Durability of Concrete Utilizing Blended Cements with Elevated Levels of Fly Ash

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ABSTRACT

The benefits of using fly ash have been increasingly recognized for the last 25 years. Additions of fly ash result in improved resistance to sulphate attack, mitigation against alkali-silica reactivity, decreased permeability, and improved resistance to thermal cracking. Partial replacement of Portland cement with fly ash contributes to sustainability by increasing the recycled materials content of blended cements, reducing greenhouse gas emissions, conserving raw material resources, and reducing landfill volumes and disposal costs. Fly ash has many benefits; however, there remains some reluctance within the industry to use elevated levels of fly ash in concrete production. While the long-term improvement of durability and increased service life of structures is well recognized, higher levels of fly ash replacement frequently result in slower strength gain, additional curing requirements, and the perception of delayed construction schedules.

This paper presents the results from a comprehensive study to determine the effect of binary blends with Class F fly ash on the properties of concrete. The properties of concrete with different levels of fly ash replacement were compared to concrete with an interground blend of general use (type GU) hydraulic cement and fly ash. The microstructure of concretes with blended and interground cementitious materials was analyzed by scanning electron microscopy (SEM), and the impact on concrete durability is discussed. The results of the study demonstrate that excellent early age durability of concrete can be achieved with fly ash replacement at a level that satisfies LEED requirements by intergrinding Portland cement clinker with fly ash.

INTRODUCTION

Concrete is used more than any other building material in the world. The concrete industry carries a great responsibility for the implementation of sustainable development to reshape the future of our society, the industry itself, and for the global benefits as well. The beneficial use of by-products that reduce CO_2 emissions and increase the use of recycled material is no longer questioned from a sustainability standpoint; however, the reluctance of the industry, government agencies, and engineering community continues to hinder the use of supplementary cementitious materials (SCM), such as fly ash, at any significant levels. While the demand for “green construction” to satisfy LEED requirements is growing, concrete exposed to extreme environmental conditions, such as freezing and thawing cycles, exposure to chloride ions, and sulphate ions, is typically designed with relatively low levels of SCMs.

The contribution of fly ash to a long-term durability and strength development has been the subject of extensive research (1, 2), and despite excellent performance, a perception of slower strength gain and possible construction delays continues to affect materials selection.

Fly ash can be added directly to the concrete mix during ready-mix or precast operations. This requires an additional storage capacity and is not always practical.

Blended cements are easier to handle, and the risk of batching errors is reduced and production controls are improved. Pre-blended cements are a mixture of Portland cement and fly ash or silica fume with each component retaining its unique morphology and size distribution. The microstructure of interground fly ash and Portland cement clinker is altered as fly ash particles are crushed resulting in a significant increase of surface area available for pozzolanic reactions (3, 4).

The research program, focused on the durability of concrete utilizing interground fly ash and Portland cement clinker, confirmed an excellent resistance to attack by sulphates at low and elevated temperatures and to exposure to freezing and thawing cycles. The ability to resist penetration by chloride ions was in the range expected for high performance concrete (HPC). Plastic properties of concrete and the compressive strength development were improved when compared with concrete with fly ash additions (5).

This paper presents the results of the study of properties of the concrete mixes developed to meet the requirements of the Canadian Standards Association (CSA) A23.1 exposure classes C-XL, C-1, C-2, F-2, and N. The SEM analysis of the fly ash and interground fly ash/Portland cement provides an insight into how the altered morphology and microstructure affects properties of concrete.

EXPERIMENTAL PROGRAM

In this study, concrete mixes with interground fly ash and Portland cement were developed to meet the CSA criteria for five exposure classes. Within each class, control equivalent mixes were also designed for comparison. The testing protocol was specific to the requirements of concrete properties outlined for each class of exposure. All concrete mixes utilized Lehigh type GU cement, Genesee fly ash, GUb-30F interground blend, Villeneuve coarse and fine aggregate, and Grace admixtures. SEM analysis of the fly ash and interground fly ash and Portland cement is also presented.

PROPERTIES OF INTERGROUND BLEND OF FLY ASH AND PORTLAND CEMENT

An interground blend of type GU clinker and class F (low calcium) fly ash was used in the study. The fly ash content of the interground blend is 30% by total mass of cementitious materials, which meets the CSA designation GUb-30F and HSb. The properties of the material are presented in Table 1.

