SILICA FUME IN SHOTCRETE

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By John Wolsiefer, Sr. and D.R. Morgan

SYNOPSIS: Silica fume was first used in shotcrete in Norway in the nineteen seventies. In the early nineteen eighties the use of silica fume developed in North America, first in Western Canada and then in the United States. Silica fume has been added to both wet-mix and dry-mix shotcrete in a variety of different forms, including: as-produced, uncompacted silica fume; compacted low density silica fume; compacted high density silica fume; and as a slurry. This paper examines the influence of addition of the first three of the above forms of silica fume on the properties of plastic and hardened wet-mix and dry-mix shotcrete, compared to the performance of plain control Portland cement shotcretes. Parameters evaluated included the batching, mixing, conveying and shooting characteristics of the shotcretes. Plastic shotcrete properties evaluated included: slump and air content in the as-batched and applied wet-mix shotcrete; thickness to bond break (sloughing) on shotcrete applied to both vertical and overhead surfaces; and rebound on vertical and overhead surfaces. Properties of the hardened shotcrete evaluated included: compressive strength at 1, 7, 28 and 63 days; flexural strength at 7 and 28 days; boiled absorption and volume of permeable voids; drying shrinkage; rapid chloride permeability, and electrical resistivity. It is shown that all three forms of silica fume can be successfully used to substantially improve both the plastic and hardened properties of the shotcretes studied, relative to plain control Portland cement shotcretes. There are some differences in the performance characteristics of shotcretes made with the different forms of silica fume, particularly with respect to shooting characteristics; these differences are discussed in the paper.

INTRODUCTION

Silica fume is a highly pozzolanic mineral admixture, which has been mainly utilized to improve concrete durability, strength and as a Portland cement replacement. Silica fume has been primarily used in the United States, Canada and the Scandinavian countries, but is now finding increasing use elsewhere in the world. Significant improvements in both dry-mix and wet-mix shotcrete have been achieved through the use of silica fume. This paper concentrates on the evaluation of silica fume characteristics to produce shotcrete with superior performance for applications such as rock stabilization, tunnel linings, and infrastructure rehabilitation.

Silica fume was first used in shotcrete in Norway in the nineteen seventies where the country's rocky terrain facilitated the development of shotcrete tunnel lining. Later on in the early nineteen eighties, the use of silica fume shotcrete developed in the western hemisphere, first in Western Canada and then in the United States (1). Silica fume shotcrete projects are varied in application and include: rock slope stabilization, highway and rail tunnel linings; rehabilitation of beams, columns and abutments on highway substructures; rehabilitation of marine structures, such as piles, sea walls, dock supports; rehabilitation of chemical plant structures; and the creation of artificial rockscapes for zoos and marine aquariums.

ACKNOWLEDGMENTS

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SILICA FUME IN SHOTCRETE

Improvements in shotcrete performance and production techniques achieved through the use of silica fume include the following:

- High compressive and flexural strength along with the elimination of the need for use of accelerators to achieve high early (1 to 3 day) strength.
- Reduction of rebound loss in dry—mix shotcrete by up to 50%, thus improving material cost effectiveness.
- Increased one-pass overhead application thicknesses up to 18 in. (457 mm), without accelerators, thus improving productivity. The thickness of application on vertical surfaces can be almost limitless, with the right combination of equipment materials and construction procedures.
- The combination of silica fume and steel fibers generates synergistic improvements in crack control, impact resistance and toughness.
- Higher bonding strength *for* rehabilitation projects.
- Improved cohesion to resist washout, in tidal repair of piles and seawalls.
- Increased freeze/thaw durability produced by lower permeability. (Note: wet-mix shotcrete must be properly air entrained.)
- Enhanced resistance to chemical attack from: chlorides, nitrates, sulfates, acids and alkali aggregate reactions:
- High electrical resistivity and low permeability mitigating corrosion of rebar and steel mesh in concrete rehabilitation applications in chloride environments.

WET-MIX AND DRY-MIX SHOTCRETE PROCESS

Shotcrete is a cement/aggregate mortar or concrete mix that is shot at high velocity onto a surface, by compressed air. There are two basic processes for shotcreting; the wet-mix and the dry-mix processes. Silica fume admixtures can be introduced quite easily in either process. In the dry-mix process the silica fume can be introduced as:

- a premix in super sacks (typically 1 metric tonne) with cement, aggregates, silica fume and fibers, if required;
- dry-mix transit mix with cement and aggregate batched at the plant and the silica fume and fibers batched into the transit mix on the job site;
- weight calibrated volumetric batching on site, with silica fume added in bags (25 kg) or as a preblended Portland-silica fume cement;
- silica-fume slurry addition at the nozzle (a recent innovation in Europe).

In the wet-mix process, the silica fume can be introduced as:

- transit mix just like ready mix concrete, with the silica fume bulk batched at the plant (either central mix or dry batch plant) along with the cement admixtures and aggregates;
- transit mix concrete, from a ready mix plant, with the silica fume batched in bags (25 kg) at the job site;
- slurry addition at the batch plant.

Dry-mix shotcrete tends to be preferred in applications such as the following:

- in remote or difficult to access sites, where provision of wet-mix shotcrete would be difficult; e.g. certain mining applicati6ns and repair of offshore structures;
- where small volumes of intermittent shotcrete supply are required; e.g. tunnel repair in active road or rail tunnels or small volume remedial projects.

In recent years, the wet-mix process has been gaining in usage. Its advantages over dry-mix include:

- better control over water cement ratio through in plant batching (in the dry mix process the nozzleman controls the water content);
- less rebound, greater rates of placement and productivity and hence lowers cost;
- less dust and more homogeneity in mixing (2, 3).

