Surface resistivity for assessing the chloride transport through ultra-high-performance concrete

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Abstract. In this study, surface resistivity of the non-proprietary ultra-high-performance concretes (UHPCs) using traditional aggregates were evaluated. Four plain UHPCs were batched using various cementitious materials at a constant water-to-cementitious materials ratio of 0.21 with an aggregate-to-cementitious materials ratio of 1.20. The 28-day surface-resistivity was measured for a duration of 60 minutes (10 minutes intervals). The influence of testing time on surface resistivity of the studied UHPCs was also examined. The results of this study highlighted that surface resistivity of UHPC could be used with confidence to assess its chloride penetration resistance. The outcome of the study also revealed that the binary blend UHPC containing silica fume, as a partial replacement of Portland cement, displayed the highest surface resistivity, lowest chloride ion penetration, and highest compressive strength amongst the studied UHPCs. Time of testing had a minor effect on surface-resistivity of the studied UHPCs.

1 Introduction

Chloride attack is one of the most serious threats to concrete's long-term durability. It is responsible for over 40% of concrete structural failures [1]. It corrodes steel in the presence of oxygen and water, dramatically reducing the structure's strength and stiffness. Chloride ions can arise from the concrete itself or from external sources. Some of the examples of chloride sources are: use of a chloride-rich chemical admixture, aggregate containing high-chloride, use of seawater during concrete mixing, concrete is exposed to seawater (e.g., offshore structures), or use of de-icing salts in concrete pavements [2]. There are several test methods to measure the chloride permeability of concrete. However, most of the methods to measure the chloride permeability are time-consuming, require expensive equipment, and are difficult for assessing the chloride permeability of existing structures [3]. As a point of reference, the salt ponding test suggested by AASHTO T259 takes 90 days to get the results and the accelerated test by ASTM C1202 takes 48 hours to complete. It would be advantageous if a user-friendly, short, and cost-effective non-destructive test can be developed to assess the chloride penetration into concrete structures.

Recently developed, the surface resistivity test (SRT) is used to determine the electrical resistivity of water-saturated concrete in kΩ-cm as a measure of its resistance to chloride ion penetration. The fundamental benefit of the SRT is that it takes less than 5 minutes to obtain readings, whereas the more widely used RCPT takes more than 2 days to complete, including sample preparation [4]. This is a significant time saving. The Louisiana Transportation Research Center performed a cost-benefit analysis, which showed that implementation of the device will save the Department approximately $101,000 in personnel costs in the first year [5]. It is estimated that contractors will save about $1.5 million annually in quality control costs (According to the Federal Highway Administration-FHWA website). The other advantages are the non-destructive nature of SRT, ease of personnel training and testing operation, simplicity and handiness of apparatus, and the overall cost-effectiveness as compared to both the RCPT or salt ponding test.

Ultra-High-Performance Concrete (UHPC) is a new type of concrete that has emerged in recent decades because of its outstanding strength and durability [6-8]. As applications of UHPCs are getting popular in chloride-rich environments, especially in bridge construction, it is necessary to examine and understand the performance of UHPCs using SRT. Karim et al. [9] showed that surface resistivity of UHPCs is inversely related to rapid chloride penetration. In another study, Smiths [10] developed a relationship between the rapid chloride permeability and instantaneous resistivity measurements, and the rate of diffusion of chlorides into concrete. The results showed a strong relationship between resistivity and the amount of charge passed using rapid chloride permeability test.

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This study examined the influence of binder type and content on mechanical strength, surface resistivity, and rapid chloride penetration of selected plain Ultra-High-Performance Concretes (UHPCs).

2 Experimental works

2.1. Materials

In this study, two types of fine aggregates (concrete sand and masonry sand) were used with sizes varying from 0.075 to 4.75 mm. The relative density of the graded aggregates was determined by using the modified Andreasen and Andersen method at various distribution moduli (0.20–0.25) [11]. A distribution modulus of 0.21 yielded the highest density [7]. The specific gravity of the combined fine aggregates was 2.80 and its absorption was 0.45 percent. Table 1 shows the gradation distribution of the fine aggregates used in this study. ASTM Type V Portland cement was used as a main binding material. To observe the effect of pozzolanic materials, Class F fly ash and silica fume replaced the Type V cement at different substitution percentages. The gradation curve of the cementitious materials is presented in Fig. 1.

Table 1. Aggregate gradation distribution.

Sieve no.	Sieve opening (mm)	Retained (%)
#4	4.75	0.00
#8	2.38	23.5
#16	1.19	20.1
#30	0.595	17.0
#50	0.297	15.1
#100	0.149	13.0
#200	0.074	11.3

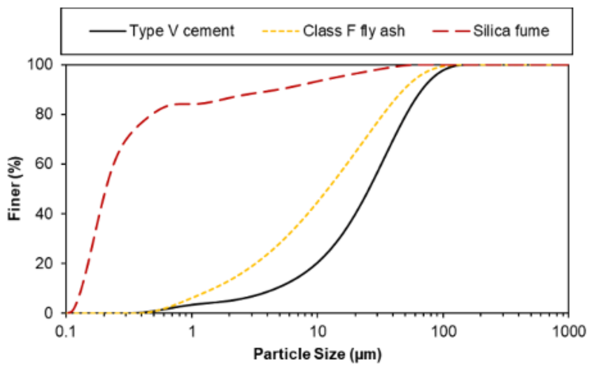

Fig. 1. Gradation of cementitious materials.

