ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 116-M27

Effects of Mixture Proportioning, Curing, and Finishing on Concrete Surface Hardness

by Kamran Amini, Seyedhamed Sadati, Halil Ceylan, and Peter C. Taylor

With adoption of winter maintenance strategies that typically include incorporation of aggressive deicer chemicals, pavement surfaces in cold regions are exposed to the risk of scaling damage. Reduced ride quality due to surface deterioration can eventually lead into a variety of maintenance and repair programs. Such pavement preservation programs impose significant charges to the owner agencies, while raising concerns regarding the safety issues associated with work zone areas. The present study addresses the correlation between surface hardness and concrete hardened properties. Moreover, factors that influence the concrete performance with respect to surface-abrasion resistance (hardness) were investigated. Of special interest was the relationship between surface hardness and concrete salt-scaling performance.

An extensive investigation was carried out to assess the effects of various mixture proportions, curing regimes, and finishing times on surface hardness of the concrete specimens. In addition, compressive strength, depth-sensing indentation (DSI), and salt scaling tests were used to evaluate the correlation between concrete surface hardness and performance. A scaling quality classification table using abrasion mass loss values was developed. The results reflect further understanding of the relationship between abrasion resistance and salt scaling resistance that can cause defects when more than two cycles of abrasion testing are applied.

Keywords: curing; finishing; salt scaling; slag cement; surface hardness.

INTRODUCTION

In response to the need for sustainable development, research related to reducing the carbon footprint of the construction industry has become an issue of great interest. Production of portland cement is the main source of CO_2 emission in concrete production. Considerable energy is expended in producing cement including that required for initial mining, raw material processing, calcination processes, and achieving high kiln temperatures. The average emission due to cement production is estimated to range from 0.7 to 1.0 ton of CO_2 per ton of produced cement.[1,2] Partial replacement of cement with supplementary cementitious materials (SCMs) has been considered as a potentially ideal method of producing a more environmentally friendly concrete. This is of special interest for the U.S. transportation infrastructure, in which more than 60% of the interstate highway system is paved with concrete.[3]

With an expected design life of up to 50 years, these pavement systems must be durable. However, several cases of premature failure, due either to structural deficiencies, construction issues, or material distress, are reported by state agencies each year. Surface wear under traffic loading and/or environmental conditions are among the mechanisms that can reduce ride quality, leading to a need for major rehabilitation of rigid pavement systems.[4] In addition to the fatigue damage induced by repeated loading over the life of pavement, the other mechanical mode of distress under traffic loading is known as abrasion deterioration, which over the course of years can yield varied damage patterns. It is well established that the use of hard and dense aggregate can promote abrasion resistance of concrete, while the use of more porous aggregate types diminishes such resistance.[4] It also has been traditionally accepted that abrasion resistance is reflected by concrete compressive strength. In other words, a high-quality binder system and a proper curing regime can help secure desired uniformity of concrete and resistance to mass loss caused by abrasion.[5]

Surface damage caused by deicers used in subzero environments is another cause for a damage to the surface texture and reduced ride quality. The action of freezing-and-thawing cycles accompanied by chemical reaction between salt and the cement paste can cause scaling of the exposed surfaces,[4] and it has been shown that abrasion resistance, as a measure of surface hardness, is among the factors affecting salt-scaling resistance of concrete.[6-8]

It is generally expected that SCMs will enhance the mechanical properties and durability of concrete through pozzolanic reactions. The extent of improvement, however, depends on physicochemical properties, the replacement rate of the SCM, and the nature of the deteriorating mechanism. Considering its potential for both hydraulic and pozzolanic activities, slag cement is typically considered as a SCM that could be used at dosages up to 50% of the total binder mass.[9]

RESEARCH SIGNIFICANCE

Given the increasing interest in the use of green concrete mixtures produced with high-volume cement replacement in infrastructure construction, it is important to fully investigate the long-term properties of such materials. A comprehensive experimental program was undertaken in this study to address the effect of high-volume slag cement on abrasion resistance and salt scaling potential of concrete designated for use in rigid pavement construction. Interactions related to air content, curing regime, and finishing timeline were also investigated. The results obtained from this work are expected to illuminate the role of slag cement with respect to long-term performance of rigid pavement systems.

ACI Materials Journal, V. 116, No. 2, March 2019.
MS No. M-2018-224, doi: 10.14359/51714457, received June 13, 2018, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

Table 1—Chemical analysis of cementitious materials used in concrete mixtures, %

Properties	Cement	Fly ash	Slag cement
Alkalis (Na_2O_e)	0.88	1.9	0.4
Loss on ignition	2.2	2.65	0.75
Insoluble residue	0.7	—	—
Free lime	0.8	—	—
SiO_2	20.6	52.5	37.2
AlO_3	4.5	25.4	11.9
Fe_2O_3	2.7	6.6	0.5
CaO	62.7	6.1	37.9
MgO	2.0	1.6	9.5
SO_3	3.6	0.9	3.0

EXPERIMENTAL PROCEDURE

Materials

Different binders of Type I portland cement, Class C fly ash, and slag cement (ground-granulated blast-furnace slag with a 28-day activity index of 120) were incorporated in binary and ternary systems, and Table 1 presents the chemical and physical characteristics of these cementitious materials. Polycarboxylate-based high-range water-reducing admixture (HRWRA) and vinsol-based air-entraining admixture (AEA) were employed with dosages adjusted to achieve initial slump and air content values of 50 ± 10 mm and 2 to 9%, respectively. Continuously graded crushed limestone aggregate with 19 mm nominal maximum size (NMS), a bulk specific gravity of 2.68, and an absorption value of 0.81% was selected. A well-graded limestone fine aggregate with fineness modulus of 2.97, 1.5% water absorption, and 2.62 specific gravity was also used. The particle-size distributions of these aggregates are shown in Fig. 1.

