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High Durability Concrete Using High-Carbon Fly Ash and Pulp Mill Residuals

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ABSTRACT

This research project evaluated the strength and durability of two high-carbon fly ash materials in non-air entrained concrete with fibers from residual solids from pulp and paper mills to produce high-durability concrete. The improvement in concrete durability was achieved without depending on air-entraining admixtures, but rather with another by-product, a paper industry fibrous residual. A total of eight concrete mixtures were produced, one reference mixture, four concrete mixtures made with a spent activated carbon sorbent, and three mixtures made with high-carbon fly ash. Concrete mixtures were made using these high carbon materials included the fibrous residual with varying dosage rates. Testing included fresh concrete properties, compressive strength, resistance to freezing and thawing, and resistance to salt scaling. The results of this project show that concrete containing high-carbon fly ashes can meet durability specifications in a freezing and thawing environment without the use of regular or specialty chemical air entraining admixtures.

BACKGROUND AND OBJECTIVES

This research project was undertaken to evaluate the use of high-carbon fly ash in non-air entrained concrete with fibers from residual solids from pulp and paper mills to produce high-durability concrete without depending on any regular or specialty chemical air-entraining admixtures. Typically, concrete that is resistant to freezing and thawing is required to be air entrained, which is achieved by the addition of an air-entraining agent (AEA). Quantity and quality of the air content has become a standard measure of the durability of concrete in a freezing and thawing. For example, the ACI 318 Building Code [ACI 2008] specifies the amount of entrained air that is to be included in a concrete mixture for developing resistance to freezing and thawing environment. The air entrained in the concrete must also meet specified criteria for bubble size and spacing within the mortar fraction of the concrete to provide the necessary durability. The amount of the air-entraining agent for a particular concrete mixture is affected by many parameters. They include variations in the quality and quantity of cement and fly ash, type and amount of chemical admixtures including AEA, mixing time, ambient air and concrete temperature, aggregate fineness, placing and compaction, and other similar factors [Mehta 1986] [Plant, Pigeon, and Saucier 1989]. The fineness of cement or fly ash is probably the most important factor since the fineness, and especially the carbon content, affects the air content of the fresh concrete [USDOT-FHWA 2003]. Minor variations in the carbon content of cement or fly ash would also have an impact on the air entrainment. Finding an admixture that could address all of these types of variables and still provide a consistently durable concrete is desirable. The new technology described in this study is to incorporate pulp and paper mill residual solids to provide the necessary freezing and thawing resistance to the concrete; and therefore, the necessary durability [Naik, Kraus, and Chun 2003; Naik, Chun, and Kraus 2005; Chun and Naik 2005; Chun and Naik 2004; Naik, Chun, and Kraus 2002] to the concrete even when it contains high-carbon fly ash. The addition of a recyclable material into the concrete in place of a manufactured chemical admixture (AEA) produces a "green" concrete that is desirable for a sustainable society as well as sustainable, durable concrete construction.

During a previous research project recently completed at the UWM Center for By-Products Utilization (UWM-CBU) for the U.S. Department of Energy (U.S.-DOE) [Naik, Kraus, and Chun 2003], it was discovered that when non-air entrained concrete containing residuals from pulp and paper mills was subjected to a freezing and thawing environment and to salt-scaling testing, it performed similar to a concrete that was air entrained with a chemical AEA. Concrete containing between 0.5% and 1.0% of residuals (by weight of total concrete) achieved noticeable and significant increase in the durability properties of the concrete mixtures. The test results of this project had shown that up to twice the resistance to freezing and thawing, and three times the resistance to salt-scaling could be achieved by incorporating residual solids in concrete without the use of any chemical AEA [Naik, Chun, and Kraus 2005; Chun and Naik 2005].