Table 1: Properties of CSA blended Portland cement type GUb-30F.

Chemical Analysis	
SO_3	2.19%
Loss on ignition	0.99%
Alkalies from clinker (as Na_2O eq.)	0.39%
Physical Properties	
Blaine	538 m^2/kg
Retained on 45 μm	4.08%
Autoclave expansion	-0.018%
Vicat initial set	123 min
False set	93 min
Air content	6.50%
Compressive strength at 1 day	13.1 MPa
Compressive strength at 3 days	20.4 MPa
Compressive strength at 7 days	25.7 MPa
Compressive strength at 28 days	38.9 MPa

A SEM micrograph of fly ash is presented in Photo 1. Spherical glassy fly ash particles are predominantly in the range of 2 μm to 20 μm. A small amount of broken spheres are identified.

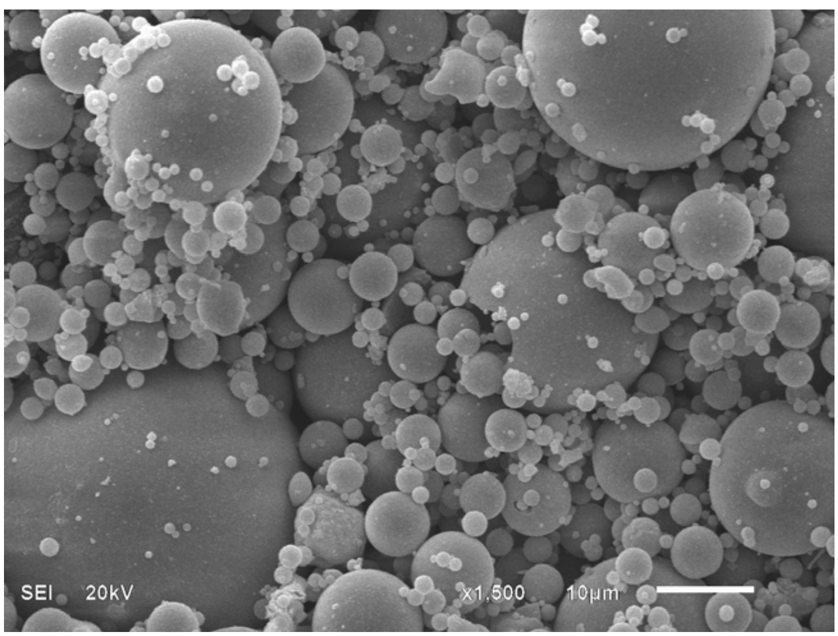

Photo 1: Fly ash originating from the Genesee power generating plant.

The SEM micrograph of GUb-30F blend is presented in Photo 2. Unhydrated cement particles are present in an estimated quantity matching the design 70%. Full spheres of glassy fly ash are in the range of 2 μm to 5 μm. It is estimated that about 50% of the fly ash spheres are crushed to smaller particles. The intergrinding process appears to increase the surface area of fly ash, and it is expected that freshly cracked spheres are more available for pozzolanic reactions between fly ash and lime in the presence of water. The accelerated pozzolanic reactions are consistent with early-age properties of concrete with interground blends reported by others.