Mixture proportion

A total of 59 sets of concrete specimens was fabricated with different binary and ternary combinations of fly ash and slag cement, water-cementitious materials ratio (*w*/*cm*), and air content, using different finishing techniques and curing regimes. Table 2 summarizes the mixture proportions of the investigated mixtures. Mixtures 1 to 23 were tested to study the effect of mixture proportions, while the effects of finishing and curing were investigated for Mixtures 24 to 27.

Mixture design and procedure

The mixing sequence consisted of introducing AEA diluted in one-third of the water into the coarse aggregate and mixing until foam was formed. The process continued by homogenizing the fine and coarse aggregate for 30 seconds before introducing the cementitious materials along with the remaining water. The concrete was again mixed for 3 minutes and kept at rest for 3 minutes before remixing for an additional 3 minutes. The first group of specimens that were prepared for studying the effects of mixture proportioning on abrasion resistance were finished immediately after casting and subjected to 28 days of standard moist curing according to ASTM C31.[10] The remaining specimens were subjected to the following finishing scenarios and curing regimes.

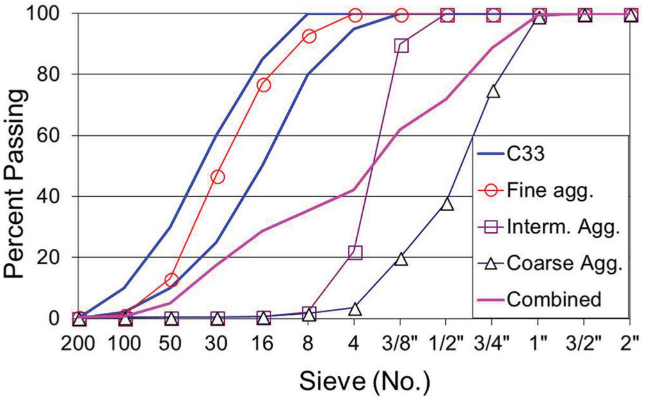


Fig. 1—Particle-size distribution of fine and coarse aggregate.

Finishing—The times for applying the finishing, using a wooden trowel, were chosen as follows:

(a) Immediately after casting.
(b) After bleeding had slowed or stopped.
(c) At initial setting time.

The same operator finished all the slabs under instructions to apply the same amount of effort in all cases. After finishing, all specimens were covered with plastic sheeting for 24 hours, after which they were demolded and cured for 28 days in accordance with ASTM C31.[10]

Curing regimes—All curing specimens were finished immediately after casting, and covered with plastic sheeting for 24 hours before demolding. After demolding, the specimens were subjected to different curing regimes as follows:

- 28m BNQ: BNQ 2621-900,[11] 28 days of standard moist curing and 14 days of air curing.
- 7m and 3m: 7 and 3 days of moist curing followed by 14 days of air drying.
- 3c, 7c, and 28c: White-pigmented membrane-forming curing compound was applied to specimen surfaces immediately after finishing. Specimens were left for 3, 7, and 28 days at room temperature of 24 ± 2°C prior to 14 days of air drying. Curing compound was removed from the surface of 3c specimens after 3 days to terminate curing. For the 28c regime, additional curing compound was applied to the surface of specimens each 7 day within a 21-day interval. No additional curing compound was applied on the 7c and 28c specimens at their ages of 7 and 28 days, respectively.

The last two (3 and 7 days of curing) regimes would be more practical in the field.

Testing program

The abrasion resistance of specimens' surface was determined as a measure of surface hardness using a rotating-cutter drill press in accordance with ASTM C944.[12] After the specified curing intervals, 100 x 50 mm cylinders were dried at 50°C for 3 days, and after a blast of compressed air was used to ensure that they were free of dust, the initial weights of the cylinders were measured. The surface of each specimen was then subjected to the rotating-cutter drill press at 197 N for 2 minutes, after which all the resulting dust was

Table 2—Mixture compositions

Mixture No.	Air content	Slag, %	*w/cm*	Materials, kg/m^3					
				Cement	Fly ash	Slag	CA	FA	Water
1	<3%	0	0.35	332	83	0	1210	702	145
2		20	0.35	249	83	83	1207	700	145
3		40	0.35	166	83	166	1206	699	145
4		0	0.55	242	61	0	1238	717	166
5		20	0.55	182	61	61	1235	716	166
6		40	0.55	121	61	121	1234	715	166
7	3 to 6%	0	0.35	332	83	0	1135	658	145
8		20	0.35	249	83	83	1132	656	145
9		40	0.35	166	83	166	1129	655	145
10		0	0.55	242	61	0	1161	673	166
11		20	0.55	182	61	61	1160	672	166
12		40	0.55	121	61	121	1158	671	166
13	>6%	0	0.35	332	83	0	1084	628	145
14		20	0.35	249	83	83	1081	627	145
15		40	0.35	166	83	166	1079	625	145
16		0	0.55	242	61	0	1111	644	166
17		20	0.55	182	61	61	1110	463	166
18		40	0.55	121	61	121	1107	642	166
19	3 to 6%	20	0.45	214	71	71	1140	661	160
20	3 to 6%	30	0.35	208	83	125	1131	656	145
21	>6%	10	0.4	249	71	36	1151	667	125
22	<3%	30	0.5	163	65	98	1202	697	163
23	<3%	10	0.55	212	61	30	1211	702	166
24	>6%	0	0.48	326	0	0	1163	674.6	157
25	>6%	20	0.48	261	0	65	1162	673.4	157
26	>6%	40	0.48	196	0	130	1159	472.2	157
27	>6%	60	0.48	130	0	196	1158	671	157

Notes: CA is coarse aggregate; FA is fine aggregate; 1 kg/m^3 = 1.686 lb/yd^3.

again removed using the air compressor and the specimens were weighed once again. This procedure was repeated for six cycles on duplicate specimens, after which the total mass loss was averaged and reported.

