A NEW REPAIR MATERIAL FOR CONCRETE PAVEMENTS

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Abstract: Efficient repair of concrete pavements typically requires a rapid setting material that can be placed and hardened within a relatively short period of time for quick opening of traffic. While numerous high early-strength cementitious repair materials are commercially available, many of these materials are vulnerable to early-age cracking, poor bonding, and premature deterioration, for example due to incompatibility with the existing pavement. On the other hand, concrete incorporating fly ash, which is known for its improved long-term performance, is not typically recommended as a repair material. The delay in setting time, strength gain and microstructural development at early-age of fly ash concrete impede its wider acceptance as a repair material for concrete pavements. Nevertheless, these performance limitations can be mitigated by incorporation of nanoparticles in the mixture design of fly ash concrete. In the present study, an effort was made to develop nano-modified fly ash concrete as a repair material for concrete pavements. The performance of the newly developed mixtures was compared to that of two commercial cementitious products customarily used by the regulatory bodies in Manitoba, Canada for partial depth repair of concrete pavements. The experimental scheme comprises tests on fresh, hardened and durability properties relevant to the performance of repair materials for concrete pavements. Due to their ultrafine nature, the addition of a small dosage of nano-silica particles efficiently catalyzed the kinetics of hydration reactions in the cementitious matrix at early-age. The results indicate that nano-modified fly ash concrete has superior performance in terms of strength development, bonding, and resistance to salt-frost scaling, and thus it presents a viable option for repair of concrete pavements.

1 Introduction

It has been estimated that almost one-half of all concrete pavement repairs prematurely fail, which result in significant life-cycle, economic and social losses (Al-Ostaz et al. 2010, Li et al. 2011). Efficient repair of concrete pavements typically requires a rapid setting material that can be placed and hardened within a relatively short period of time for quick opening of traffic. While numerous high early-strength cementitious repair materials are commercially available, many of these materials are vulnerable to early-age cracking, poor bonding, and premature deterioration, for example due to incompatibility with the existing concrete pavement (Li et al. 2011, Soliman et al. 2014). In addition, some studies have shown concerns of using high early-strength concrete in repair applications for pavements. These materials can lead to stress concentrations, because of their susceptibility to thermal gradients and autogenous shrinkage, resulting in high levels of micro-cracking (Bentz and Peltz 2008, Li 2009), and in turn durability issues. Hence, carefully balancing the early-age and long-term performance of cement-based repair materials remains a challenging task, which warrants further investigation.

Extensive research on the use of supplementary cementititous materials (SCMs) such as fly ash showed that incorporation of Class F fly ash improves the long-term performance and durability characteristics of concrete (Malhotra et al. 2000, Toutanji et al. 2004, Ondova et al. 2013, Huang et al. 2013). Despite the benefits of fly ash concrete, practical limitations remain unresolved in field applications. The delay in setting time, strength gain and microstructural development at early-age of fly ash concrete are considered to be the major issues, which impede its wider acceptance as a repair material (Bentz et al. 2012, Said et al. 2012, Hou et al. 2013). Moreover, a number of laboratory studies have indicated inferior scaling resistance of concrete containing dosages of fly ash in excess of 25 to 30% of the binder when subjected to cycles of freezing and thawing in the presence of de-icing chemicals (e.g. Malhotra et al. 2000, Toutanji et al. 2004, Ondova et al. 2013).

Recently, nano-technology was progressively applied to the field of concrete research, which has attracted considerable scientific interest due to the new potential uses of nanometer-sized particles in cementitious binders. Concrete with superior properties can be produced by incorporating nano-materials in fly ash concrete (e.g. Bentz et al. 2012, Hou et al. 2013). As a result of their ultrafine nature, nanoparticles can vigorously speed-up the kinetics of cement hydration in concrete (Said et al. 2012). Consequently, the delay in setting time, strength gain and microstructural development at early-age of fly ash concrete might be mitigated by incorporation of nanoparticles in the mixture. In the present study, an effort was made to develop nano-modified fly ash concrete as a repair material for concrete pavements, to achieve adequate strength, bond and durability to salt-frost scaling. The performance of the newly developed mixtures was compared to two commercial cementitious products customarily used by the regulatory bodies in Manitoba, Canada for partial depth repair of concrete pavements.