The work presented in this paper builds upon the results obtained from the U.S.-DOE project. The focus of the U.S.-DOE project was not to evaluate and develop the residuals in freezing and thawing resistant concrete, but rather to evaluate strength and fracture toughness properties of such concretes with residuals [Naik, Kraus, and Chun 2003; Naik, Chun, and Kraus 2005; Chun and Naik 2005]. The project described in this paper focused on this recent discovery to test the use of residual solids with high-carbon fly ash in high-durability concrete (HDC). This work consisted of a series of controlled laboratory experiments. The plan for further developing the technology was to determine the amount of residuals in the concrete mixture to achieve the desired durability in the concrete containing high-carbon fly ash from We Energies. The residual fibers were introduced into the concrete by re-pulping the residuals with water [Chun and Naik 2004]. The re-pulped fibers were then added to the concrete in a manner similar to the addition of the chemical admixture AEA. Laboratory concrete manufacturing included testing of durability properties to verify the performance of the pulp and paper mill residuals in HDC containing high-carbon fly ash. This project could have widespread applications throughout the U.S., and other countries to use high-carbon fly ash in the production of durable concrete.

The mechanical and durability properties of concrete using two types of high-carbon materials, high-carbon fly ash and a spent sorbent used in mercury collection were determined in this project. Specific objectives for this research were: (1) Test the effect of using residual solids in high-durability concrete when high-carbon fly ash is also used in the concrete mixtures. (2) Determine the effect of changing the type of high-carbon fly ash in concrete, and the amount of residuals needed in the concrete mixture to produce high-durability concrete. (3) Reduce landfill costs by recycling high-carbon fly ash and pulp and paper mill residuals. (4) Establish mixture proportions for high-durability concrete when high-carbon ash is used. (5) Collect test data on physical, mechanical, and chemical characteristics of materials used for high-durability concrete, as well as establish strength and durability properties of hardened concrete mixtures.

MATERIALS

Portland cement

ASTM Type I portland cement was used in this research. The properties of the cement met the chemical and physical property requirements of the ASTM Standard Specification for Portland Cement [ASTM C 150].

Aggregates

One source of clean concrete sand was used in this project as the fine aggregate for the concrete mixtures. Natural sand was used from a source in southeastern Wisconsin. The physical properties of the sand met the requirements of the ASTM Standard Specification for Concrete Aggregates [ASTM C 33]. Selected physical properties of the sand include: specific gravity (SSD basis), 2.66; fineness modulus, 2.7; and absorption, 1.4%. For the coarse aggregates, a crushed quartzite with a maximum nominal size of 19 mm was obtained from a source in south-central Wisconsin. The physical properties of the coarse aggregates met the requirements of the ASTM C 33. Selected physical properties of the coarse aggregates include: specific gravity of 2.66; and absorption of 0.4%.

High-carbon fly ash and spent activated carbon sorbent

Two sources of high-carbon materials were used for this project, both from We Energies. A spent activated carbon sorbent from We Energies' Presque Isle Power Plant in Marquette, Michigan, and a high-carbon fly ash from We Energies' Valley Power Plant in Milwaukee, Wisconsin, were used in concrete mixtures. The spent activated carbon was used in a mercury removal system at the plant. The spent sorbent was originally manufactured from lignite coal, and contained sulfur and coal fly ash. The high-carbon fly ash obtained from the Valley Power Plant is generated from burning bituminous coal. The chemical composition and physical properties of the high-carbon materials are presented in Table 1 and Table 2, respectively, together with the requirements of ASTM C 618 for coal fly ash. The chemical composition of the high-carbon ashes did not meet ASTM C 618 requirements for Class F fly ash (insufficient amount of SiO_2 + Al_2O_3 + Fe_2O_3 and very high carbon contents. The high-carbon sorbent also contained some Class C fly ash that had passes through the electrostatic precipitator and was collected with the spent activated carbon sorbent. The carbon content (as measured by the loss on ignition), of the Valley high-carbon ash was higher than the Presque Isle sorbent, 26% versus 17%, respectively. This was the opposite of what was expected, particularly since the Presque Isle material was originally described as spent activated carbon sorbent. This indicates that the activated carbon content of the Presque Isle sample was not a major component of the used sorbent in the sample used for this research project. Physical properties of the Valley Power Plant high-carbon ash also did not meet ASTM C 618 requirements. The high-carbon ash from the Valley plant did not meet fineness requirements, or the strength activity index. An interesting result of the physical tests is that the Presque Isle spent activated carbon sorbent met ASTM C 618 requirements for reactivity with cement. The compressive strength of mortar mixtures that had 20 percent of the cement replaced with the sorbent exhibited more than 120 percent of the compressive strength of similar mixtures using only portland cement.