SHOTCRETE TEST PROGRAM

A study was undertaken to evaluate the performance characteristics of three different silica fume product forms in both wet-mix and dry-mix shotcrete. The product forms studied were:

- as-produced uncompacted silica fume (USF);
- compacted low density silica fume (CLDSF); and
- compacted high-density silica fume (CHDSF).

The performance characteristics evaluated included: rebound loss, thickness to bond breaking (sloughing) on overhead and vertical surfaces, compressive strength, flexural strength, drying shrinkage at 50% relative humidity, chloride permeability, electrical resistivity, boiled absorption and volume of permeable voids. The above parameters were compared to the performance of a shotcrete control mix prepared with plain Portland cement.

SHOTCRETE MIX DESIGNS

The wet-mix and dry-mix shotcrete mix designs used are shown in Tables 1 and 2 below. These silica fume shotcrete mix designs are typical of those being utilized in rock slope stabilization and tunneling projects in the United States and Canada. The cement was a Portland Type I, with aggregates meeting the requirements of the ACI Standard Specification for Materials, Proportioning, and Application of Shotcrete, ACI 506.2 Gradation No.2. The plain control mixes are labeled A (Wet) and E (Dry).

Table 1– Wet-Mix Shotcrete Mix Designs (kg/m^3)

Mix number	A	B	C	D
Mix Description	PC	USF	CLDSF	CHDSF
Portland Cement, Type 1	401	350	353	359
Silica Fume	0	47	48	46
Coarse Aggregate (SSD)	485	485	475	467
Concrete Sand (SSD)	1,257	1,213	1,239	1,263
Water	171	177	177	176
Water Reducer (ml)	887	1,952	1,952	1,922
Superplasticizer (ml)	0	1,957	1,597	1,360
AEA (ml)	118	296	296	296
W/C + SF	0.43	0.45	0.44	0.44
Total	2,294	2,297	2,296	2,314

The silica fume mix designs, prepared with the different product forms, namely uncompacted (USF), compacted low density silica fume (CLDSF), and compacted high density silica fume (CHDSF) are designated B, C, D respectively for the wet-mix and F, G, Ii respectively for the dry-mix shotcretes. The silica fume dosage averaged 13% (by weight of cement) for all silica-fume shotcrete mix designs. A naphthalene sulphonate based superplasticizer was utilized for the wet shotcrete mix, to control the water cement ratio.

Table 2– Dry-Mix Shotcrete Mix Designs (kg/m^3)

Mix Number	E	F	G	H
Mix Description	PC	USF	CLDSF	CHDSF
Portland Cement, Type 1	425	373	373	373
Silica Fume	0	49	49	49
Coarse Aggregate (SSD)	495	491	491	491
Concrete Sand (SSD)	1,216	1,204	1,204	1,204
Water (Estimate)	163	165	165	165
W/C + SF (Estimate)	0.38	0.39	0.39	0.39
Total	2,300	2,281	2,281	2,281

Superplasticizer is not required for dry-mix shotcrete, since most of the water in the mix is added at the shotcrete nozzle; contact time for the water reacting with the cement and silica fume is too short for effective water reduction before the mix is actually consolidated in place on the shotcrete surface. The wet-mix shotcrete was brought to the field test site by transit truck, with the silica fume and superplasticizer added on site. A shotcrete piston pump was utilized for the application of the wet-mix shotcrete. The dry-mix shotcrete was weight batched in premixed super sacks with cement, aggregate and silica fume all premixed. The dry-mix was premoisturized to a moisture content of 3 to 4%, prior to discharge in a rotating barrel feed shotcrete gun.

THICKNESS TO BOND BREAK AND REBOUND LOSS

Silica fume addition to shotcrete increases adhesion and cohesion. Consequently, the shotcrete building thickness attainable on overhead and vertical surfaces is substantially improved. Thickness to bond break (sloughing) and rebound loss were measured in a specially constructed rebound chamber. These parameters are shown in Tables 3 and 4 below.

In the wet shotcrete mix, the overhead thickness was increased from 3.5 inches (90 mm) to 11 inches (280 mm) for the C mix (CLDSF) design, as compared to the A control mix design. The thickness increase was greater for the dry-mix shotcrete, where the mix design F (USF) was 15 inches (380 mm), compared to 2.5 inches (65 mm) for the E (PC) shotcrete mix design. The dry-mix shotcrete overhead rebound was decreased from the control’s 42.7% to an average of 21.4%, for the three product forms. The vertical rebound was reduced from 45.5% in the plain control mix to 22.8%, on average for the three product forms. The wet-mix shotcrete rebound percentages were low in all mixtures.

Table 3 – Wet-Mix Shotcrete Plastic Properties

Mix Number	A	B	C	D
Mix Description	PC	USF	CLDSF	CHDSF
Ambient Temperature, °C	9	10	13	14
Shotcrete Temperature, °C	14	12	15	13
Slump of Shotcrete, cm				
Base Shotcrete	3.8	5.1	4.6	10.2
After SF + HRWR		5.1	3.6	2.0
Air Content, %				
Base Shotcrete	8.5	7.2	8.0	7.4
After SF + HRWR	—	6.4	5.8	5.8
As-shot	4.8	3.9	3.2	2.6
Thickness to Bond Break				
Overhead Application, cm	8.9	12.7	27.9	17.8
Vertical Application, cm	30.5	33.0	38.1	40.6
Overhead Rebound, %	15	12.9	12.3	10.4
Vertical Rebound, %	3.4	2.7	3.7	3.9

In summary, the wet-mix data variance for the three product forms shows no significant difference in thickness to bond break (sloughing) and rebound loss. For the dry-mix shotcrete, there is a greater thickness for uncompacted silica fume (UCF) of 15 inches (380 mm) compared to 11 inches (280 mm) and 9 inches (230 mm) for the CLDSF and CHDSF mixes respectively. Although there is a difference in thickness, as the compacted silica fume density increases, the minimum overhead thickness of 9 inches (230 mm) in the highest density fume is more than adequate for most shotcrete applications.