2 Experimental program

2.1 Materials

General use (GU) portland cement and fly ash (Class F), which meet the requirements of CAN/CSA-A3001 (2008) standard, were used as the main components of the binder. Their chemical and physical properties are shown in Table 1. In addition, colloidal nano-silica (aqueous solution with 50% solid content of SiO_2) was incorporated in all binders. The mean particle size of the nano-silica was 35 nm, and the viscosity (cP), density (g/cm^3) and pH were 8, 1.4 and 9.5, respectively. Four mixtures were prepared and a non-chloride accelerator admixture, complying with ASTM C494/C494M (2013) for type C and E (Standard Specification for Chemical Admixtures for Concrete), was used in one mixture to accelerate the setting time. Locally available coarse aggregate (natural gravel with max. size of 9.5 mm) and fine aggregate (well graded river sand with fineness modulus of 2.9) were used. The specific gravity and absorption were 2.65 and 2%, respectively for gravel and 2.53 and 1.5%, respectively for sand. In order to achieve a good workability level, a high-range water reducing admixture (HRWRA) based on polycarboxylic acid and complying with ASTM C494/C494M (2013) was added to all mixtures to maintain a slump range between 50 and 100 mm. In addition, an air-entraining admixture according to ASTM C233/C233M (2014) (Standard Test Method for Air-Entraining Admixtures for Concrete) was used to provide a fresh air content of 6±1%. For comparison purposes, two commercial cementitious repair materials, commonly used by regulatory bodies in the province of Manitoba, were evaluated. Their composition, physical and mechanical properties are shown in Table 2 according to each manufacturer's datasheets.

2.2 Procedures

A normal setting concrete mixture (designated as N) was prepared with GU cement and 30% fly ash (replacement by mass of the base binder [385 kg/m^3] comprising GU cement and fly ash); nano-silica was added at a single dosage of 6% by mass of the base binder (i.e. a solid content of 23 kg/m^3). In addition, a corresponding rapid setting concrete mixture (designated as R) was produced with an accelerating, admixture. For both mixtures, the total cementitious materials (ternary binder: GU cement, fly ash and nano-silica) content and water-to-cementitious material ratio (w/cm) were kept constant at 408 kg/m^3 and 0.38, respectively. Constituent materials were mixed in a high-shear mixer according to ASTM C 192 (2013) (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). To attain homogenous dispersion of components; a specific sequence of mixing was adopted based on experimental trials. First, approximately 15% of the mixing water was added to the aggregate while mixing for 30 s. The cement and fly ash were then added to the aggregate and mixed together for 1 min. The colloidal nano-silica and the admixtures (air-entraining admixture, HRWRA and accelerator) were added to the remaining water while stirring vigorously for 45 s to obtain a liquid phase containing well-dispersed nanoparticles and admixtures. Finally, the liquid phase was added to the binder and aggregates and mixing continued for 2 min. After mixing and casting the concrete, a vibrating table was used to ensure good compaction for specimens. Polyethylene sheets were used to cover the surface specimens of for 24 h. The specimens were then demolded and cured in a standard curing room (maintained at a temperature of 23 ± 2 °C and relative humidity of more than 95%) until testing. The proportions of the two mixtures are shown in Table 3. For the commercial repair products A and B, the manufactures' recommendations were carefully followed in the proportioning, mixing, casting and curing procedures (Table 2).

Table 1: Chemical and physical properties of the cement and fly ash

	Chemical Composition								*Physical Properties*	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	$CaCO_3$	Blaine (m^2/Kg)	Specific Gravity
GU	19.8	5.0	2.4	63.2	3.3	3.0	0.1	--	410	3.17
Fly Ash	56.0	23.1	3.6	10.8	1.1	0.2	3.2	--	290	2.12

Table 2: Summary of the composition, physical and mechanical properties for commercial repair materials according to manufacturers' datasheet

	A	B
Composition (% by weight)		
Hydraulic cement	√	7-13
Silica sand, crystalline	√	>60
Titanium dioxide	√	0.1-1
Borax	√	1-5
Physical properties		
Specific gravity	2.7	2.75
Water content (l per 22.7 kg)	2.13-2.84	1.6-1.77
Mixing time (min)	4-5	4
Extension*	50%	50%
Curing procedures	Wet cure the surface with water and polyethylene sheets at least one day, or use a curing compound	
Compressive strength (MPa) ASTM C 109		
2 h	13.8	-
3h	24.1	24.1
1 day	34.5	37.9
7 days	48.3	58.6
28 days	-	68.9
Flexural strength (MPa) – ASTM C 78		
3 hr	2.8	-
Slant shear bond (MPa) – ASTM C 882		
1 day	10.4	-
7 days	13.8	-

* Coarse aggregate extension by weight of repair material per bag (22.7 kg).
√ Chemical composition by weight not provided but stated.