Table 1. Chemical Composition of High-Carbon Materials

Item	Presque Isle Spent AC Sorbent (% by mass)	Valley high-carbon fly ash (% by mass)	Requirement of ASTM C 618	
			Class F fly ash	Class C fly ash
Silicon dioxide, SiO_2	21.9	39.7	—	—
Aluminum oxide, Al_2O_3	16.5	19.0	—	—
Ferric oxide, Fe_2O_3	5.1	5.6	—	—
$SiO_2 + Al_2O_3 + Fe_2O_3$	42.5	64.3	70 min.	50 min.
Calcium oxide, CaO	17.4	4.1	—	—
Magnesium oxide, MgO	4.5	1.3	—	—
Sodium oxide, Na_2O	4.7	1.2	—	—
Potassium oxide, K_2O	0.7	1.3	—	—
Titanium oxide, TiO_2	1.0	0.7	—	
Sulfur trioxide, SO_3	8.6	0.5	5.0 max.	5.0 max.
Loss on ignition at 750ºC	17.4	26.2	6.0 max.*	6.0 max.

* Under certain circumstances, up to 12.0% max. LOI may be allowed.

Table 2. Physical Properties of High-Carbon Materials

Item	Presque Isle Spent AC Sorbent	Valley high-carbon fly ash	Standard requirement of ASTM C 618 for Class F fly ash and Class C fly ash
Fineness, amount retained on 45-µm (No. 325) sieve (mass %)	3.5	46.9	34 maximum
Strength activity (% of Control) 7 days 28 days	 123.4 130.5	 59.8 64.0	 75 minimum, at either 7 or 28 days
Water requirement (% of Control)	103	112	105 maximum
Autoclave expansion (%)	-0.08	-0.02	Between -0.80 to +0.80
Density (g/cm^3)	2.49	2.12	—
As-received moisture content (%)	1.4	0.5	3.0 maximum

Fibrous residual

The source of fibrous residual used in this project was from a fiber reclaim process and was obtained from Biron, Wisconsin. The as-received moisture content of the residual solid was 253% (% of oven-dry mass). Since cellulose fibers can decompose readily in a warm and humid environment, the residual solid was stored at 4°C (40°F) until its use in concrete mixtures. Before adding the residual solids to the concrete, the fibers were first de-flocculated by mixing in water. This not only has the benefit of uniformly distributing the fibers into the concrete, but allows for the fibers to be added as a liquid. Thus, for concrete production, such fibers can be added to concrete mixtures using standard equipment that a typical concrete producer uses for addition of admixtures.

Water-reducing and high-range water-reducing admixtures

A high-range water-reducing admixture (HRWRA) was used in several of the concrete mixtures containing the Presque Isle spent activated carbon sorbent. The high-range water-reducing admixture was polycarboxlate-based, and met the requirements of ASTM Standard Specification for Chemical Admixtures for Concrete [ASTM C 494] as a Type A and Type F admixture, and ASTM C 1017 as a Type I admixture. The manufacturers recommended dosage rate of the high-range water-reducing admixture was 195-980 mL/100 kg of cement (3-15 fl oz/100 lb of cement). A water-reducing and set-retarding admixture was also used in three of the concrete mixtures made with Valley Power Plant high-carbon fly ash. The admixture was a modified sodium gluconate, and met the requirements of ASTM C 494 for Type B (retarding admixtures) and Type D (water-reducing and retarding admixtures). The manufacturers recommended dosage rate of the water-reducing admixture was 125-375 mL/100 kg of cement (2-6 fl oz/100 lb of cement).

MIXTURE PROPORTIONS

Presque Isle spent activated carbon sorbent – concrete mixtures

The concrete mixtures used to evaluate the Presque Isle spent activated carbon sorbent consisted of five mixtures, a reference mixture, Ref-2, that did not contain fly ash or residual solids, and four mixtures, P-11, P-12, P-13, and P-14, that contained increasing amounts of fibrous residuals, from 2 to 21 kg per cubic meter of concrete. This represented 0.07% to 0.88% of residuals by mass % of concrete. Details of the mixtures are given in Table 3.