Table 4 – Dry-Mix Shotcrete Plastic Properties

Mix Number	E	F	G	H
Mix Description	PC	USF	CLDSF	CHDSF
Ambient Temperature, °C	6	6	8	7
Shotcrete Temperature, °C	14	16	14	13
Thickness to Bond Break				
Overhead Application, cm	6.4	38.1	27.9	22.9
Vertical Application, cm	20.3	45.7	55.9	45.7
Overhead Rebound, %	42.7	20.4	25.2	18.6
Vertical Rebound, %	45.4	21.1	22.9	24.6

COMPRESSIVE AND FLEXURAL STRENGTH

Compressive strength was measured at 24 hours, 7 days, 28 days, and 63 days, by testing cores extracted from the shotcrete panels. It can be seen from the strength data, shown in Table 5 and Figure 1 (found on page 12), that silica fume generated significant increases in the wet-mix shotcrete compressive strength

Table 5 – Wet-Mix Shotcrete Hardened Properties

Mix Number	A	B	C	D
Mix Description	PC	USF	CLDSF	CHDSF
Compressive Strength (Mpa)				
24 hours	14.5	21.7	16.8	17.3
7 days	—	44.4	38.6	35.1
28 days	43.8	63.5	55.9	57.4
63 days	44.0	69.7	64.0	64.9
Flexural Strength (Mpa)				
7 days	—	4.9	3.8	4.1
28 days	5.3	6.7	6.0	6.5
Boiled Absorption (%)				
28 days	5.9	6.6	6.9	6.3
Volume of Permeable Voids (%)				
28 days	12.9	14.3	14.9	13.9
Specific Gravity	2.30	2.30	2.30	2.34

The plain control mix shotcrete compressive strength was 6,390 psi (44 MPa) compared to an average of 9,590-psi (66.1 MPa), in the silica fume shotcretes, which is a 50% increase in compressive strength. The dry-mix shotcrete silica fume shotcrete compressive strengths were also higher than the Plain control, though not as pronounced, as in the wet-mix shotcretes. This is illustrated in Table 6 and Figure 2 (found on page 13). The flexural strength specimens were cut from the shotcreted panels for 28 day testing. The silica fume wet-mix designs were also tested at 7 days. The flexural strength data is shown in Tables 5 and 6, for the wet-mix and dry-mix shotcretes respectively. The greatest strength improvement is again in the wet-mix silica fume shotcretes. The flexural strengths were higher in the dry-mix shotcretes; this could be attributable to a higher in situ cementitious content, as the increased rebound in dry-mix shotcrete is primarily due to aggregate loss. In summary, with respect to compressive and flexural strength of the hardened shotcrete, there is little difference in performance between the three silica fume product forms.

BOILED ABSORPTION AND PERMEABLE VOIDS

The boiled absorption, volume of permeable voids and bulk specific gravity, was measured after immersion and boiling according to ASTM C642 test procedures. The data is presented in Tables 5 and 6 for wet-mix and dry-mix shotcretes respectively. All the wet-mix shotcretes have absorption and permeable voids test results that are between “good” and “excellent”, with all the dry-mix shotcrete data extremely low, being in the “excellent” category (2).

Table 6 – Dry-Mix Shotcrete Hardened Properties

Mix Number	E	F	G	H
Mix Description	PC	USF	CLDSF	CHDSF
Compressive Strength (Mpa)				
24 hours	—	—	24.7	23.7
29 hours	31.1	33.8	—	—
7 days	44.2	49.2	45.2	44.4
28 days	53.8	59.9	58.7	54.9
Flexural Strength (Mpa)				
28 days	7.4	8.4	6.6	7.5
Boiled Absorption (%)				
28 days	4.9	2.7	3.6	4.0
Permeable Voids (%)				
28 days	11.2	6.3	8.3	9.2
Specific Gravity	2.38	2.40	2.37	2.37

RAPID CHLORIDE PERMEABILITY AND ELECTRICAL RESISTIVITY

Chloride permeability and electrical resistivity data was generated from cores cut from the shotcrete panels. The tests were conducted to the requirements of the "Standard Method of Test for Rapid Determination of Chloride Permeability of Concrete", AASHTO Designation 1277-83. Chloride permeability and electrical resistivity are very important characteristics in evaluating the ability of shotcrete, in a rehabilitation application, to slow down or prevent corrosion of steel reinforcement. The rapid chloride permeability data is shown in Figure 3 (found on page 14) for wet-mix shotcrete and in Figure 4 (found on page 15) for dry-mix shotcrete. In spite of the fairly good strength, absorption and permeable void data, for the plain Portland cement shotcrete control, the rapid chloride permeability was 6,800 coulombs for the wet-mix shotcrete, and 2,573 coulombs for the dry-mix shotcrete. The values are in the "high" and "moderate" classification respectively for concrete (4) as shown in Table 7.

Table 7 – Chloride Permeability based on Charge Passed

Charge passed (coulombs)	Chloride Permeability	Typical of:
> 4,000	High	High water cement ratio (+ 0.6) conventional concrete.
2,000 to 4,000	Moderate	Moderate water cement ration (0.4 to 0.5) conventional concrete.
1,000 to 2,000	Low	Low water cement ratio (0.4) conventional concrete.
100 to 1,000	Very Low	Latex modified concrete, silica-fume concrete (5% to 15%) and internally sealed concrete.
<100	Negligible	Polymer impregnated concrete, polymer concrete and silica-fume concrete (15% to 20%).