2.2 Mixture design

A total of four plain UHPCs were used to determine their strength, surface resistivity, and chloride permeability. The unit contents of the studied UHPCs are given in Table 2. The water-to-cementitious materials ratio and fine aggregate-to-cementitious materials were kept constant at 0.21 and 1.20, respectively, for all studied UHPCs. In the binary UHPCs, Type V cement was partially replaced with 10% and 20% Class F fly ash (F10 and F20), and 5% silica fume (SF5). The UHPC containing 100% Type V cement was used as the control (C100).

Table 2. Mixture Proportions of UHPC**s**.

ID	C	F	SF	Agg.	HRWRA	W
	kg/m^3					
C100	1101	-	-	1174	12.1	226
SF5	1046	-	39	1174	12	215
F10	991	82	-	1174	10.8	215
F20	881	163	-	1174	11	215

Note : C =Cement ; F=Class F fly ash ;SF=Silica fume; Agg.=Aggregate ; HRWRA=High-range-water-reducing admixture ; W=Water.

2.3. Casting, curing, and testing

The mixing process of the studied UHPCs is presented in Fig. 2. The flow properties of the studied UHPCs were measured according to ASTM C230 [12] before pouring into the molds. Compressive strength of the studied UHPCs was evaluated according to ASTM C39 by crushing 50 mm diameter and 100 mm height cylinders [13]. This test was conducted on three samples for each UHPC at the age of 28 days. The Surface Resistivity Test (SRT) was used to determine the electrical resistivity of water-saturated UHPCs. Test specimens (100 mm diameter and 200 mm height cylindrical sample) were taken out of the curing room and excess surface water was wiped out using paper towels. Four lines were drawn with a marker on the samples that were spaced 90° from one another before numbering each line. The resistivity meter, as shown in Fig. 3, was calibrated with the strip provided by the manufacturer to ensure proper functioning. The measuring time intervals were 10, 20, 30, 40, 50, and 60 minutes after removal from curing room for a total of 24 readings for each sample.

Fig. 2. UHPCs' mixing sequence

Fig. 3. Surface resistivity Test

3 Results and Discussion

3.1. Fresh and bulk properties

Fig. 4 shows the flow diameter of the studied UHPCs. UHPCs had a flow value in the range of 248 mm to 270 mm. The unit weights of the studied UHPCs are also shown in Fig. 4, with the highest unit weight belonging to UHPC containing 100% Type V cement. The lower specific gravity of the pozzolanic materials resulted in a slightly lower unit weight of the UHPCs made using silica fume and fly ash.

The effect of cementitious materials combinations on compressive strength of the studied plain UHPCs are shown in Table 3. When silica fume content replaced 5% by weight of Type V cement, the compressive strength improved by nearly 6%. The lowest compressive strength of the binary UHPCs was obtained when fly ash replaced 20% by weight of Type V cement. The very fine silica fume accelerated the early age pozzolanic reactivity and facilitated the higher compressive strength as compared to the other studied UHPCs without silica fume.

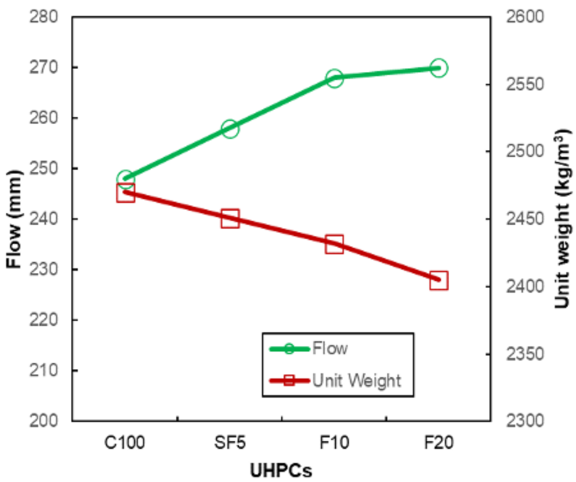

Fig. 4. Flow (ASTM C230) and unit weight of UHPCs.

Table 3. Average compressive strength results of the studied UHPCs.

ID	28 Days (MPa)	Standard deviation	Percent Difference (%)
C100	125.7	2.3	-
SF5	133.3	3.5	6.05
F10	124.0	3.5	-1.35
F20	122.9	2.5	-2.23

3.2 Surface resistivity

3.2.1 Effect of cementitious materials compositions

The average surface resistivity (SR) results for the studied UHPCs are shown in Table 4. A strong microstructure resulting from the high cement content, low water-to-cementitious materials ratio, and high-reactivity of the silica fume produced an excellent surface resistivity of the studied UHPCs. The UHPCs containing silica fume exhibited the highest SR readings representing better resistance against chloride ion penetration. A five percent replacement of Portland cement by silica fume increased the SR by 62% as compared to the control UHPC (C100). UHPCs containing 10% and 20% fly ash by weight of total cementations materials displayed slightly reduced SR as compared to that of the C100.