Table 3: Proportions of mixtures per cubic meter of concrete

Mixture ID.	Cement (kg)	Fly ash (kg)	Nano-silica (kg)	Water* (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	HRWRA (l/m^3)	Accelerator (l/m^3)
NF30	269	116	46	131	830	830	1.93	0
RF30	269	116	46	131	830	830	1.54	6.93

*****Adjusted amount of mixing water considering the water content of nano-silica.

2.3 Testing methods

To determine the setting time of the mixtures, the mortar fraction of each mixture (portion passing sieve #4 [4.75 mm]) was placed in a container at room temperature as specified by ASTM C 403 (2008) (Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance). At regular time intervals, the resistance of the mortar to penetration by standard needles was determined. More than ten penetration readings were recorded for each mixture to determine the setting time curve. The initial and final setting times are defined at a penetration resistance of 3.5 MPa and 27.6 MPa, respectively.

For each mixture, triplicate 100×200 mm concrete cylinders were prepared for the compressive strength test according to ASTM C 39 (2012) (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). After 24 h of mixing, the cylinders were demolded and placed in a standard curing room (maintained at a temperature of 23 ± 2 °C and with a relative humidity of more than 95%) until they were ready for testing. The compressive strength of the mixtures was determined at different ages (8h and 1, 3, 7 and 28 days).

The bond strength between the mixtures and concrete substrate was tested at 7 and 28 days for triplicate 75x150 mm composite cylinders by using procedures adapted from ASTM C 882 (2013) (Standard test method for bond strength of epoxy-resin systems used with concrete by slant shear). Each composite cylinder was cast in two stages; firstly, while the mold was slanted at 30º, a typical concrete mixture (350 kg GU cement with 15% fly ash as a binder and 0.38 w/cm) used for pavements was poured and rodded to fill one-half of the mold as a substrate. At 90 days, after wire brushing and cleaning the slanted concrete surface, the samples were placed in an upright position in molds which were filled with the repair mixtures. After curing the samples at 23 ± 2 °C and 95% relative humidity for 7 and 28 days, the bond strength was tested by loading the cylinders to failure in compression.

ASTM C672/C672M (2012) (Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals) was conducted for all the mixtures to evaluate the resistance of the mixtures to surface scaling due to harsh winter conditions encountered in Canada. Slab specimens (two replicates for each mixture) had a surface area of at least 0.045 m^2 and 75 mm depth. At 28 days, the surfaces of specimens were covered with approximately 6 mm of de-icing salts (4% calcium chloride solution). The specimens were then exposed to 50 freezing-thawing cycles. Each cycle consisted of 16 to 18 h freezing at -18°C followed by 6 to 8 h thawing at 23 ± 2.0°C and a relative humidity of 45 to 55% (laboratory conditions). Every five cycles, the surfaces of the specimens were thoroughly flushed with water and the debris was collected on a filter paper and oven dried before weighing. After visual examination of the surface, the solution was replaced with a fresh one to continue the test.

3 Results and discussion

3.1 Setting time

From a plot of penetration resistance versus elapsed time (Figure 1), the times of initial and final setting were determined. A curve for a reference mixture (30% fly ash concrete without nano-silica) is included in Figure 1 for comparison. The commercial products A and B had very short hardening time intervals (40 to 60 min), as indicated by the acute increase of penetration resistance curves (Figure 1). This implies critical placement, finishing and curing issues, since all these processes should be done within 40 minutes for mixtures A and B. This may impede the quality of the repair process and cause surface cracking at early-age. Also, when large patches are required to be repaired, there will be a high potential for cold joints as repair mortars/concretes are typically mixed on site in small batches. Comparatively, the N and R nano-modified fly ash concrete mixtures had longer setting times, which would allow more flexibility in the repair process of concrete pavements. Even the R mixture (RF30) had ample time (approximately 210 min) for placement, finishing and curing operations. The effect of higher dosages of fly ash on retarding the setting time of concrete is well-documented (ACI 232.2R, 2002) [refer to the reference mixture in Figure 1]. However, the setting times of the nano-modified fly ash concrete mixtures were significantly accelerated relative to the reference mixture without nano-silica. For example, the initial setting time for NF30 was 360 min compared to 540 min for the reference mixture (30% fly ash without nano-silica). Correspondingly, the nano-modified concrete mixtures (NF30 and RF30) exhibited final setting times of 515 and 335 min, respectively, which are 62% and 40%, respectively of the final setting time of the reference mixture. This is attributed to the addition of ultrafine nano-silica particles (average particle size of 35 nm and specific surface of 80 m^2/g), which sped up the kinetics of hydration reactions and in turn alleviated the retarding effect of fly ash on the mixtures. In addition, this trend was magnified with the incorporation of an accelerating admixture in the R mixture (RF30).