A depth-sensing indentation (DSI) system was employed to evaluate surface hardness of the concrete specimens. The device was a testing machine with a high-precision load cell and a standard Vickers attached indenter in the shape of a square-based pyramid with a thickness of 0.3 mm. Square specimens of size 100 x 100 mm were cut from the middle of the beams perpendicular to the surface, and the indentation areas were carefully selected using a 100× digital zoom function so that the indenter could only touch the cement paste within the topmost 5 mm of the surface. With all tests conducted by the same operator, the indent test was performed very carefully to ensure that the results were obtained from the paste only and not affected by aggregate and/or air voids. The DSI test was performed at least 10 times at a selected maximum load level of 50 N, and the average values were reported.

Scaling specimens were cast in accordance with the BNQ NQ 2621-900[11] test method. This method requires rectangular prisms of size 300 x 200 x 82 mm or an equivalent surface area of 0.06 m^2. After applying the specified curing regime, 7 days of pre-saturation was carried out using brine with 3% NaCl concentration. The specimens were then subjected to freezing and thawing (F-T) cycles of 16 hours freezing and 8 hours thawing for 45 days. After every five cycles, the test surfaces were washed with a similar deicing solution and the residues collected and dried in an oven at 110°C for 24 hours. Thereafter, the weight of the dried residues was measured and the average for the two specimens reported.

RESULTS AND DISCUSSIONS

Abrasion resistance

Figure 2 shows abrasion-mass-loss evolution, relative to total mass loss, of the concrete specimens for six test cycles. It can be generally observed that, on average, 45% of the total abrasion mass loss can be attributed to the first two cycles, with each further cycle causing about 14% of the total mass loss. This implies that a two-cycle abrasion test would be sufficient to provide a useful estimation of the surface-layer hardness, while more testing cycles provide information about the base materials, and might result in misleading information with respect to concrete surface layer. Therefore, two challenges can be specified with respect to the abrasion resistance of concrete: 1) reducing the total abrasion mass loss; and 2) improving the quality of the surface layer so that during abrasion testing, each cycle contributes equally. In that direction, the uniformity of a concrete specimen can also be quantified through abrasion test. With these goals in mind, the effects of mixture proportion, curing regime, and finishing technique on the abrasion resistance of concrete specimens will be investigated in the following sections.

Effect of different factors on abrasion resistance

Mixture proportion—Figures 3(a) and (b) represent the total mass loss of concrete mixtures proportioned with different slag cement and air contents for *w*/*cm* of 0.35 and 0.55, respectively. For the mixtures made with *w*/*cm* of 0.35 (Fig. 3(a)), no significant trend in mass loss as a function of slag cement and/or air content was evident, with results varying between 3.5 and 6.5 g (0.008 and 0.014 lb). This is most likely due to the dominant effect of *w*/*cm* over air content and slag cement incorporation, so use of a *w*/*cm* as low as 0.35 secured a high-quality paste. For mixtures proportioned with *w*/*cm* of 0.55 (Fig. 3(b)), on the other hand, use of slag cement resulted in a significant reduction in total abrasion mass loss. This could be attributed to the enhanced paste quality in light of the pozzolanic activity of the slag cement,[13-15] as well as lower risk of bleeding in the mixtures' fresh state. It should be noted that the improving impact of slag cement on concrete abrasion is a compound effect, meaning that the effect of changes in both the fresh state (lowering the bleeding) and the hardened state (higher density and strength) resulting from the use of slag cement alters the concrete abrasion resistance. It was observed that while the total mass loss increased with higher air content, this trend somehow diminished as a result of slag-cement incorporation.

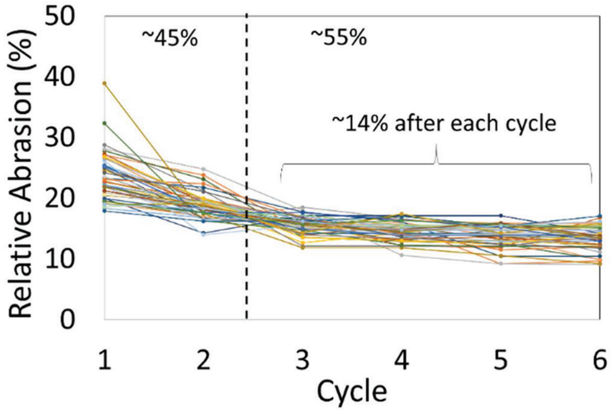
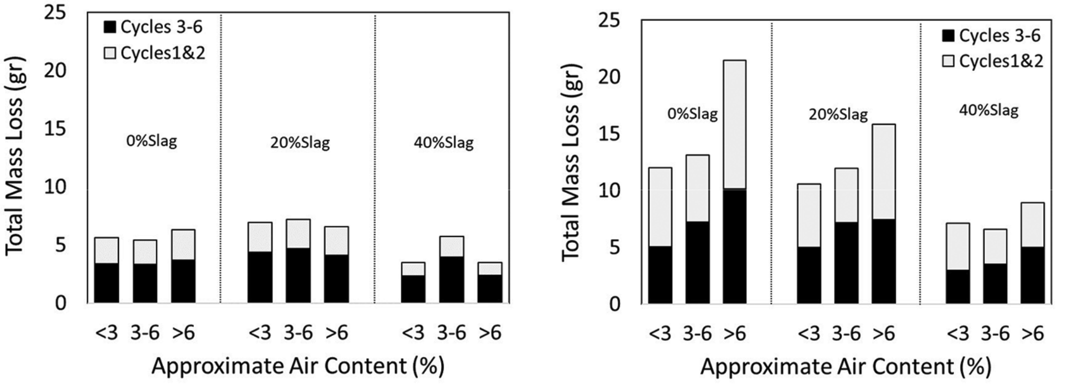


Fig. 2—Abrasion resistance of mixtures for six cycles.