Table 4. Average SRT Results of Plain UHPCs.

ID	28 Days (kΩ-cm)	Standard deviation	Percent Difference (%)
C100	49.6	0.8	-
SF5	80.0	3.2	62.0
F10	46.6	1.4	-6.4
F20	45.8	1.6	-8.3

3.2.2 Effect of testing time

Table 5 represents the effect of testing time on SR over a one hour test period. As can be seen, the SR decreased consistently during the 60-minute testing duration. A standard deviation of 0.8 to 3.2 was observed for UHPCs tested at different times. The highest standard deviation was observed for the binary UHPC containing 5% silica fume and the lowest was for the control UHPC. Figure 5 shows the normalized surface resistivity of the UHPCs tested at 10 minutes and 60 minutes. As can be seen in Fig. 5, up to 10% reduction was observed in surface resistivity value when the sample was tested after 60 minutes as compared to 10 minutes. The change in moisture condition of the sample during testing adversely affects the surface resistivity of the studied UHPCs [14-15].

Table 5. SR Over One Hour Test Period for Plain UHPCs (kΩ-cm).

ID	Time (minute)					
	10	20	30	40	50	60
C100	51	50	49	49	50	49
SF5	86	80	80	78	79	77
F10	48	48	47	46	45	45
F20	47	48	46	45	44	44

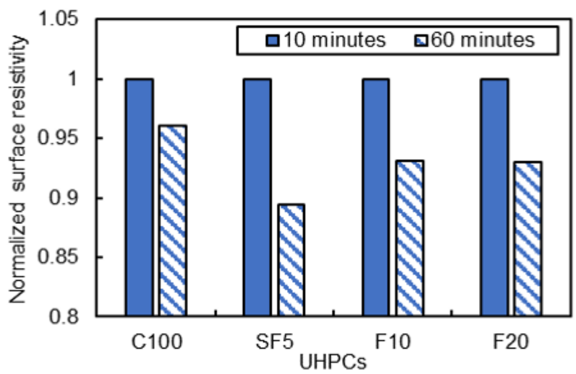

Fig. 5. Effect of testing time on surface resistivity.

3.3 Rapid chloride permeability

As shown in Table 6, increases in the percentage of cement replacement by fly ash resulted in the reduction of the RCPT measurements. When compared with the result of the control UHPC (C100), the percentage increases in the coulombs for the UHPCs containing 10% and 20% of fly ash were approximately 21% and 29%, respectively. Similar to the surface resistivity, amongst all studied UHPCs, the mixture containing silica fume demonstrated the best resistance against chloride ion penetration. The UHPC made with 5% silica fume content showed a 32% reduction in charge passed when compared with the control mixture. As shown in Fig. 6, a correlation was developed between the RCPT results and 60-min surface resistivity of the studied UHPCs with a R^2 of 0.91.

Table 6. Average RCPT Results of Plain UHPCs.

ID	28 Days (kΩ-cm)	Standard deviation	Percent Difference (%)
C100	665	74	-
SF5	453	29	31.8
F10	802	63	-20.7
F20	858	49	-29.1

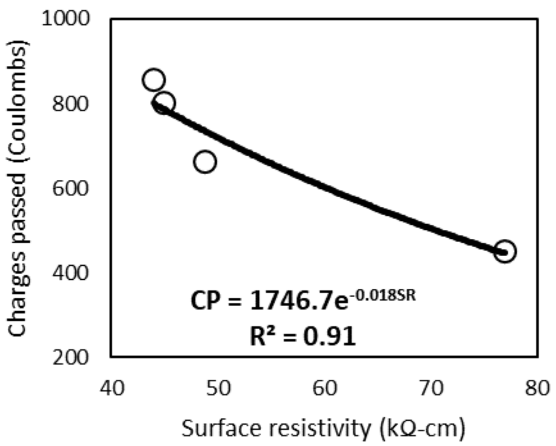

Fig. 6. Correlation between RCPT and SR.

4 Conclusions

Based on the results of this study, the following conclusions can be drawn:

- Cementitious material types and combinations had more influence on surface resistivity and chloride ion penetration resistance than it had on the mechanical strength of the studied UHPCs.
- When silica fume replaced a portion of cement, the SRT readings increased, whereas the inclusion of fly ash had the opposite impact on the surface resistivity of the studied UHPCs. The lowest SRT reading was obtained when fly ash substituted 20% by weight of Portland cement.
- On average, 7% lower surface resistivity was observed for the UHPCs tested at 60 minutes as compared to the UHPCs tested at 10 minutes.
- The 28-day cured binary UHPC containing only 5% silica fume produced averagely 32% fewer passing charges than the control UHPC.

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