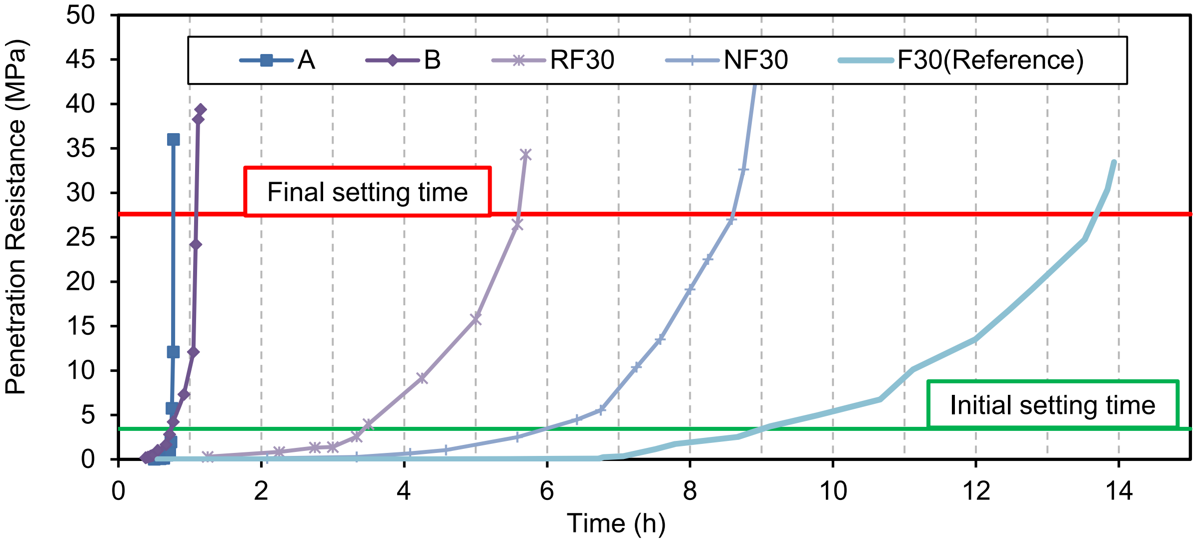

Figure 1- Penetration resistance versus time for the commercial products and nano-modified fly ash mixtures

3.2 Compressive strength

Figure 2 shows the average compressive strengths of the specimens at different curing ages. For the compressive strength, the results generally indicated that the commercial products (A and B) gained the highest compressive strength after 8 h; however, the increase of strength for these products was not significant until 1 day, and the R mixture RF30 achieved a comparable compressive strength of 15 MPa at 1 day. The rate of strength development for products A and B was insignificant up to 3 days. This was statistically supported by the analysis of variance (ANOVA), at a significance level $\alpha = 0.05$. ANOVA is a statistical model used to analyze the differences between group means and their variation among and between groups. According to ANOVA, exceeding the F_{cr} for an F-distribution density function indicates that the variable tested has a statistically significant effect on the average results (Montgomery 2014). For example, for product A, ANOVA for the change of compressive results at 8 h and 3 days had F value of 6.71 which is smaller than the corresponding critical value (F_{cr}) of 7.71. This insignificant change in compressive strength up to 3 days can be attributed to the substantially rapid reactions during the first 8 h, which might have formed thick hydration shells that discounted the diffusion of water and kinetics of hydration afterwards (Mehta and Monteiro, 2014). Comparatively, the rate of strength development of the nano-modified fly ash concrete mixtures was significant (an increase of 80 and 63% for NF30 and RF30, respectively) up to 3 days. For instance, ANOVA for the compressive strength results at 1 and 3 days for the N and R mixtures yielded F values of 71.4 and 26.5, respectively which are larger than the corresponding critical value (F_{cr}) of 7.71. The results of the nano-modified fly ash concrete mixtures at 28 and 56 days indicated that there was continuous and significant improvement in strength beyond the age of 7 days in comparison to the commercial products. The significant increase in strength of fly ash concrete mixtures with time is ascribed to the synergistic effects of nano-silica (physical filler and pozzolanic effects, Said et al. 2012) and fly ash (pozzolanic effect, Malhotra et al. 2000).

For specimens from the R mixture (RF30), the average early age (1, 3 and 7 days) strength significantly increased (43%) in comparison to the normal mixture (NF30). ANOVA, at a significance level $\alpha = 0.05$, for the results at 1 day showed that variation in the type of mixture from N to R had F value of 17.5, which is larger than the critical value (F_{cr}) of 7.71. This significant change in compressive strength at early-age for the R mixture was attributed to the presence of the accelerating admixture, which sped up the rate of hydration reactions, and consequently increased the early-age strength. However, this trend diminished between 7 to 56 days for the R mixture, which conforms to effect of accelerators on the compressive strength development of at later ages due to the slower diffusion of pore water through thick hydration products to continue hydration. On the contrary, for the N mixture, the compressive development was significant after 7 days (70% increase between 7 to 56 days) and achieved the highest strength at 56 days (46 MPa), which is consistent with the well-documented trend of Class F fly ash in concrete (Mehta and Monteiro, 2014).