Figure 4 shows the correlation between mixture proportion and abrasion mass loss of the first two cycles relative to the total mass loss. The dashed line presents the required mass-loss limit (32%) for the first two cycles (out of six cycles, based on this study) to achieve uniform quality throughout the concrete depth. It can be observed that concrete uniformity is influenced by *w*/*cm*, slag cement, and air content, with *w*/*cm* having the greatest impact. It is evident that for mixtures proportioned with *w*/*cm* of 0.35, the performance was close to the mass-loss limit line, likely owing to low risk of bleeding in such mixtures. In addition, the effect of slag cement replacement and air content seems to be negligible for mixtures proportioned with *w*/*cm* of 0.35, while at higher *w*/*cm*, both slag cement and air can improve the surface hardness. Comparing the results corresponding to *w*/*cm* of 0.55 in Fig. 3(b) and 4 indicates that, although air entrainment increases the total mass loss, it can improve abrasion resistance of the surface layer (first two cycles), possibly by mitigating the risk of bleeding that consequently improves the surface hardness and increase the surface resistance to abrasion. For example, for *w*/*cm* of 0.55 and a given slag cement replacement, the minimum surface abrasion was achieved by the mixtures with 3 to 6% air content (Fig. 4). Moreover, although entrained air contributes to lower bleeding, it simultaneously reduces concrete hardness, so it is likely that this disadvantage of air entrainment governs its effects when concrete contains more than 6% air.

Finishing—Figure 5 illustrates the effect of finishing time on abrasion resistance. All investigated mixtures were proportioned with a fixed *w*/*cm* of 0.48, more than 6% air content, and slag cement replacement varying from 0 to 60%. Finishing time significantly influenced abrasion resis-



(a) (b)

Fig. 3—Total abrasion of mixtures made with w/cm *of: (a) 0.35; and (b) 0.55. (Note: 1 g = 0.002 lb.)*

tance of the mixtures, and finishing after the cessation of bleeding improved abrasion resistance by up to 40%.

The results reflected a decrease in abrasion mass loss when up to 40% slag cement was used, and a higher mass loss with greater slag-cement content. The lowest sensitivity with respect to finishing time was observed for the concrete proportioned with 40% slag cement, while the highest variation in results was attributed to the plain concrete specimens. In general, the observed data suggests that cessation of bleeding should be considered as the optimal time for finishing concrete mixtures. In general, the highest mass loss was observed for specimens finished right after casting.

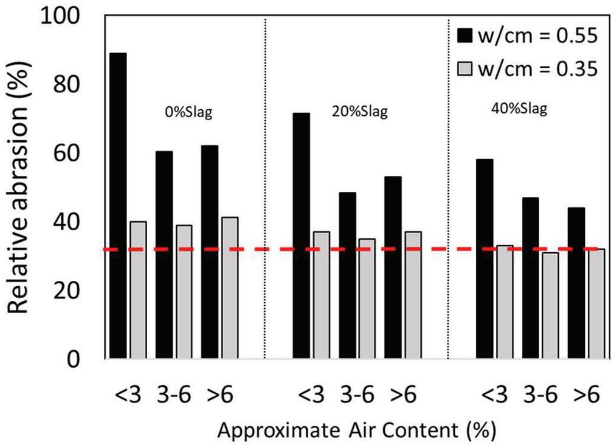


Fig. 4—Abrasion after two cycles relative to total mass loss of mixtures.

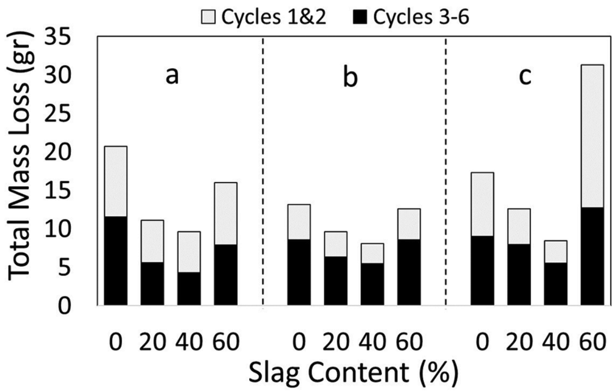


Fig. 5—Total abrasion of mixtures subjected to different finishing. (Note: 1 g = 0.002 lb.)

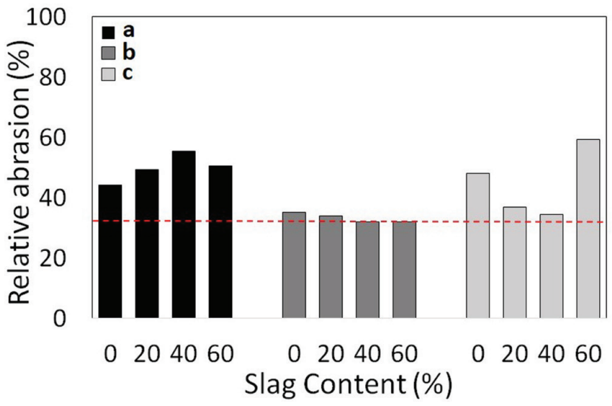


Fig. 6—Abrasion after two cycles relative to total mass loss of finishing specimens.

