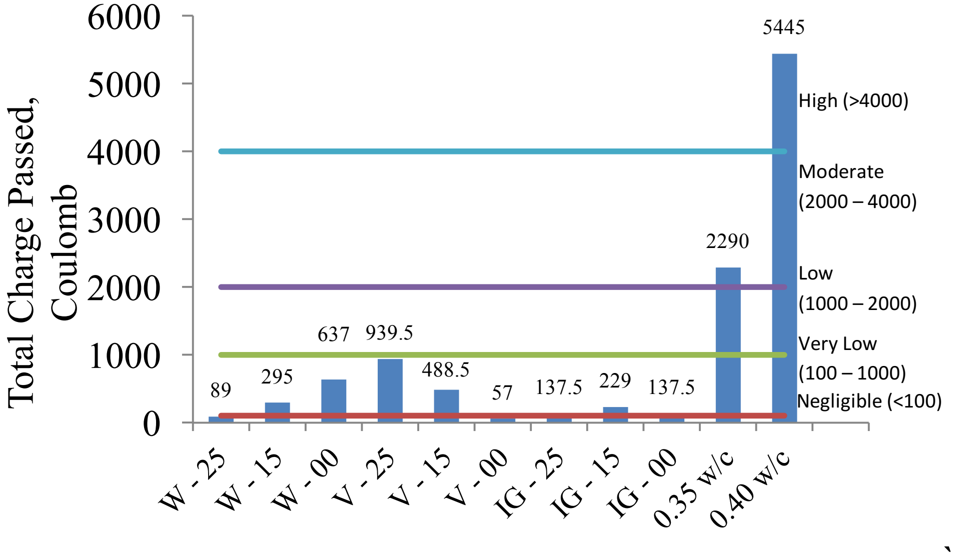

**Figure 2: Total Charge Passed for UHPC and RC Mix, [Chia, 2002]**

**Table 3: Chloride Permeability Rating**

| Chloride permeability | Charge (Coulomb) | Typical concrete |
|---|---|---|
| High | > 4000 | High w/c ratio (> 0.6) |
| Moderate | 2000 - 4000 | Moderate w/c ratio (0.4 - 0.5) |
| Low | 1000 - 2000 | Low w/c ratio (< 0.4) |
| Very low | 100 - 1000 | Latex-modified concrete, internally sealed concrete |
| Negligible | < 100 | Polymer impregnated concrete, polymer concrete |

From Figure 2, all of the UHPC mixes have a rating of “very low” chloride permeability with two mixes falling into the “negligible” category. The mixes containing white cement averaged 340 coulombs passed, a 102% difference compared to Portland I / GGBFS. The mixes containing Portland type V averaged 495 coulombs passed, a 194% percent difference. As noted for mass loss in the freeze-thaw test results, while the variations appear large, the base values are actually small, signifying the good chloride penetration performance of all of the UHPC mixes considered.

## 6. CONCLUSION

- All of the UHPC mixtures tested displayed exceptional resistance to freeze-thaw. All of the specimens tested experienced mass loss that was well below the mass loss limit in over 60 cycles of freeze-thaw.
- All of the UHPC mixtures show high resistance to chloride ion penetration. Concretes made with the Portland Type I / GGBS Cement blend showed the least permeability, followed by specimens made with white cement and Portland type V cement. Concretes containing silica powder at 25% showed slightly higher ion permeability than those with 15% silica powder.

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