Table 3. Mixture Proportions and Fresh Properties of Concrete Made with Presque Isle Spent Activated Carbon Sorbent

Mixture Designation	Ref-2	P-11	P-12	P-13	P-14
Fibrous Residual, BR (mass % of concrete)	0	0.07	0.29	0.59	0.88
Cement, C (kg/m^3)	349	261	260	258	255
Presque Isle Sorbent, P (kg/m^3)	0	86	85	85	84
Water, W (kg/m^3)	152	148	151	147	156
Sand, SSD (kg/m^3)	879	882	875	866	852
Crushed Stone, 19 mm max., SSD (kg/m^3)	1070	1060	1060	1050	1040
Fibrous Residual, BR (kg/m^3)	0	2	7	14	21
HRWRA (L/m^3)	0.94	3.63	4.96	3.97	6.35
W/Cm	0.43	0.43	0.44	0.43	0.46
Slump (mm)	70	65	160	30	50
Air Content (%)	1.2	1.3	0.9	1.3	1.0
Air Temperature (°C)	26	26	26	26	26
Concrete Temperature (°C)	26	--	26	26	--
Density (kg/m^3)	2450	2440	2440	2420	2410

Mixture P-11 contained the lowest amount of fibrous residuals, 2 kg/m^3; and, Mixture P-14 contained the highest amount of residuals, 21 kg/m^3. All concrete mixtures contained HRWRA. The dosage of HRWRA increased as the quantity of residuals was increased in the mixture. The W/Cm ratios of this series of mixtures containing the sorbent (0.43 – 0.46) were more appropriate for durable concretes than that obtained without HRWRA (0.76 - 0.77). Slump for all of the mixtures, with the exception of Mixture P-12, was between 50 and 75 mm. Mixture P-12 had a slump of 160 mm. This is attributed to the high-dosage of HRWRA used in Mixture P-12. The dosage of HRWRA for Mixture P-12 was 4.96 L/m^3, but should have been lower, between 3.6 and 4.0 L/m^3.

Valley Power Plant high-carbon fly ash – concrete mixtures

Non-air-entrained concrete mixtures used to evaluate the Valley Power Plant high-carbon fly ash consisted of three mixtures containing approximately 50 kg/m^3 of Valley high-carbon fly ash and a reference mixture, Ref-2, which did not contain fly ash or residual solids. The mixtures containing the high-carbon ash, V-8, V-9, and V-10, contained increasing amounts of fibrous residuals, from 7 to 21 kg/m^3, Table 4. This represents 0.30% to 0.88% of residuals by mass % of concrete. Mixture V-8 contained the lowest amount of fibrous residuals, 7 kg/m^3 and V-10 contained the highest amount of residuals, 21 kg/m^3. All concrete mixtures contained HRWRA. The dosage of HRWRA was approximately the same, regardless of the residual content, but much higher than the reference mixture, Ref.-2. Density of the fresh concrete decreased as the amount of residuals increased in the mixture.

Table 4. Mixture Proportions and Fresh Properties of Concrete Made with Valley Power Plant High-Carbon Fly Ash

Mixture Designation	Ref-2	V-8	V-9	V-10
Fibrous Residual, BR (mass % of concrete)	0	0.30	0.59	0.88
Cement, C (kg/m^3)	349	298	293	289
Valley High-Carbon Fly Ash, V (kg/m^3)	0	48	48	47
Water, W (kg/m^3)	152	155	157	159
Sand, SSD (kg/m^3)	879	871	858	846
Crushed Stone, 19 mm max., SSD (kg/m^3)	1070	1060	1040	1030
Fibrous Residual, BR (kg/m^3)	0	7	14	21
HRWRA (L/m^3)	0.94	5.66	5.61	5.77
W/Cm	0.43	0.45	0.46	0.47
Slump (mm)	120	25	10	120
Air Content (%)	1.0	1.1	1.5	1.0
Air Temperature (°C)	26	26	26	26
Concrete Temperature (°C)	--	26	25	--
Density (kg/m^3)	2440	2420	2390	2440