The early-age results generally indicated that the compressive strength of the nano-modified fly ash concrete mixtures markedly increased with the addition of nano-silica. The results are consistent with the findings of Said et al. (2012). Hence, the slow rate of strength development for concrete incorporating Class F fly ash can be controlled by the addition of a small dosage of nano-silica. The ultrafine nature of well dispersed nano-silica effectively contributed to the strength development of mixtures up to 3 days by acting as nucleation sites for hydration reactions, which sped up the kinetics of hydration, complying with the trends of the setting time test. In addition, the strength development of the mixtures containing nano-silica up to 7 days can be mainly attributed to the filler and pozzolanic effects of the nano-silica particles. When sufficient amounts of $Ca(OH)_2$ are available in the matrix, they can be consumed by reactive nano-silica to produce secondary C-S-H (pozzolanic reaction), and thus improving the strength of the matrix. In addition, the long-term enhancement of the strength of the mixtures can be ascribed to the pozzolanic reaction of fly ash (Malhotra et al. 2000), thus improving the durability of the mixtures as will be shown in the surface scaling section of this paper.

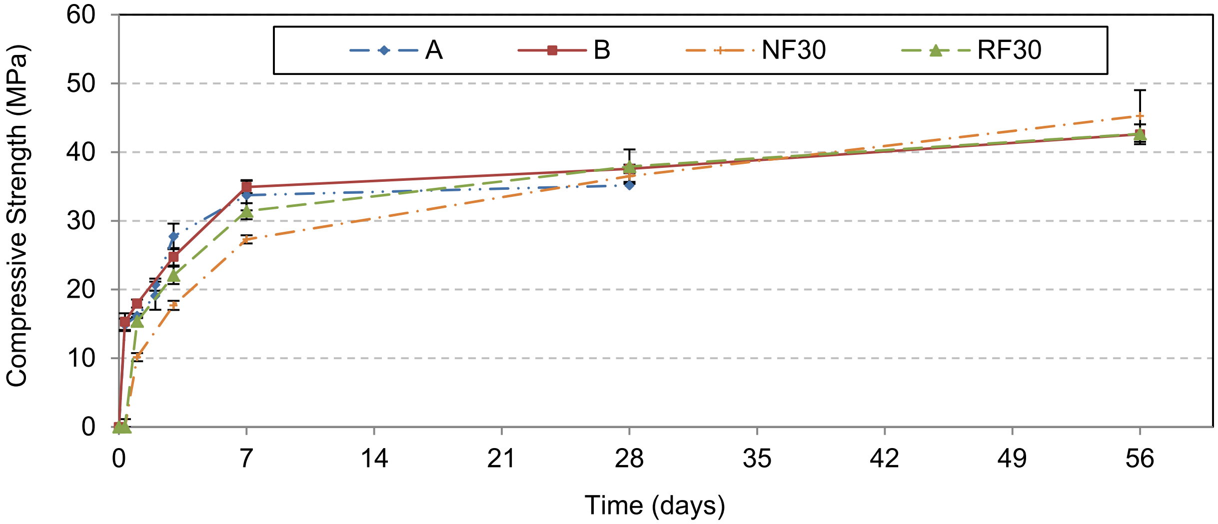

Figure 2- Compressive strength development versus time for the commercial products and nano-modified fly ash mixtures

3.3 Bond test

Bond failure is a critical cause of deterioration in pavement repairs. The modes of failure in slant shear tests were either observed in the repair material (R), joint interface between substrate concrete and repair materials (J), substrate concrete (C), or combinations of these modes. Figure 3 shows the average bond strength from the slant shear test at 7 and 28 days, in addition to the general mode of failure. The strength of each specimen was calculated by dividing the maximum load at failure by the cross-sectional area of the sloping surface. The bond strength for all the mixtures ranged from 13.9 MPa to 18.2 MPa, except for the commercial product (A) which had the lowest bond strength (10.8 MPa) and its mode of failure was mainly by crushing of the repair material (R). The increase (from 7 to 28 days) of bond strength for the commercial products A and B were lower than that of the nano-modified fly ash concrete mixtures. This can be attributed to the substantially rapid reactions in these products during the first 8 h as discussed earlier. Comparatively, the bond strength increased (from 7 to 28 days) by 47% and 54% for NF30 and RF30, respectively.