Based on historical data, concrete of this quality would have very inferior durability performance, in an aggressive chloride environment. In contrast to this data, the silica fume shotcrete reduced the chloride permeability to an average of 371 coulombs for the wet-mix shotcrete and 192 coulombs for the dry-mix shotcrete. The electrical resistivity measurements show correspondingly large improvements over the plain control shotcrete. The dry-mix silica fume shotcrete shows an average electrical resistivity of 55,290 ohms-cm, compared to the plain control mix value of 5,490 ohms-cm. All three forms of silica fume, in both wet and dry-mix shotcrete, result in between about 10 to 20 times reduction in chloride permeability, compared to the plain control portland cement shotcrete, as shown in Figure 3 below and Figure 4. This observation, together with the electrical resistivity data, is a very significant indication of the benefits of using silica fume in shotcrete for rehabilitation of deteriorated steel reinforced concrete structures in aggressive exposure environments.

DRYING SHRINKAGE

Drying shrinkage tests were conducted in accordance with ASTM C341 test procedures, using specimens cut from the shotcreted panels. Figures 7 and 8 (found on pages 18 and 19) shows the data at *56* days that uncompacted silica fume shotcrete mixes B and F, had the lowest values of drying shrinkage. The dry-mix shotcrete shrinkage was lower than for the wet-mix shotcrete, and can be best explained by the dry-mix shotcrete's lower values of water demand.

SUMMARY AND CONCLUSIONS

1. This study program has demonstrated that the three silica fume forms studied (uncompacted, compacted low density, and compacted high density) could all be readily batched, mixed and applied in both the dry-mix and wet-mix shotcrete processes.

2. There were small differences in performance data, when comparing the product forms, within the two shotcrete mix processes. With respect to the wet-mix process, when all the rebound, thickness, strength, and permeability data were evaluated, it is seen that there was generally little significant difference in performance between the different silica fume shotcretes that could not be explained by small variations in as-shot water to cement ratios and inherent test variations. The most salient difference between the different wet—mix shotcretes was in the increased thickness to bond break (sloughing) of the compacted low density silica fume (CLDSF) over that of the uncompacted material (USF). In the dry-mix shotcrete process this thickness to bond break advantage appeared to be reversed. Thus, all three silica fume product forms could be utilized for all shotcrete applications unless there was a particular requirement for extremely large one pass application thickness. In addition, some slight adjustments to the shotcrete mix proportions could be made to optimize performance for different project applications.

3. All three silica fume forms increased thickness before bond break (sloughing) in overhead applications, for both wet and dry shotcrete mixes compared to the Plain control Portland cement mix. This performance, along with the 50*%* reduction of rebound loss in the dry-mix process, indicates that the use of silica fume in shotcrete can generate significant savings through reduction in materials cost and enhanced productivity.

4. The compressive strength of shotcrete mix designs, normally used for tunnel linings and rock stabilization project applications, can be increased by silica fume usage even in a cement substitution application.

5. The measurement data for boiled absorption, and volume of permeable voids was in the "good" to "excellent" category. This data, along with exceptionally low chloride permeability and high electrical resistivity values, indicates that silica fume shotcretes are excellent materials for the repair and rehabilitation of chloride deteriorated structures.