TEST RESULTS AND DISCUSSION

Testing of concrete mixtures containing Presque Isle spent activated carbon sorbent

Compressive strength of the concrete mixtures containing Presque Isle sorbent is shown in Table 5. The strength was evaluated at the ages of 7, 28, and 91 days. All mixtures containing the sorbent achieved a higher compressive strength than the reference mixture, Ref-2, with the exception of Mixture P-14 at the age of seven days. As the amount of fibers was increased in the concrete mixtures, the compressive strength decreased, but typically was still higher than the reference mixture, Ref-2. Concrete produced with the highest amount of residuals, Mixture P-14, developed a compressive strength that was also higher than the reference mixture at both the 28 and 91-day ages.

Table 5. Compressive Strength of Concrete Made with Presque Isle Spent Activated Carbon Sorbent

Age (days)	**Compressive Strength (MPa)**				
	Mixture (Residual Content, kg/m^3)				
	Ref-2 (0)	P-11 (2)	P-12 (7)	P-13 (14)	P-14 (21)
7	44.4	50.7	49.8	43.9	39.3
28	47.5	58.6	52.1	52.0	48.7
91	49.8	64.4	60.0	58.1	52.4

The test mixtures containing the Presque Isle spent activated carbon sorbent were evaluated for resistance to freezing and thawing cycling in accordance with ASTM C 666, Procedure A. This test is based on the measurement of the relative dynamic modulus of elasticity after every 30 cycles, up to a maximum of 300 cycles. Results of the test are shown in Table 6. The reference non-air-entrained concrete mixture, Ref-2, rapidly deteriorated as freezing and thawing cycling progressed and could not be tested beyond 90 cycles. However, adding the fibrous residuals to the non-air-entrained concrete improved the resistance of the concrete to freezing and thawing significantly. The resistance to freezing and thawing cycling increased as the amount of fibrous residuals was increased. The mixture with the highest resistance to freezing and thawing, Mixture P-14, developed compressive strengths that were comparable to the reference mixture, but yet it had the highest resistance to freezing and thawing. This is a very significant result since it shows that the durability of the concrete containing the Presque Isle spent activated carbon sorbent can be increased significantly by using fibrous residuals when compared to a similar concrete mixture without residuals; and also, the desired strength can be achieved.

Table 6. Freezing and Thawing Resistance of Concrete Made with Presque Isle Spent Activated Carbon Sorbent

Mixture (Residual Content, kg/m^3)	**Relative Dynamic Modulus of Elasticity, %**										
	Number of Freezing and Thawing Cycles										
	0	31	59	90	120	150	180	210	240	270	300
Ref-2 (0)	100	74.8	60.2	52.0	--	--	--	--	--	--	--
P-11 (2)	100	98.6	98.0	94.0	87.4	68.6	58.9	40.1	--	--	--
P-12 (7)	100	96.9	95.9	92.2	83.9	72.9	60.2	58.9	--	--	--
P-13 (14)	100	98.7	98.6	97.7	96.0	94.7	92.0	83.9	80.0	70.1	57.4
P-14 (21)	100	96.2	96.3	95.3	94.6	92.5	91.0	84.5	83.7	75.3	69.2

Concrete mixtures containing the Presque Isle spent activated carbon sorbent and residuals were also tested for the resistance to surface scaling when subjected to deicing chemicals. The test was performed in accordance with ASTM C 672. This test consists of a visual rating from 0, which represents “no scaling,” to 5, which is classified as “severe scaling” where coarse aggregates are visible over the entire surface. The amount of scaled material was also weighed to further quantify the surface condition. Results of the test for resistance to salt-scaling are given in Table 7. Through 50 cycles of freezing and thawing, the two mixtures that achieved the highest resistance to salt-scaling, were the mixtures with the lowest amounts of fibrous residuals, Mixture P-11 and Mixture P-12. Although Table 7 shows the results through 50 cycles, which is the limit specified by ASTM C 672, the test was continued, and after 90 cycles, Mixture P-12 had the best performance, with a surface rating of "1." Therefore, using 7 kg per cubic meter (0.3 mass % of concrete) of fibrous residuals improved resistance to salt-scaling over the other higher or lower quantities of residuals tested. This observation needs to be further tested to find the optimum and effective addition level of fibrous residuals.