For specimens from the R mixture (RF30), the bond strength significantly increased (26% and 32% at 7 and 28 days, respectively) in comparison to corresponding specimens from the normal mixture (NF30). ANOVA, at a significance level $\alpha = 0.05$, for the results of slant shear test showed significant difference between the R mixture and the N mixture at 7 and 28 days, with F values of 67.6 and 22.3 relative to the critical value (F_{cr}) of 7.71. This can be attributed to effect of the accelerator on increasing the mechanical properties at early-age, complying with the general trends of the compressive strength (average of 20 % increase in compressive strength between RF30 and NF30 at 7 days). Generally, the nano-modified fly ash concrete had comparable or higher bond strength compared to the commercial products at 28 days, owing to the improved hydration in these mixtures due to the synergistic effects of nano-silica and fly ash. In addition, the mode of failure in these mixtures was mainly shifted to the substrate concrete at 28 days, suggesting efficient repair. It is expected that the bond strength of these mixtures will continue to improve conforming to the trends of compressive strength at later ages (56 days).

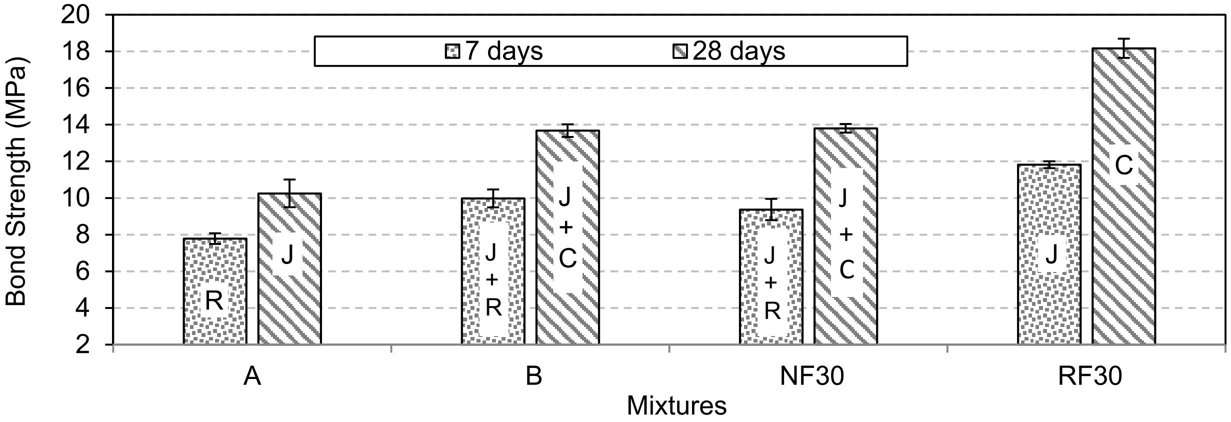

Figure 3 – Bond strength and mode of failure for the mixtures according to the slant shear test

3.4 Resistance to salt scaling

The results of surface scaling due to the combined action of de-icing salt and freezing-thawing cycles (ASTM C672) are shown in Figures 4 and 5. The commercial product A showed a high tendency to surface scaling after about 10 cycles. After 50 cycles, the commercial products A and B had cumulative mass loss of 2.4 kg/m^2 (visual rating of 3-4) and 0.5 kg/m^2 (visual rating of 1-2), receptively. According to Bureau de Normalisation du Quebec (BNQ) and Ministry of Transportation in Ontario (MTO), the failure limit in the ASTM C 672 test is 0.5 and 0.80 kg/m^2. Considering these criteria, the commercial products tested herein are deemed unacceptable as it they will likely have surface scaling issues in the field. In contrast to the commercial products, the N and R nano-modified concrete mixtures with 30% fly ash had low visual ratings (0 to 1, Figure 4) and limited surface scaling (Figure 5), except for minor pop-outs likely due to the deterioration of some porous aggregates near the surface of concrete. The nano-modified fly ash concrete mixtures had mass loss less than 0.5 kg/m^2 (maximum of 0.25 kg/m^2) after 50 cycles. It has been reported that the resistance to salt-frost scaling decreases with increasing the dosage of fly ash in concrete, which is among the key reasons that deter the wider use of higher dosages of fly ash (typically less than 20%) in concrete pavements (Toutanji et al. 2004, Ondova et al. 2013). High contents of Class F fly ash in concrete may lead to significant proportions of unbound (unreacted) fly ash particles in the paste, resulting in coarse microstructure and higher tendency to surface scaling. In the current study, incorporation of 30% fly ash in concrete only led to marginal surface scaling when the binders were modified with nano-silica, indicating improved durability of these binders.