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Figure 1– Wet-Mix Shotcrete

Compressive Strengths

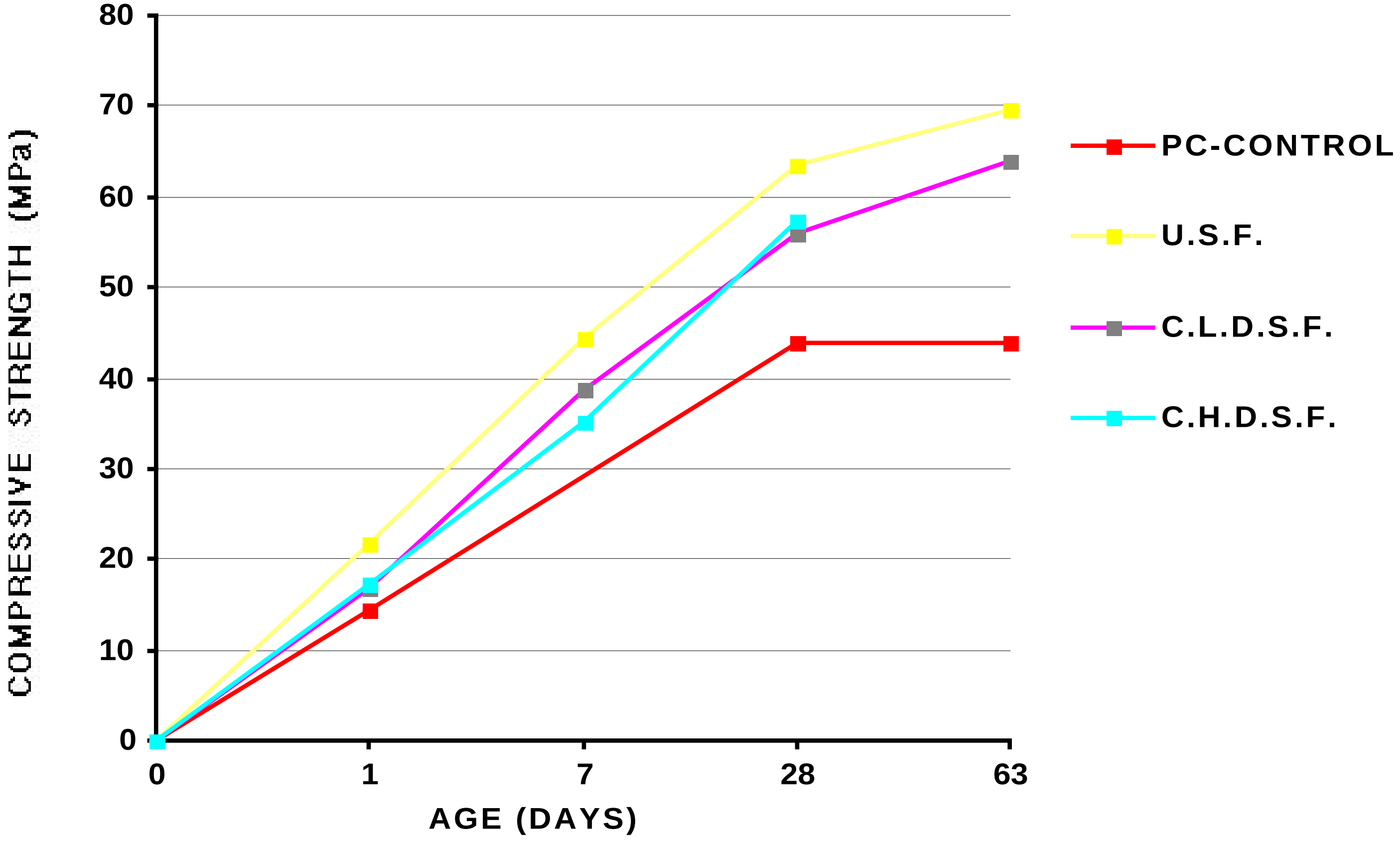

Figure 2 – Dry-Mix Shotcrete

Compressive Strength Undensified vs. Densified