Figure 6 shows the correlation between finishing time and abrasion mass loss during the first two cycles relative to the total mass loss. It can be observed that, regardless of the slag-cement content, finishing after the end of bleeding resulted in superior abrasion resistance with respect to total mass loss and uniformity. A microscopic evaluation of the near-surface area of the plain cement specimens explaining these findings is shown in Fig. 7, where it can be observed that the specimen subjected to finishing method *a* (immediately after casting; Fig 7(a)) has the greatest paste content on the surface among the three specimens, with coarse aggregates at the furthest depth below the surface. For the specimen that was finished using method *b* (after bleeding has stopped; Fig 7(b)), coarse aggregates are at the top with minimum distance from the surface. It is also evident that finishing method *c* (finishing at the initial set; Fig 7(c)) has improved the surface properties to some extent compared to method *a*. Similar results were obtained for other mixtures.

Curing regimes—Figure 8 presents the effects of different curing regimes on abrasion resistance. The investigated mixtures were prepared with a *w*/*cm* of 0.48, an air content higher than 6%, and slag cement replacements of 0, 20, 40, and 60%. The considerable spread in the data presented in this figure suggests that the curing procedure has a more pronounced effect on abrasion resistance than the slag cement incorporation and finishing time.

Although incorporation of up to 40% of slag cement improved the abrasion resistance of the mixtures, a higher slag-cement content reduced the surface hardness. This behavior can most likely be attributed to the fact that, by the time of testing, not all the cementitious materials had participated in pozzolanic reaction for the case of high slag-cement replacement. However, the effect was less significant and even a reduction in mass loss was observed when elongated curing periods of 28 days moist curing were instituted.

Independent of the slag-cement content, the minimum mass loss was observed for specimens exposed to 28 days of moist curing, while the lowest resistance to abrasion damage was delivered by the specimens subjected to only 3 days of compound curing.

Figure 9 shows the correlation between curing regime and abrasion mass loss during the first two cycles relative to the total mass loss. It is evident that incorporation of 60% slag cement negatively affects surface hardness of the specimens except for the curing regime of 28m, most likely due to the fact that at higher slag-cement replacement, 28 days of moist curing is sufficient in terms of length and method so that all the cementitious materials can participate in the pozzolanic reaction. Generally, when specimens are subjected to shorter curing periods, mixtures containing 20% of slag cement exhibited superior performance in terms of abrasion resistance.

Relationships of abrasion to surface hardness, strength, and salt scaling—Figure 10 shows the overall correlation between concrete compressive strength and abrasion mass loss obtained through this study. The investigated mixtures were proportioned with various mixture ingredients, curing conditions, and finishing scenarios. In general, a tendency to lower

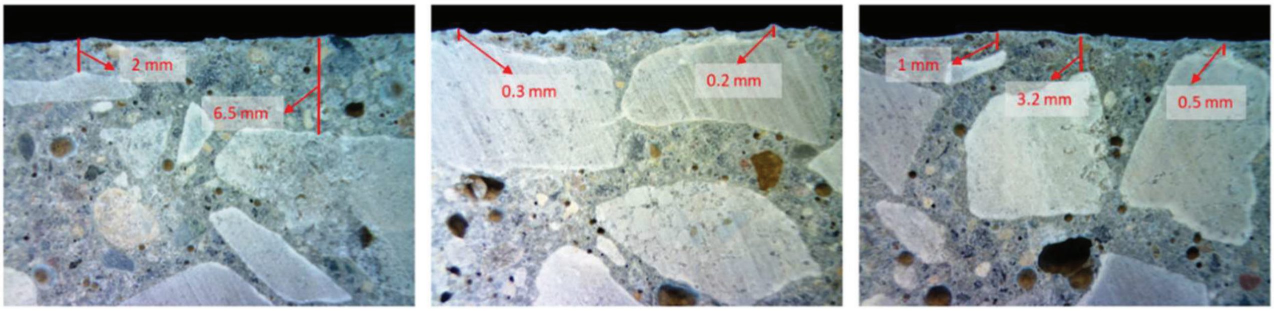


Fig. 7—Microscopic inspection of surface layer of plain specimens with different finishing procedures: Finishing a (left); Finishing b (middle); and Finishing c (right). (Note: 1 mm = 0.0394 in.)

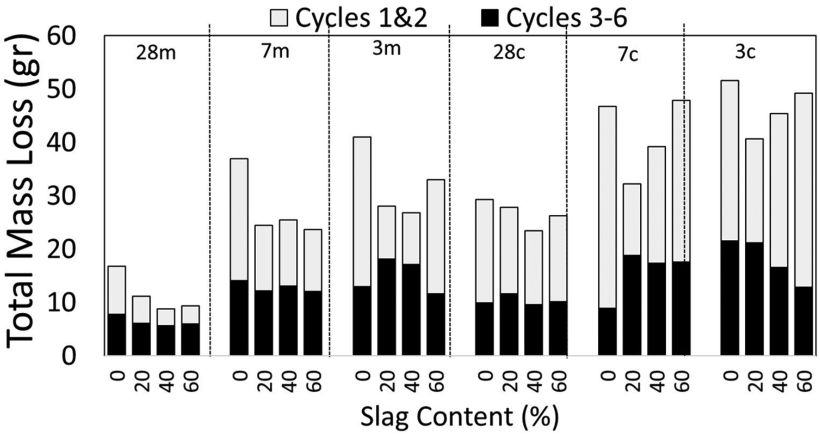


Fig. 8—Total abrasion of mixtures subjected to different curing regimes. (Note: 1 g = 0.002 lb.)