In addition ANOVA, at a significance level $\alpha = 0.05$, for the results of surface scaling showed insignificant difference between the R and the N mixtures at 50 freezing-thawing cycles, as the F value was 1.6, which is less than the critical value (F_{cr}) of 18.51. This insignificant change in surface scaling can be attributed to the incorporation of nano-silica with fly ash, which improved the reactivity and binding of Class F fly ash as indicated by the results of compressive and bond strengths at 28 days. In addition, combination of fly ash with nano-silica might have led to a dense pore structure (further densifying with time), which discounted the rate of ingress of the salt solution and in turn improved the resistance of concrete to salt-frost scaling, even at a high dosage of fly ash.

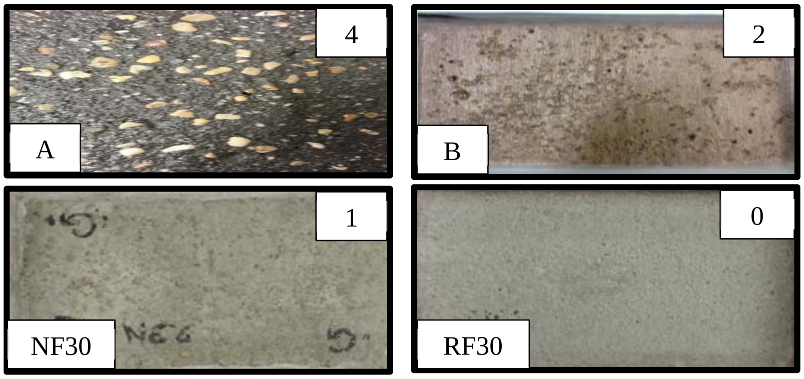

Figure 4 – Average visual ratings of slabs after 50 freezing-thawing cycles

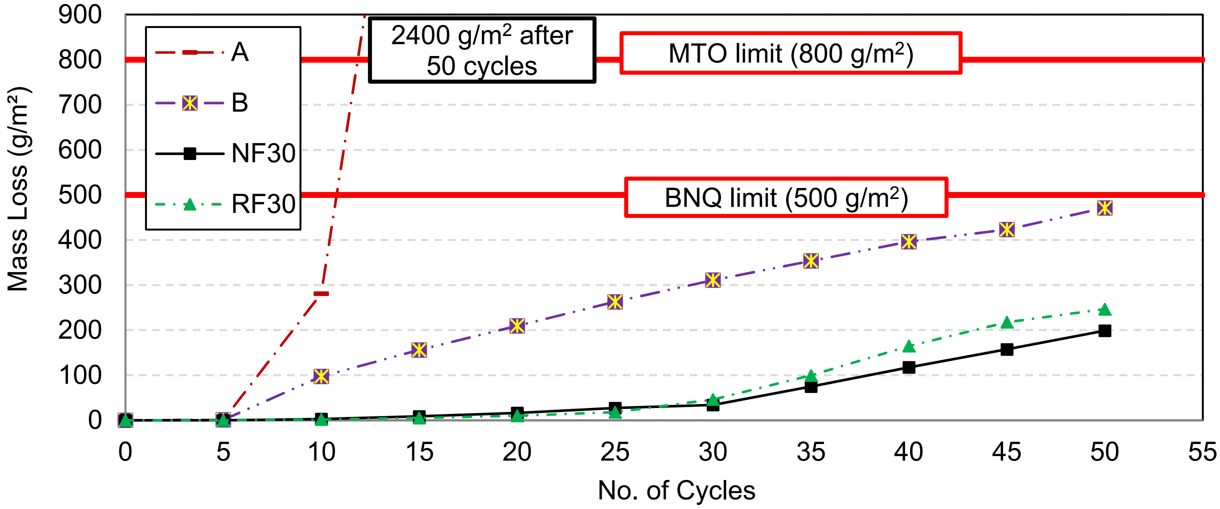

Figure 5 – Surface scaling of slabs according to ASTM C672 (14 days of moist curing followed by 14 days in air before testing)