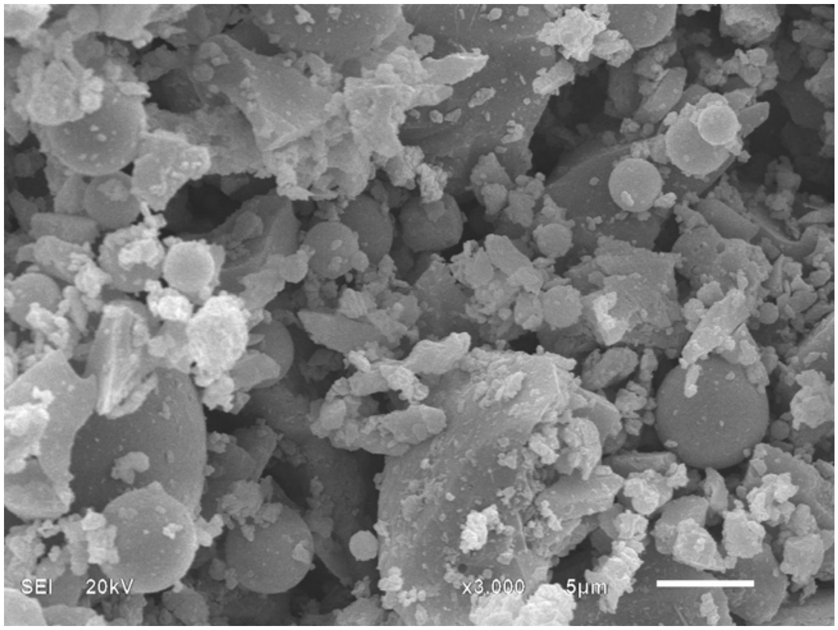

Photo 2: Interground GUb-30F blend of Genesee fly ash and Portland cement.

PROPERTIES OF CLASS C-XL CONCRETE

The mixes were designed to meet CSA requirements as well as the requirements of Alberta Transportation (AT) and The City of Calgary for the high performance concrete (HPC) mixes utilized in major infrastructure projects. The mix design criteria are presented in Table 2. This class of exposure is for structurally reinforced concrete exposed to chlorides or other severe environment with or without freezing and thawing conditions and with higher durability expectations.

Table 2: Mix design parameters.

Exposure Class	CSA A23.1-09 C-XL	Alberta Transportation HPC	The City of Calgary HPC 1
Minimum specified compressive strength at 28 days (MPa)	50 at 28 d	45	45
Size of coarse aggregate (mm)	20	20	20
Air content (%)	5-8	5–8	5–8
Maximum water cementing ratio	0.40	0.38	0.35–0.37
Minimum cement content (kg/m^3)	--	335	--
Silica fume content by mass of cementing materials (%)	--	6–8	7.5–10.0
Fly ash content by mass of cementing materials (%)	--	11–15	≤ 20
Sum of silica fume and fly ash by mass of cementing materials (%)	--	17–20	--

A total of three mixes were designed and cast for a comparison with the design properties, and the designs are presented in Table 3.

Table 3. Class C-XL and HPC mix designs.

Mix No.	GUb-30F (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	FA (%)	SF (kg/m^3)	SF (%)	Air (%)	w/cm
1: Control	0	380	60	12.6	35	7.8	5-8	0.34
2: GUb-30F	418	0	0	27.7	37	7.5	5-8	0.34
3: GUb-30F	456	0	0	27.7	34	7.5	5-8	0.33

The mixes designed with GUb-30F do not meet the AT and The City of Calgary specifications for maximum fly ash content. The fly ash content of the interground blend is higher than that in the control mix. The testing program included the following properties:

- Compressive strength (CSA A23.2-9C);
- Linear traverse (American Society for Testing and Materials [ASTM] C457);
- Rapid freezing and thawing of concrete (ASTM C666); and
- Chloride ion penetration of concrete (ASTM C1202).

The compressive strength results are presented in Table 4. The results indicate that blended Mix 2 was slightly below the City of Calgary and AT specified limit at 28 days. Compressive strengths of blended Mix 3 were higher than that of the control mix. The control mix gained strength at a lower rate than the interground high fly ash mixes.

Table 4. Compressive strength of class C-XL/HPC concrete.

Mix No.	7-day Strength Results (MPa)	28-day Strength Results (MPa)	56-day Strength Results (MPa)
1: Control	35.7	48.6	48.4
2: GUb-30F	29.5	42.8	44.3
3: GUb-30F	36.3	52.0	55.7

All mixes tested complied with the designed air content, spacing factor, and paste content as determined on hardened concrete.

The results of the resistance of concrete to rapid freezing and thawing cycles (F/T) are summarized in Table 5. All mixes showed excellent resistance to F/T cycles; the control mix, however, experienced a somewhat larger drop of the relative dynamic modulus of elasticity (RDM).

Table 5. Resistance of class C-XL/HPC concrete to rapid freezing and thawing.

Mix No.	Relative Dynamic Modulus of Elasticity (%) at 320 Cycles	Specification for HPC
1: Control	96	> 85% at 300 cycles
2: GUb-30F	100	
3: GUb-30F	102	

The testing for the chloride ion penetrability of C-XL/HPC mixes indicated that all results were below the specified limit of 1000 coulombs at 28 days (Table 6). Concrete mixes with interground blend provided a better resistance to penetration by chlorides.

Table 6. Resistance to chloride ion penetration.