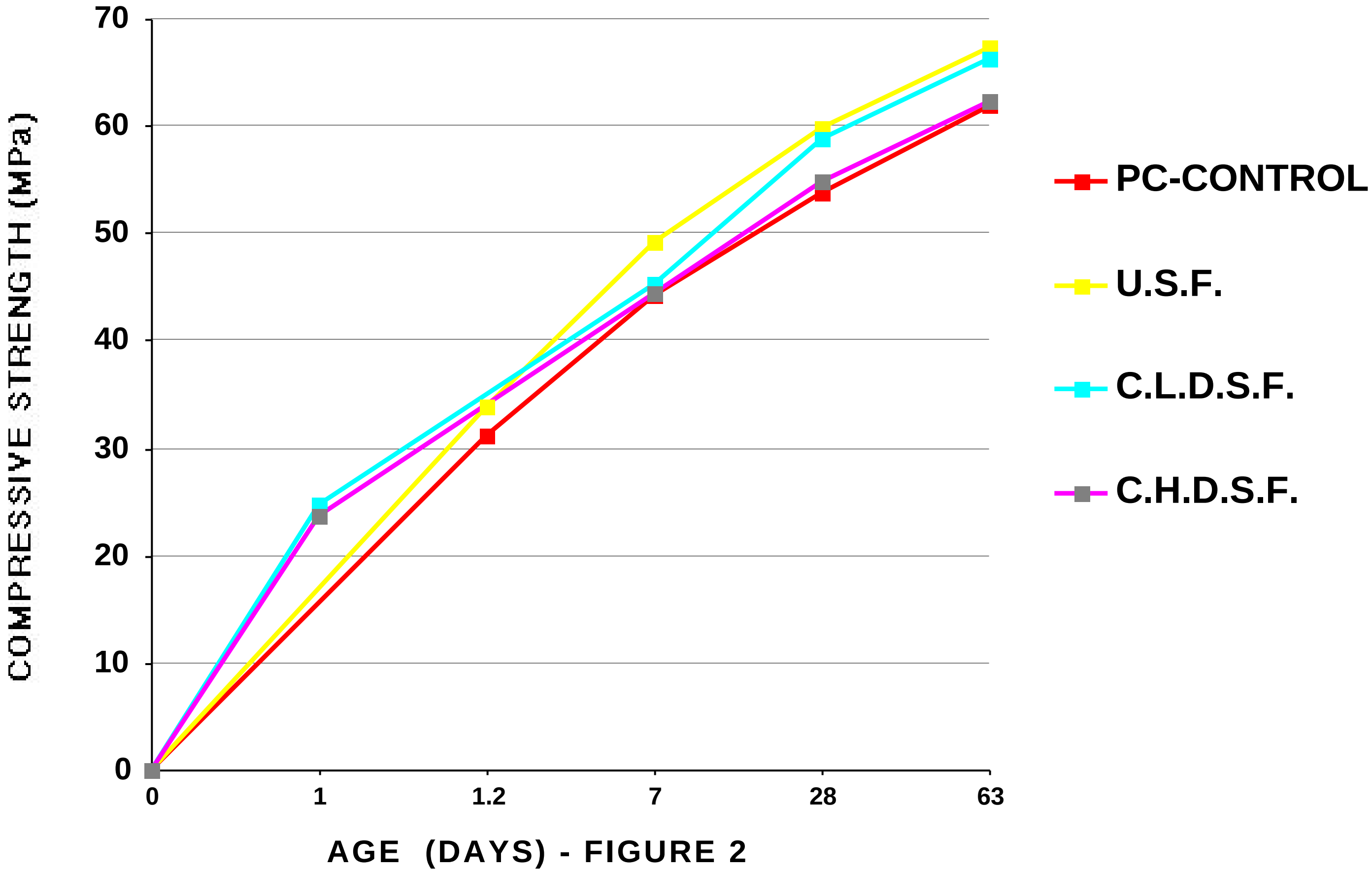

Figure 3 – Wet-Mix Shotcrete

Rapid Chloride Permeability

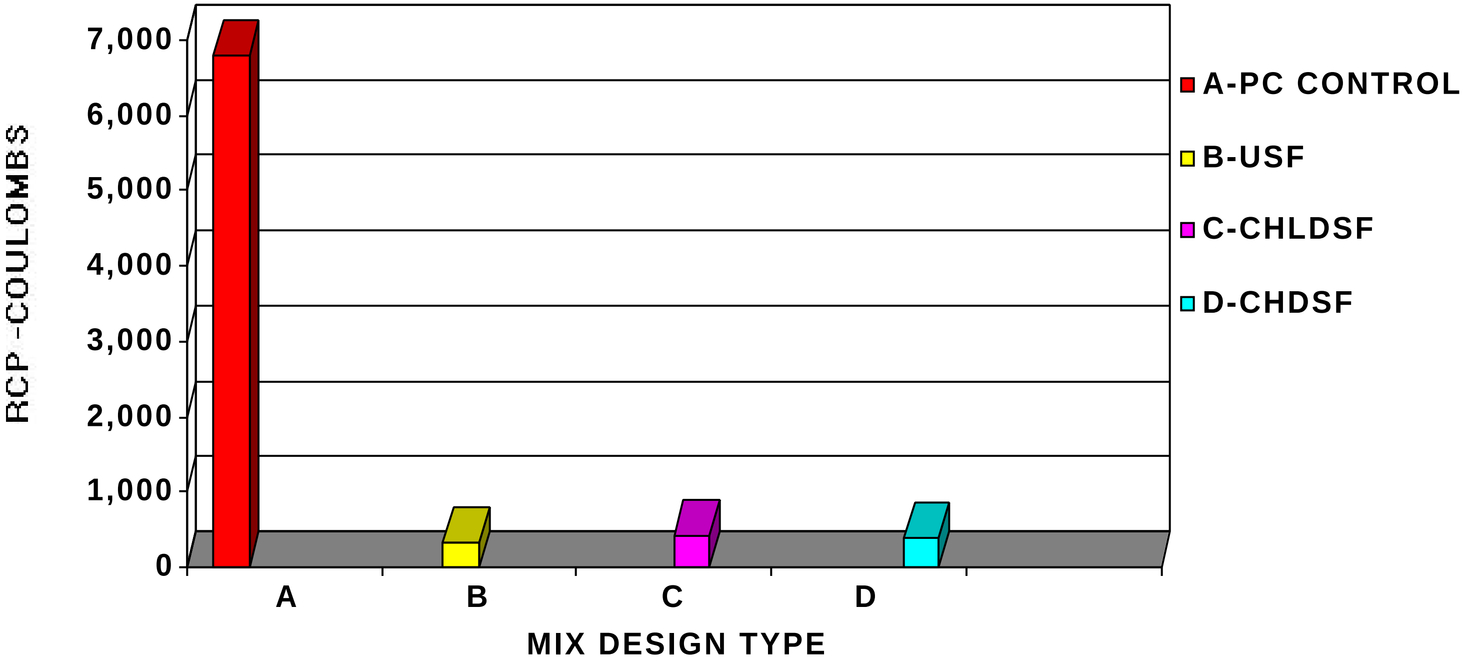

Figure 4 - Dry-Mix Shotcrete

Rapid Chloride Permeability