Table 7. Salt-Scaling Resistance of Concrete Made with Presque Isle Spent Activated Carbon Sorbent

Cycle	Visual Rating (VR) and Cumulative Spall (CS), kg/m^2									
	Mixture (Residual Content, kg/m^3)									
	Ref-2 (0)		P-11 (2)		P-12 (7)		P-13 (14)		P-14 (21)	
	VR	CS	VR	CS	VR	CS	VR	CS	VR	CS
5	0	0	0	0	0	0	1.5	1.44	2	3.39
10	0	0	0	0	0	0	n.a.	2.48	n.a.	7.61
15	1	0.01	1	0.00	1	0.01	2.5	2.86	3	9.21
20	1.5	0.02	1	0.00	1	0.01	2.5	3.04	3.5	9.93
25	1.5	0.02	1	0.01	1	0.01	2.5	3.15	3.5	10.44
30	1.5	0.05	1	0.00	1	0.01	2.5	3.42	3.5	11.47
35	3	0.06	1	0.01	1	0.01	2.5	3.53	4	11.65
40	3	0.27	1	0.01	1	0.01	2.5	3.73	4	12.44
45	3	0.45	1	0.01	1	0.01	2.5	4.12	4	13.29
50	4	0.58	1	0.01	1	0.01	2.5	4.59	5	14.42

Testing of concrete made with Valley Power Plant high-carbon fly ash

Compressive strength of the concrete mixtures containing the high-carbon fly ash from the Valley plant are shown in Table 8. Compressive strength of the concrete was evaluated at the ages of 7, 28, and 91 days. All mixtures containing the Valley fly ash had a compressive strength that was lower than the reference mixture, Ref-2, without fibrous residuals and without high-carbon fly ash. As the amount of fibers was increased in the concrete mixtures, the compressive strength decreased. However, at the age of 91 days, the strength ranged from 29.8 to 34.7 MPa, which was 60 to 70% of the strength of the reference mixture, Ref-2. New mixture proportioning is necessary to achieve a compressive strength higher than 30 MPa. The test mixtures containing the high-carbon fly ash from the Valley plant were also evaluated for resistance to freezing and thawing cycling in accordance with ASTM C 666, Procedure A. Results of the test are shown in Table 9.

Table 8. Compressive Strength of Concrete Made with Valley Power Plant High-Carbon Fly Ash

Age (days)	Compressive Strength (MPa)			
	Mixture (Residual Content, kg/m^3)			
	Ref-2 (0)	V-8 (7)	V-9 (14)	V-10 (21)
7	44.4	25.0	27.0	20.8
28	47.5	30.6	30.2	25.6
91	49.8	34.7	34.1	29.8

Table 9. Freezing and Thawing Resistance of Concrete Made with Valley High-Carbon Fly Ash

Mixture (Residual Content, kg/m^3)	**Relative Dynamic Modulus of Elasticity, %**							
	Number of Freezing and Thawing Cycles							
	0	31	59	90	120	150	180	210
Ref-2 (0)	100	74.8	60.2	52.0	--	--	--	--
V-8 (7)	100	93.2	90.0	84.9	82.4	75.6	69.1	64.7
V-9 (14)	100	91.0	77.0	74.5	56.7	33.6	--	--
V-10 (21)	100	91.1	79.0	69.9	51.9	41.2	--	--

All mixtures containing the high-carbon fly ash and residuals had a higher resistance to freezing and thawing than the reference mixture. The mixture with the highest resistance to freezing and thawing was Mixture V-8, the mixture contained 7 kg/m^3 of fibrous residuals (0.30 mass % of concrete). This mixture also had the highest compressive strength of the three mixtures produced with the Valley Power Plant high-carbon fly ash, but had lower compressive strength than the reference mixture, Ref-2. The resistance to freezing and thawing cycling can be increased if the compressive strength is increased to a level comparable to the reference mixture, greater than 35 MPa. All concrete mixtures containing residuals and high-carbon fly ash performed better than the reference mixture Ref-2.