Mix No.	Penetrability to Chloride Ion at 28 Days (coulombs)	Specification for C-XL/HPC
1: Control	664	< 1000 coulombs
2: GUb-30F	530	
3: GUb-30F	554	

All mixes researched in this study exhibit the sound properties expected from class C-XL/HPC concrete. Despite an elevated fly ash content that is higher than that specified by AT and The City of Calgary, all the properties were comparable or improved when compared with the control concrete.

PROPERTIES OF CLASS C-1 CONCRETE

CSA defines class C-1 concrete as a structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. The minimum compressive strength at 28 days is 35 MPa, entrained air is in the range of 5% to 8%, maximum water to cementing materials ratio (w/cm) is 0.4, and the chloride ion penetrability at 56 days is less than 1500 coulombs.

Three mixes were designed for analyses; a control mix did not contain interground GUb-30F blend, the blended mixes were designed at two levels of cementitious materials, and the w/cm ratio was increased from 0.33 to 0.37 (Table 7).

Table 7: Mix designs for class C-1 exposure.

Mix No.	GUb-30F (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Air (%)	w/cm
1: Control	0	380	95	5-8	0.33
2: GUb-30F	460	0	0	5-8	0.33
3: GUb-30F	420	0	0	5-8	0.37

A summary of the plastic and hardened concrete properties is presented in Table 8.

Table 8: Properties of class C-1 concrete.

Mix Property	1: Control	2: GUb-30F	3: GUb-30F
Setting time (min), initial/final	535/655	505/590	660/750
Compressive strength (MPa), 7 days/28 days/56 days	23.7/33.4/40.8	34.7/45.3/51.0	28.8/40.5/47.3
Air content (%)/spacing factor (mm)	8.0/0.14	6.7/0.15	7.2/0.13
Relative dynamic modulus of elasticity (%) at 350 cycles	99	104	106
Scaling resistance, mass loss(kg/m^2), 30 cycles/50 cycles	0.07/0.18	0.11/0.20	0.07/0.10
Penetrability to chloride ion at 56 days (coulombs)	2008/901	1763/738	1517/857

The results of the setting time confirm that the initial set and final set are increased for the GUb-30F Mix 3 with the higher w/cm ratio. The GUb-30F Mix 2 shows marginal difference between the initial set of the concrete when compared to the control mix; however, the final set is reduced for the GUb-30F Mix 2 by 65 minutes. The reduction of the final set should be expected since the intergrinding of GUb-30F results in finer product than a mixture of Portland cement and added fly ash. It should be noted that the finishing characteristic of concrete is more affected by the initial set than the final set, and therefore, Mix 2 and Mix 3 tested in this program are expected to require a similar effort for surface finishing.

All mixes tested met the strength specification for CSA C-1 class of exposure, except for the control mix, which is below by 1.6 MPa. The high air content of 8.0% for the control mix would account for the lower strength; however, the mix achieved over 40 MPa at 56 days. The difference of 1.3% in air between with GUb-30F Mix 2 and control Mix 1 would account for 2 MPa to 3 MPa compressive strength variations, though GUb-30F Mix 2 performs consistently 10 MPa to 11 MPa better than the control mix with the same w/cm ratio. The GUb-30F mixes gain strength earlier than the control, and GUb-30F Mix 3 had a similar strength gain rate as the control mix at 28 and 56 days (41% and 64% compared with 41% and 72%). The GUb-30F Mix 2 had higher strengths at 7 days and lower strength gains at 28 days and 56 days, but still achieved the higher strengths at each test date.

The results of the linear traverse testing on hardened concrete indicate that the air entrained mixes comply with the CSA A23.1-09 limits for the air content of hardened concrete and for the spacing factor.

The limits for the freeze/thaw durable concrete are 60% of the initial relative dynamic modulus at 300 cycles. The results indicate that the RDM is in the range expected from HPC mixes for all concrete tested in the program. The differences in the results reported for the mixes are statistically insignificant, but the interground blends performed somewhat better than the control mix. All the mixes meet the requirements for freeze/thaw durability.

The scaling resistance of concrete exposed to de-icing chemicals was conducted in accordance with ASTM C672. Concrete specimens were cured in the 100% relative humidity room for 14 days and then at 50% humidity for an additional 14 days prior to exposure to a de-icing salt solution. As per The City of Calgary specifications, the procedure was modified to record cumulative mass loss at each five cycles. The City of Calgary specification for HPC applications is less than 0.40 kg/m^2 mass loss at 30 cycles. The test was completed at 50 cycles to satisfy AT requirements. However, Alberta Transportation does not specify the limits for the mass loss. All results are below the mass loss specified for HPC at 30 cycles.