4 Conclusions

- The study indicates that the high early-strength of rapid setting cementitious materials is an insufficient criterion to consider a product acceptable as a repair material.
- The commercial products had adverse performance with respect to placement/finishability. On the contrary, the nano-modified fly ash concrete mixtures had ample time for placement/finishability, which would contribute to improving the quality of the repair process. Yet, the incorporation of 6% nano-silica by mass of cementitious materials reduced the initial and final setting times by 180 and 320 min, in comparison to the reference concrete with 30% fly ash.
- The compressive strength was considerably improved for mixtures incorporating 30% Class F fly ash and nano-silica, which indicates that the inherently slower rate of strength development of concrete containing Class F fly ash can be controlled by the addition of small dosages of nano-silica. The synergistic effects of nano-silica and fly ash improved the early-age and long-term compressive and bond strengths of concrete.
- In comparison to the commercial products, the nano-modified concrete mixtures with 30% fly ash had limited surface scaling, which suggests that the addition of nano-silica to fly ash improved its reactivity and binding, and thus improved the resistance of concrete to salt-frost scaling.
- The overall results indicate that the nano-modified fly ash concrete developed in this study has balanced performance in terms of hardening time, strength development, bonding, and resistance to salt-frost scaling; thereby, it presents a viable option for repair of concrete pavements.

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6 References

ACI 232.2R. 2002. Use of fly ash in concrete. *Reported by ACI Committee 232*, Farmington Hills, MI: American Concrete Institute.

Al-Ostaz, A., Irshidat, M., Tenkhoff, B., Ponnapalli, P. S. 2010. Deterioration of bond integrity between repair material and concrete due to thermal and mechanical incompatibilities. *Journal of Materials in Civil Engineering*, 22(2), 136-44.

ASTM C39. 2012. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *ASTM International*, West Conshohocken, PA, 04.02.

ASTM C403. 2008. Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance. *ASTM International*, West Conshohocken, PA, 04.02.

ASTM C672. 2012. Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals. *ASTM International*, West Conshohocken, PA, 04.02.

ASTM C882. 2013. Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear. *ASTM International*, West Conshohocken, PA, 04.02.

Bentz, D.P., and Peltz, M. A. 2008. Reducing thermal and autogeneous shrinkage contributions to early-age cracking. *ACI Materials Journal*, 105(4), 414-420.

Bentz, D.P., Sato, T., Varga, I., and Weiss, W.J. 2012. Fine limestone additions to regulate setting in high volume fly ash mixtures. *Cement and Concrete Composites*, 34(5), 11-17.

BNQ NQ 2621-900. 2002. Determination of the Scaling Resistance of Concrete Surfaces Exposed to Freezing-and-Thawing Cycles in the Presence of Deicing Chemicals. *Bureau de normalisation du Québec*, Annexe A, pp. 19-22.

CAN/CSA-A3001. 2008. Cementitious Materials for Use in Concrete. *Canadian Standards Association*, Mississauga, Ontario, Canada.

Hou, P., Kawashima, S., Wang, K., Corr, D., Qian, J., and Shah, S. 2013. Effects of colloidal nanosilica on rheological and mechanical properties of fly ash–cement mortar. *Cement and Concrete Composites*, 35(1), 12-22.

Huang, C., Lin, S., Chang, C., and Chen, H. 2013. Mix proportions and mechanical properties of concrete containing very high-volume of Class F fly ash. *Construction and Building Materials*, 46, 71-78.

Li, M. 2009. Multi-scale design for durable repair of concrete structures. PhD thesis, University of Michigan, USA, 425p.

Li, M., and Victor, C.L. 2011. High-early-strength engineered cementitious composites for fast, durable concrete repair-material properties. *ACI materials journal*, 108(1), 3-12.

Malhotra, V.M., Zhang, M.H., Read, P.H., and Ryell, J. 2000. Long-term mechanical properties and durability characteristics of high-strength/high-performance concrete incorporating supplementary cementing materials under outdoor exposure conditions. *ACI Materials Journal*, 97(5), 518-525.

Mehta, P.K. and Monteiro, P.J.M. 2014. *Concrete: Microstructure, Properties and Materials*. McGraw Hill Education, California, USA.

Montgomery, D.C. 2014. *Design and Analysis of Experiments*, John Wiley and Sons, Arizona, USA.

MTO LS-412. 1997. Method of Test for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals. *Ministry of Transportation*, Ontario Laboratory Testing Manual, Ontario, Canada.

Ondova, M., Stevulova, N., and Meciarova, L. 2013. The potential of higher share of fly ash cement replacement in the concrete pavement, *Procedia Engineering*, 65, 45-50.

Said, A.M., Zeidan, M.S., Bassuoni, M.T., and Tian, Y. 2012. Properties of concrete incorporating nano-silica. *Construction and Building Materials*, 36, 838-844.

Soliman, H., and Shalaby, A. 2014. Characterizing the performance of cementitious partial-depth repair materials in cold climates. *Construction and Building Materials*, 70, 148-157.

Toutanji, H., Delatte, N., Aggoun, S., Duval R., and Danson, A. 2004. Effect of supplementary cementitious materials on the compressive strength and durability of short-term cured concrete. *Cement and Concrete Research*, 34(2), 311-319.