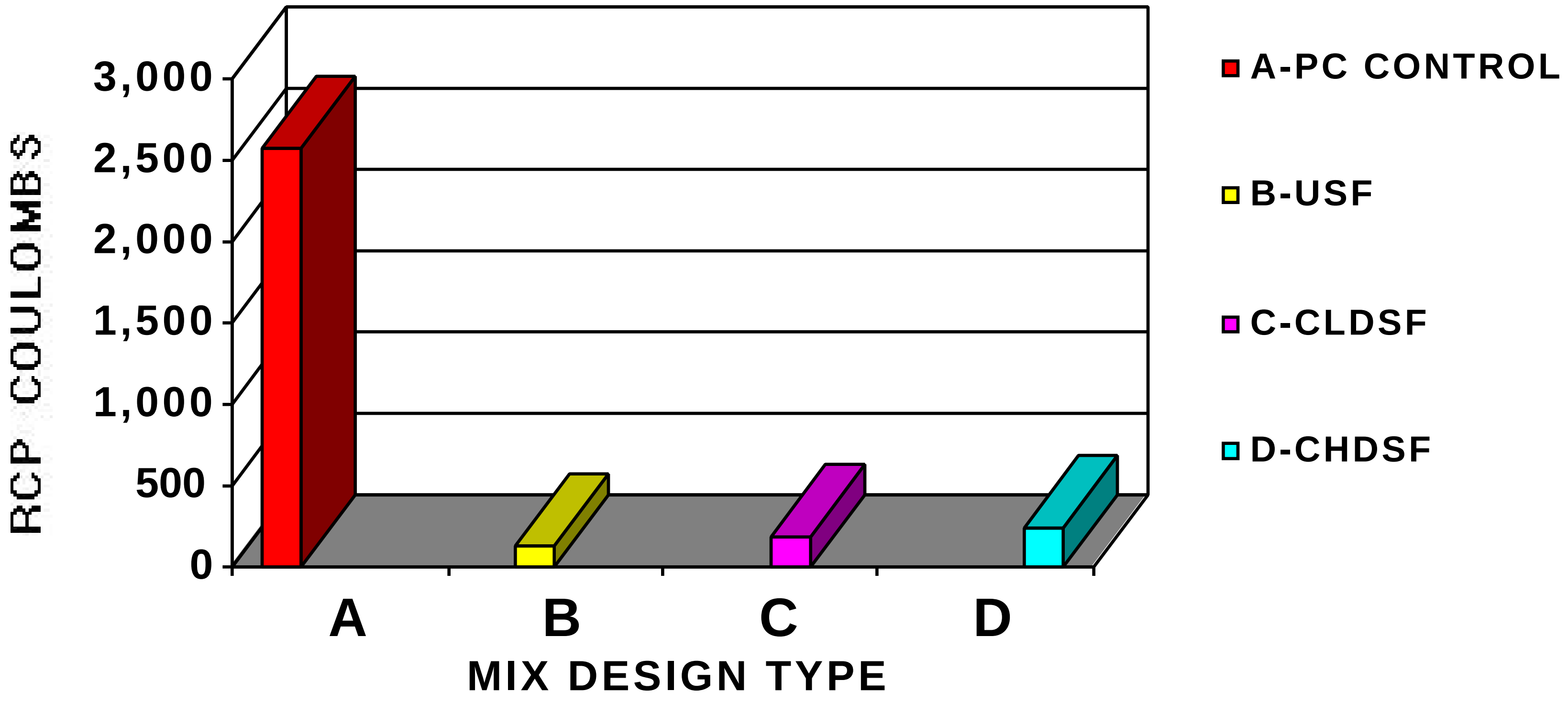

Figure 5 – Wet-Mix Shotcrete

Electrical Resistivity

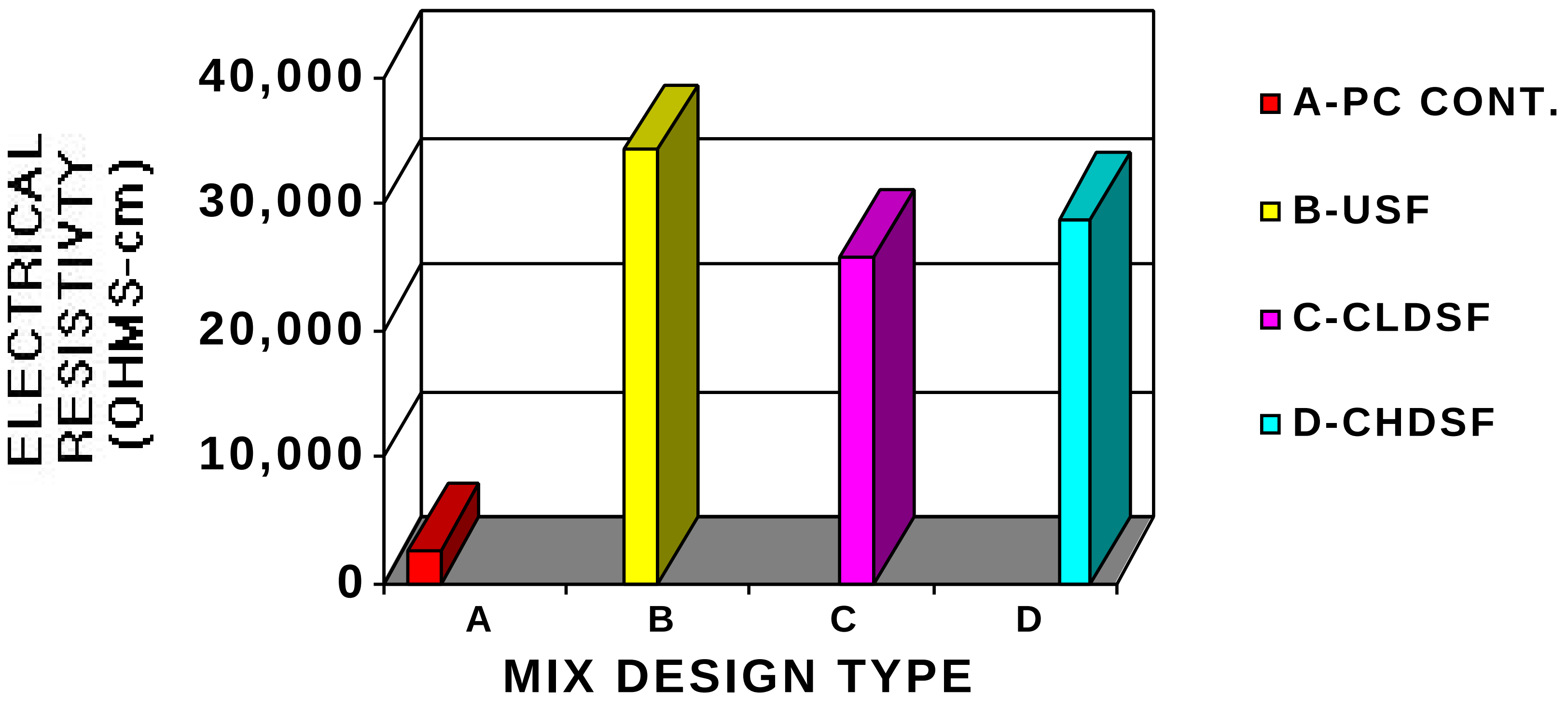

Figure 6 – Dry-Mix Shotcrete

Electrical Resistivity

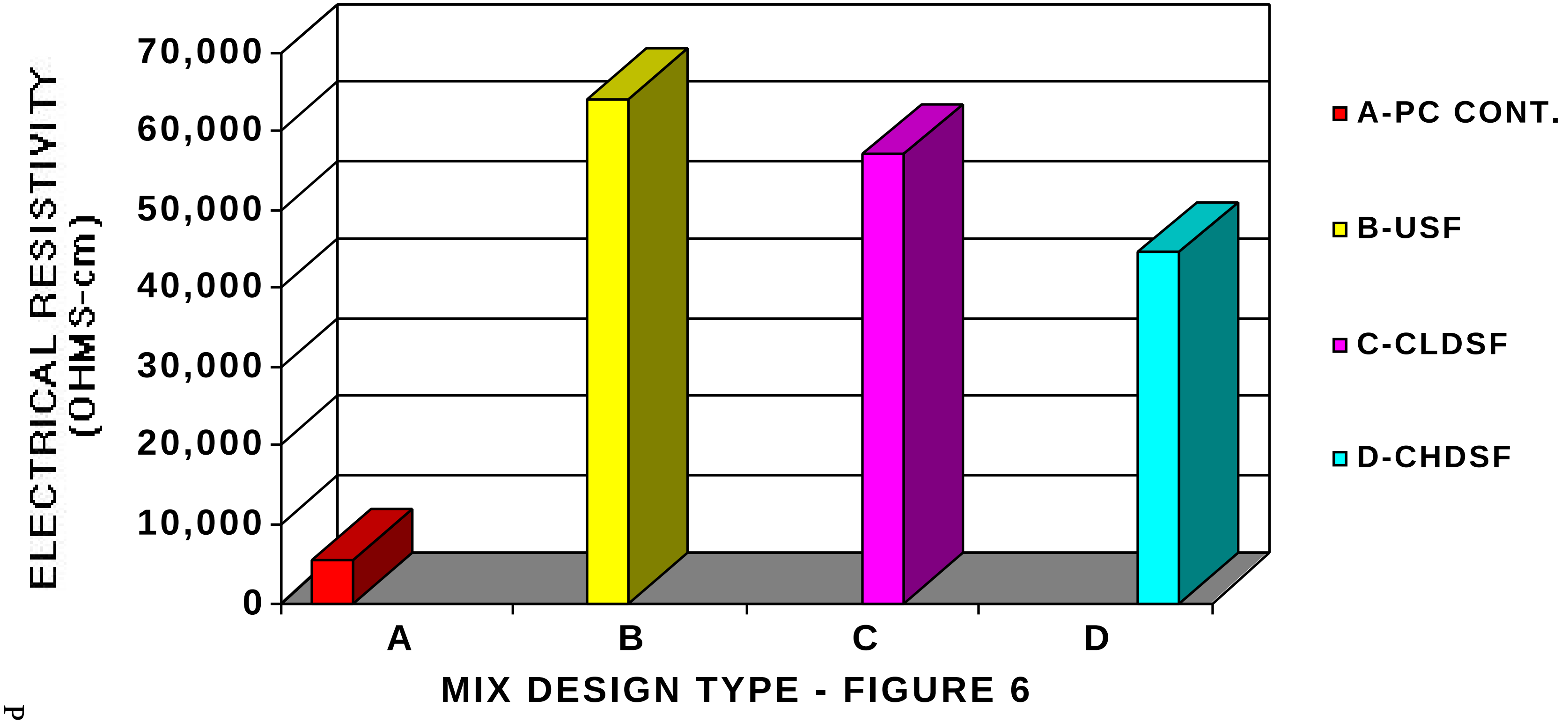