All the results are below the specified limit of 1500 coulombs at 56 days. The 56-day results are statistically similar; however, interground blends had an improved resistance to penetration by chlorides.

PROPERTIES OF CLASS C-2 CONCRETE

CSA defines class C-2 concrete as a non-structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. The minimum compressive strength at 28 days is 32 MPa, entrained air is in the range of 5% to 8%, and the maximum w/cm ratio is 0.45. The two mixes designed for the C-2 exposure had the same total cementitious materials content and the same w/cm ratio to demonstrate if there are any benefits of using an interground blend for exterior flatwork applications (Table 9).

Table 9: Mix designs for class C-2 exposure.

Mix No.	GUb-30F (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Air (%)	w/cm
1: Control	0	265	115	5-8	0.42
2: GUb-30F	380	0	0	5-8	0.42

Tested properties of C-2 concrete mixes are summarized in Table 10.

Table 10: Properties of class C-2 concrete.

Mix Property	1: Control	2: GUb-30F
Setting time (min), initial/final	645/810	590/710
Compressive strength (MPa), 7 days/28 days/56 days	16.7/23.7/31.6	25.7/37.2/43.4
Air content(%)/spacing factor (mm)	8.5/0.10	5.7/0.17
Relative dynamic modulus of elasticity (%) at 320 cycles	97	89
Scaling resistance, mass loss(kg/m^2), 30 cycles/50 cycles	0.08/0.13	0.21/0.26

The results of setting time confirm that the initial set and final set is significantly less for the GUb-30F mix than the control mix. The GUb-30F mix shows a decrease of 55 minutes for the initial set and 100 minutes for the final set. The reduction of the initial and final set should be expected since the intergrinding of GUb-30F results in finer product than a mixture of Portland cement and added fly ash.

The strength specification CSA class C-2 of exposure is 32 MPa at 28 days. The strength of the control mix was below the specified strength by 8.3 MPa at 28 days and 0.4 MPa at 56 days, while the GUb-30F mix was above the specified strength by 5.2 MPa at 28 days and 11.4 MPa at 56 days. The high air content of 7.9% for the control mix would account for some of the lower strengths in the control mix. The difference of 2.8% in air between with GUb-30F Mix 1 and control Mix 2 would account for 5 MPa to 6 MPa, though the GUb-30F mix performs consistently 9 MPa to 13 MPa better than the control mix with the same w/cm ratio. The GUb-30F mix gained strength earlier than the control mix, and had similar strength gain rate as the control mix at 28 days (45% and 42%). The 56-day strengths show a higher strength gain for the control mix (89%) than the GUb-30F mix (69%). The increase of compressive strength at earlier ages as seen in the GUb-30F mix should be expected since the intergrinding of GUb-30F results in finer product than a mixture of Portland cement and added fly ash thus accelerating pozzolanic reactions in concrete.

The results of the linear traverse testing on hardened concrete indicate that the air entrained mixes comply with the CSA A23.1-09 limits for the air content of hardened concrete and for the spacing factor. The relative dynamic modulus of elasticity indicated that the freezing and thawing resistance of class C-2 concrete is in the range typically specified for HPC. The mix with interground fly ash and Portland cement had lower RDM than that of the control mix.

PROPERTIES OF CLASS F-2 CONCRETE

CSA classification for class F-2 concrete includes concrete in an unsaturated condition exposed to freezing and thawing but not to chlorides. The specified strength at 28 days is 25 MPa, the maximum w/cm is 0.55, and the concrete is air entrained.

The concrete mixes were designed for exterior walls in buildings. All three mixes have the same water cementing ratio. Mix 1 contains type GU cement and fly ash for comparison. Mix 2 and Mix 3 utilize GUb-30F interground blend. These two mixes have two different amounts of GUb-30F in the mixes. The reason for the change was to evaluate the performance of the GUb-30F with varied levels of SCMs. The control Mix 1 has 25.7% fly ash by total mass of cementitious materials in comparison with the 30% fly ash content in the GUb-30F. Mix designs are presented in Table 11.