Concrete mixtures containing the Valley Power Plant high-carbon fly ash was also tested for the resistance to surface scaling when subjected to deicing chemicals. Results of the test for resistance to salt-scaling are given in Table 10. Through 50 cycles of freezing and thawing, the two mixtures that achieved the highest resistance to scaling, were the mixtures with the lowest amounts of fibrous residuals, Mixture V-8, containing 7 kg/cubic meter (0.30 mass % of concrete), and Mixture V-9, which contained 14 kg/cubic meter (0.60 mass % of concrete) of residuals. The lowest amount of residuals contained in Mixture V-8 had the best performance, with a visual rating still at zero (no visible scaling) at 50 cycles. All concrete mixtures containing residuals and high-carbon fly ash performed better than the reference concrete Mixture Ref-2.

Table 10. Salt-Scaling Resistance of Concrete Made with Valley Power Plant High-Carbon Fly Ash

Cycle	**Visual Rating (VR) and Cumulative Spall (CS) (kg/m^2)**							
	Mixture (Residual Content, kg/m^3)							
	Ref-2 (0)		V-8 (7)		V-9 (14)		V-10 (21)	
	VR	CS	VR	CS	VR	CS	VR	CS
5	0	0	0	0.01	0	0.01	0	0.67
10	0	0	0	0.01	0	0.02	0	0.86
15	1	0.01	0	0.01	0	0.02	0.5	1.01
20	1.5	0.02	0	0.01	0	0.02	0.5	1.10
25	1.5	0.02	0	0.02	0	0.02	1.5	1.32
30	1.5	0.05	0	0.02	0	0.02	1.5	1.36
35	3	0.06	0	0.02	0	0.03	2	1.58
40	3	0.27	0	0.02	0	0.03	2	1.93
45	3	0.45	0	0.02	0.5	0.03	2.5	2.16
50	4	0.58	0	0.03	0.5	0.04	2.5	2.77

CONCLUSIONS

The following general conclusions can be drawn from this project:

- The chemical and physical properties of the high-carbon fly ash (Valley Power Plant) and the spent activated carbon sorbent (Presque Isle Power Plant) did not meet the requirements of ASTM C618. However, the activity with cement exhibited by the spent activated carbon sorbent was very high. This indicates that based upon strength, this material would be a useful material in construction. Similarly, although the high-carbon fly ash from the Valley Power Plant exhibited lower activity with cement, the ash could also be used in selected concrete construction applications.
- Concrete containing the spent activated carbon sorbent achieved a higher compressive strength than the reference mixture, particularly at the later ages of 28 and 91 days. All mixtures containing the high-carbon fly ash (Valley Power Plant) had a compressive strength that was lower than the reference mixture without fibrous residuals or high-carbon ash. As the amount of fibers was increased in the concrete mixtures, the compressive strength decreased, but the difference was less at the later age of 91 days.
- Concrete containing the spent activated carbon sorbent exhibited increased resistance to freezing and thawing as the amount of residuals was increased.
- All mixtures containing the high-carbon fly ash and residuals achieved a higher resistance to freezing and thawing than the reference mixture. The mixture with the highest resistance to freezing and thawing was the mixture that contained 7 kg/m^3 of fibrous residuals (0.30 mass % of concrete).
- Concrete made with the spent activated carbon sorbent that contained the lowest amounts of fibrous residuals, Mixture P-11 and Mixture P-12, achieved the highest resistance to salt-scaling.
- Through 50 cycles of freezing and thawing, the two mixtures that achieved the highest resistance to salt-scaling, were the mixtures with the lowest amounts of fibrous residuals, Mixture V-8, containing 7 kg/cubic meter (0.30 mass % of concrete), and Mixture V-9, which contained 14 kg/cubic meter (0.60 mass % of concrete) of residuals.
- The results of this project show that high-carbon coal combustion products can be used for concrete in a freezing and thawing environment for many varied types for concrete construction applications.

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