Figure 7 – Drying Shrinkage of Wet-Mix Shotcrete

Uncompacted vs. Compacted Silica Fume

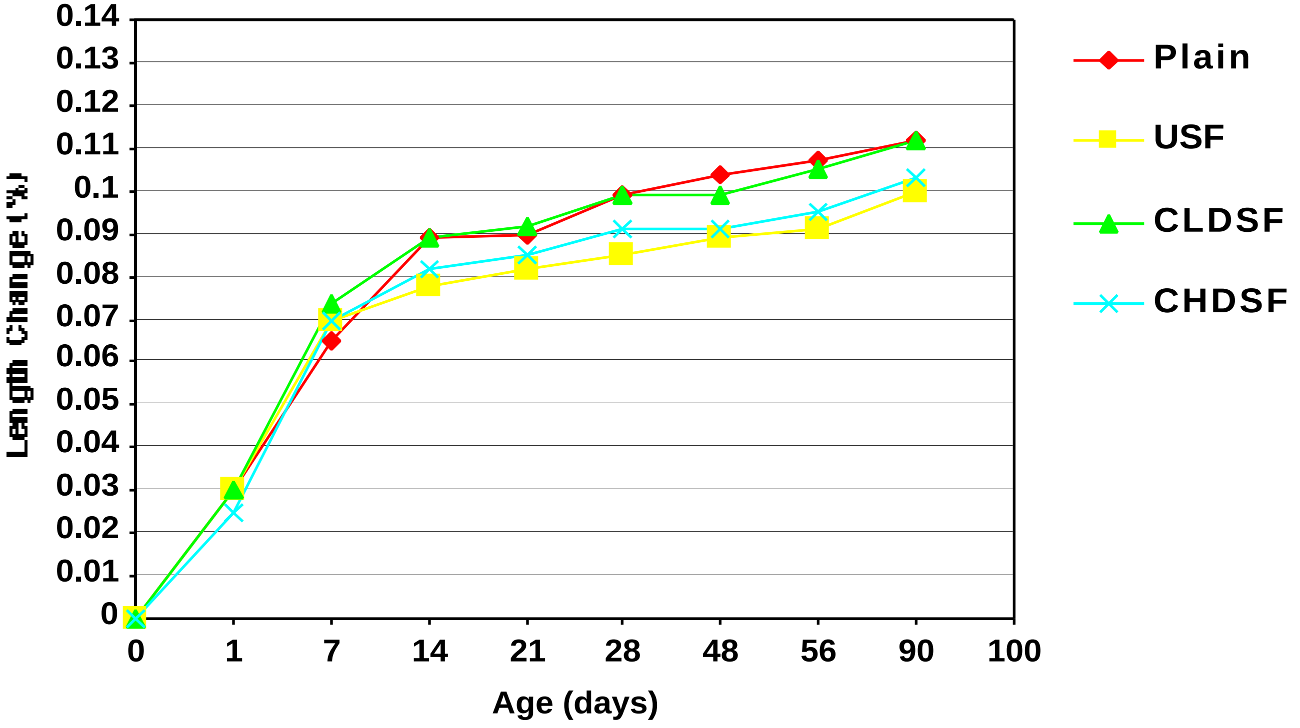

Figure 8 – Drying Shrinkage of Dry-Mix Shotcrete

Uncompacted vs. Compacted Silica Fume