Table 11: Mix designs for class F-2 exposure.

Mix No.	GUb-30F (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Air (%)	w/cm
1: Control	0	245	85	4-7	0.50
2: GUb-30F	330	0	0	4-7	0.50
3: GUb-30F	300	0	0	4-7	0.50

The mixes were tested for the setting time and compressive strength only and the results are presented in Table 12.

Table 12: Properties of class F-2 concrete.

Mix Property	1: Control	2: GUb-30F	3: GUb-30F
Setting time (min), initial/final	490/640	450/595	430/570
Compressive strength (MPa), 7 days/28 days/56 days	15.6/28.5/31.9	15.1/25.7/31.9	14.6/25.3/30.1

Setting times of the GUb-30F mixes exhibit only a marginal difference between the two levels of interground blend, but the setting time for the control mix is somewhat longer than that of interground blends. Compressive strength development is similar for all concrete mixes. The test results indicate that at the lower cementitious materials content, the differences in performance between the mixes are not significant.

PROPERTIES OF CLASS N CONCRETE

Class N concrete is defined as concrete that is not exposed to chlorides or to freezing and thawing in footings, interior slabs, walls, and columns. The mix parameters are designed for the structural design and the entrainment is not required. Two mixes were designed to have the same w/cm and same amount of cementitious materials. The control mix utilized type GU cement and type F fly ash and was compared to the interground blend GUb-30F (Table 13).

Table 13: Mix designs for class N exposure.

Mix No.	GUb-30F (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Air (%)	w/cm
1: Control	0	263	91	<3	0.46
2: GUb-30F	354	0	0	<3	0.46

The mixes were tested for the setting time and compressive strength only, and the results are presented in Table 14.

Table 14: Properties of class N concrete.

Mix Property	1: Control	2: GUb-30F
Setting time (min), initial/final	515/595	480/590
Compressive strength (MPa), 7 days/28 days/56 days	26.4/39.9/51.3	27.9/42.0/49.5

The results of setting time confirm that the initial set is shorter for the GUb-30F mix than the control mix; however, the final set was the same for both mixes. The GUb-30F mix shows a decrease of 35 minutes for the initial set. The reduction of the initial set should be expected since the intergrinding of GUb-30F results in finer product than a mixture of Portland cement and added fly ash. The strength development is similar for both mixes indicating that, similarly to class F-2 mixes, at lower levels of cementitious materials the difference in the performance is not significant.

DISCUSSION

The analysis of the concrete mixes designed and analyzed for this study confirmed that the properties of concrete are comparable or improved when an interground blend of Portland cement and fly ash (GUb-30F) is incorporated in the mix. These findings are valid for all classes of exposure presented in this paper when compared with control mixes designed with Portland cement and additions of fly ash. The following conclusions are drawn from the study:

1. The SEM analysis of the fly ash and interground fly ash/Portland cement blend confirmed that larger spheres of fly ash were crushed, likely exposing more surface area for pozzolanic reactions with lime – in concrete. The intergrinding process eliminated the majority of the spheres larger than 5 μm.

2. The amount of total cementitious materials was the highest in concrete designed for class C-XL/HPC and was reduced for subsequent classes of exposure with lower expectations for strength and durability. Regardless of the exposure class, all concrete incorporating interground GUb-30F blends was designed to have more fly ash and less Portland cement than the corresponding control mixes.

3. HPC mixes with the interground blend of cementitious materials exceeded AT and The City of Calgary limits for the fly ash content, but the specified performance criteria were met. An exception was Mix 2, which had lower compressive strength than Mix 3 and Mix 1: Control.

4. All concrete mixes designed for class C-1 and C-2 met the CSA performance criteria. Reduced initial and final setting time with the interground blends make it a viable option in flatwork applications. Durability performance of class C-1 interground blend mixes meets the performance criteria specified for HPC.

5. The improvements in performance of concrete mixes with the interground blends are smaller when the total cementitious materials levels are lower, such as in the concrete designed for exposure class F-2 and N.

6. The use of interground GUb-30F in concrete allows for less Portland cement and more fly ash to achieve a comparable or better performance than more traditional concrete with fly ash additions – a viable approach in “green construction”.

7. Further research of interground Portland cement/ fly ash blends should focus on LEED projects for new construction where the minimum cement reductions for exterior applications cannot be achieved due to durability concerns.

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