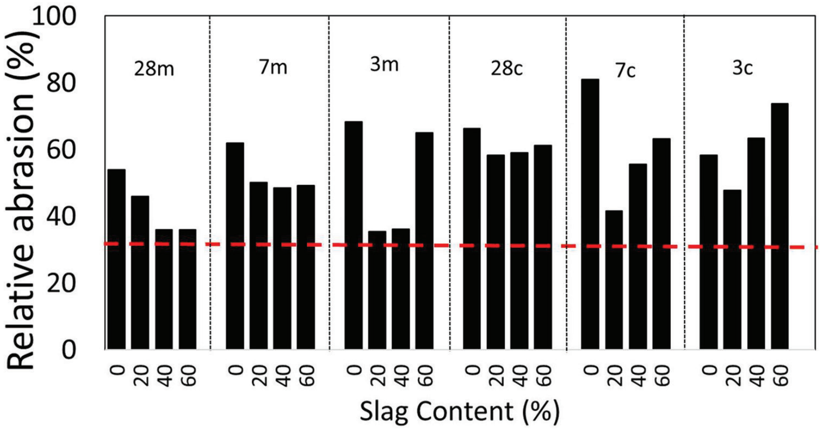


Fig. 9—Abrasion after two cycles relative to total mass loss of curing specimens.

abrasion mass loss as a reduction in compressive strength was expected considering results reported in the literature.[4] It was observed that an increase in compressive strength above a certain limit, approximately 35 MPa (5000 psi), did not enhance concrete resistance against abrasion.

It can be seen in the figure that there are some crossings between the data points, indicating that specimens with same compressive strength values may exhibit different abrasion resistance. This is not surprising given that the investigated mixtures were subjected to various curing regimes and finishing timelines.

Correlation between surface micro hardness and abrasion mass loss of the concrete specimens are illustrated in Fig. 11. A strong correlation was observed that was best represented by a linear fit with a R^2 of 0.86. The results presented in this figure demonstrate reduction in abrasion mass loss as a function of increase in surface micro hardness, regardless of the concrete mixture proportions—that is, *w*/*cm*, slag cement, and air content.

It has been shown that there is a robust relationship between abrasion and salt scaling mass loss values,[16] even though this relationship can be deceptive when the mixtures contain slag cement. For example, Fig. 12 illustrates the relationship between salt scaling and abrasion mass loss for different binary systems. Although the figure initially shows no clear trend, comparisons among different abrasion test cycles help in developing the following interpretations. The correlation between abrasion and salt scaling can be best noticed for a given mixture when abrasion mass loss values reflect only the surface layer hardness (cycles 1 and 2), and this correlation

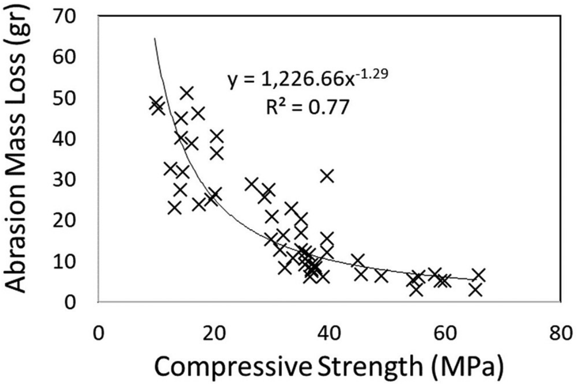


Fig. 10—Relationships between compressive strength and abrasion resistance of mixtures. (Note: 1 MPa = 145 psi.)

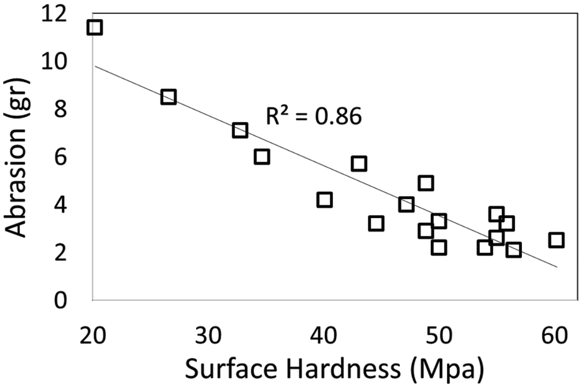


Fig. 11—Relationship between surface micro hardness and abrasion resistance of mixtures. (Note: 1 MPa = 145 psi.)

becomes insignificant/poor when further cycles are applied. According to this figure, correlation between abrasion and salt scaling may vary depending on the slag-cement content, so it would be challenging to develop a generalized model derived from such a correlation. Table 3, therefore, categorizes salt scaling values based on abrasion mass loss, in a three-dimensional space. Further data may be collected to adjust this table with ASTM and BNQ standard classifications.

CONCLUSIONS

Effects of various mixture proportions involving different *w*/*cm*, slag cement, and air content, as well as various curing regimes and finishing times on the surface-abrasion resistance (hardness) of concrete were assessed. In addition, the correlation between surface hardness and concrete hardened performance was evaluated. Based on the results reported herein, the following conclusions can be highlighted:

- Among the investigated mixture constituents, *w*/*cm* was found to have the highest impact on concrete surface hardness, so that the effect of slag cement and air content variation on the performance of concrete specimens made with *w*/*cm* of 0.35 was negligible, while an adequate level of air entrainment (3 to 6% air content) was found beneficial for mixtures made with *w*/*cm* of 0.55.
- For a given slag cement replacement, mixtures made with 3 to 6% air content exhibited the least abrasion mass loss compared to mixtures containing <3% (non-air entrained) or higher than 6% air content. In addition, while slag cement replacement up to 40% appeared to improve surface properties, at higher replacement levels, it negatively affected concrete abrasion resistance.
- The lowest sensitivity to finishing time was observed for concrete proportioned with 40% slag cement, while the highest spread in results was attributed to plain concrete. In general, mixtures finished after cessation of bleeding exhibited superior performance with respect to concrete surface hardness.
- Curing method and length appeared to have more pronounced effects on abrasion resistance than slag-cement incorporation and finishing time. Regardless of the slag cement content, the minimum mass loss was found in specimens exposed to 28 days of moist curing, while the minimum resistance to abrasion damage was delivered by specimens subjected to only 3 days of compound curing. In addition, plain specimens exhibited higher susceptibility to curing regime than mixes containing slag cement.
- A fairly linear relationship between surface micro hardness and abrasion mass loss was established. It was also found that abrasion becomes independent of compressive strength after a certain limit of strength, approximately 35 MPa (5000 psi), was reached.
- The salt-scaling classification table was developed based on abrasion mass loss results. The table may be useful for researchers and engineers in the field for quickly estimating in-place concrete salt-scaling resistance and quality.

Table 3—Salt scaling classification based on abrasion mass loss

Salt scaling mass loss range, g/m^2	Abrasion mass loss range, g			
	0% SC	20% SC	40% SC	60% SC
0 to 500	—	—	—	—
500 to 1000	0 to 10	0 to 5	0 to 5	—
1000 to 1500	10 to 30	5 to 15	0 to 5	—
1500 to 2000	30 to 45	10 to 20	5 to 15	—
>2000	>45	>20	>15	>5

Notes: SC is slag cement; 1 g/m^2 = 0.0002 lb/ft^2.

AUTHOR BIOS

Kamran Amini *is a Quality Control Manager at Titan America, LLC. He received his PhD from Iowa State University, Ames, IA. His research interest includes durability of concrete and cement-based materials, nondestructive testing, pervious concrete, patching materials, and self-consolidating concrete.*

ACI member **Seyedhamed Sadati** *is an Assistant Scientist at Iowa State University. He is a member of ACI Committees 236, Material Science of Concrete; 325, Concrete Pavements; and 555, Concrete with Recycled Materials. His research interests include durability of concrete and cement-based materials, sustainability, and properties of concrete made with recycled aggregate.*

Halil Ceylan *is Professor in the Civil, Construction, and Environmental Engineering (CCEE) Department at Iowa State University.*

Peter C. Taylor, *FACI, is the Director of the National Concrete Pavement Technology Center at Iowa State University. He is President-Elect of the Iowa Chapter – ACI.*

ACKNOWLEDGMENTS

This study is based on work supported in part by the Portland Cement Association (PCA) through the Education Foundation's J. P. Gleason Fellowship.

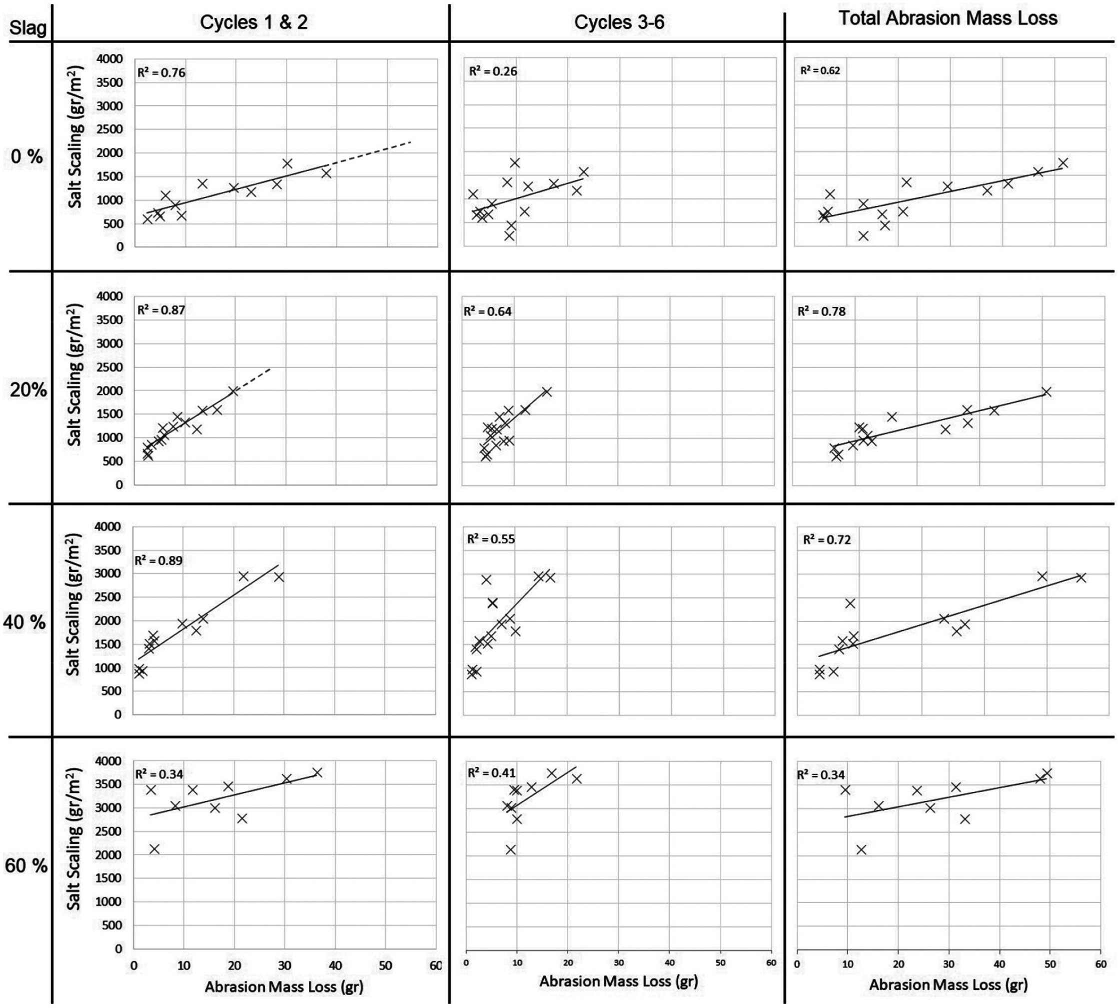


Fig. 12—Relationship between salt scaling and abrasion mass loss of mixtures. (Note: Dashed lines are extended trendlines to predict salt scaling up to 2100 kg/m^2; 1 kg/m^2 = 0.2 lb/ft^2.)

The conclusions expressed herein are the conclusions of the authors and not necessarily those of the PCA. The authors gratefully acknowledge this support.

REFERENCES

1. Carrasco-Maldonado, F.; Spörl, R.; Fleiger, K.; Hoenig, V.; Maier, J.; and Scheffknecht, G., "Oxy-Fuel Combustion Technology for Cement Production – State of the Art Research and Technology Development," *International Journal of Greenhouse Gas Control*, V. 45, 2016, pp. 189-199. doi: 10.1016/j.ijggc.2015.12.014

2. Olivier, J. G. J.; Janssens-Maenhout, G.; Muntean, M.; and Peters, J. A., "Trends in Global CO$_2$ Emissions: 2015 Report," European Commission, Joint Research Centre, 2015, 80 pp.

3. Suraneni, P.; Monical, J.; Unal, E.; Farnam, Y.; and Weiss, J., "Calcium Oxychloride Formation Potential in Cementitious Pastes Exposed to Blends of Deicing Salt," *ACI Materials Journal*, V. 114, No. 4, July-Aug. 2017, pp. 631-641. doi: 10.14359/51689607

4. Kosmatka, S., and Wilson, M., *Design and Control of Concrete Mixtures: The Guide to Applications, Methods, and Materials*, Portland Cement Association, Skokie, IL, 2011, 458 pp.

5. Sonebi, M., and Khayat, K., "Testing Abrasion Resistance of High-Strength Concrete," *Cement, Concrete and Aggregates*, V. 23, No. 1, 2001, pp. 34-43. doi: 10.1520/CCA10523J

6. Glinicki, M., and Zielinski, M., "Frost Salt Scaling Resistance of Concrete Containing CFBC Fly Ash," *Materials and Structures*, V. 42, No. 7, 2009, pp. 993-1002. doi: 10.1617/s11527-008-9438-y

7. Tremblay, M.-H.; Lory, F.; Marchand, J.; Scherer, G. W.; and Valenza, J. J., "Ability of the Glue Spall Model to Account for the Deicer Salt Scaling Deterioration of Concrete," *Proceedings, 12th International Congress on the Chemistry of Cement*, Montreal, QC, Canada, 2007.

8. Amini, K.; Cetin, K.; Ceylan, H.; and Taylor, P., "Development of Prediction Models for Mechanical Properties and Durability of Concrete Using Combined Nondestructive Tests," *Journal of Materials in Civil Engineering*, ASCE, V. 31, No. 2, 2019, p. 04018378. doi: 10.1061/(ASCE)MT.1943-5533.0002569

9. ACI Committee 233, "Slag Cement in Concrete and Mortar (ACI 233R-03) (Reapproved 2011)," American Concrete Institute, Farmington Hills, MI, 2003, 18 pp.

10. ASTM C31/C31M-10, "Standard Practice for Making and Curing Concrete Test Specimens in the Field," ASTM International, West Conshohocken, PA, 2010, 6 pp.

11. BNQ NQ 2621-900, "Determination of the Scaling Resistance of Concrete Surfaces Exposed to Freezing-and-Thawing Cycles in the Presence of De-icing Chemicals," Bureau de Normalisation du Québec, Québec, QC, Canada, 2002, pp. 19-22.

12. ASTM C944/C944M-12, "Standard Test Method for Abrasion Resistance of Concrete or Mortar Surfaces by the Rotating-Cutter Method," ASTM International, West Conshohocken, PA, 2012, 5 pp.

13. Puertas, F.; Palacios, M.; Manzano, H.; Dolado, J. S.; Rico, A.; and Rodríguez, J., "A Model for the C-A-S-H Gel Formed in Alkali-Activated Slag Cements," *Journal of the European Ceramic Society*, V. 31, No. 12, 2011, pp. 2043-2056. doi: 10.1016/j.jeurceramsoc.2011.04.036

14. Richardson, I. G.; Brough, A. R.; Groves, G. W.; and Dobson, C. M., "The Characterization of Hardened Alkali-Activated Blast-Furnace Slag Pastes and the Nature of the Calcium Silicate Hydrate (C-S-H) Phase," *Cement and Concrete Research*, V. 24, No. 5, 1994, pp. 813-829. doi: 10.1016/0008-8846(94)90002-7

15. Brough, A., and Atkinson, A., "Sodium Silicate-Based, Alkali-Activated Slag Mortars: Part I. Strength, Hydration and Microstructure," *Cement and Concrete Research*, V. 32, No. 6, 2002, pp. 865-879. doi: 10.1016/S0008-8846(02)00717-2

16. ACI Committee 201, "Guide to Durable Concrete (ACI 201.2R-08)," American Concrete Institute, Farmington Hills, MI, 2008, 49 pp.